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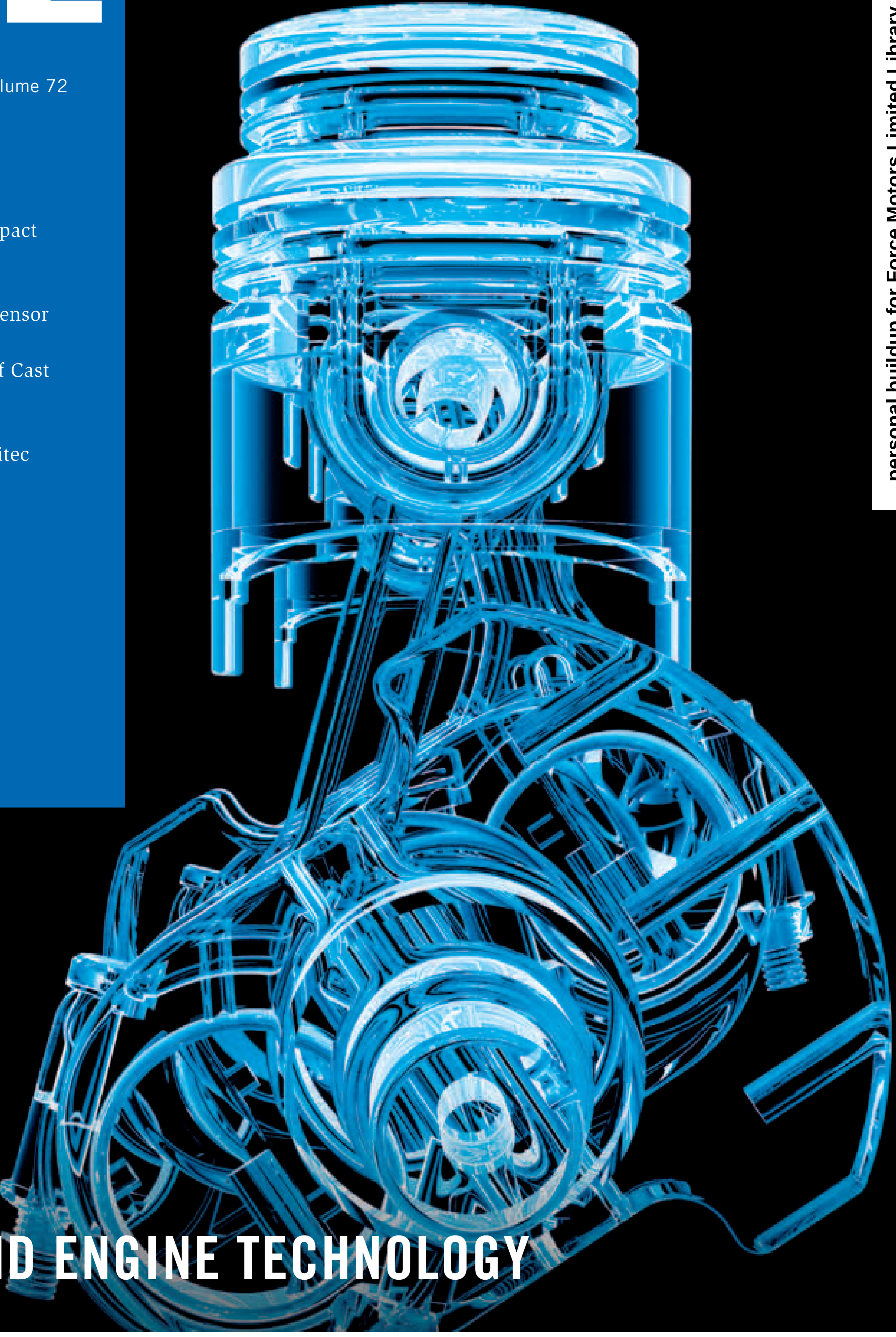

DEVELOPMENT of a Compact Range Extender Engine

IN-CYLINDER Pressure Sensor

LIFETIME ESTIMATION of Cast Iron Components

SPECIAL 25 Years of Emitec

HIGH-END ENGINE TECHNOLOGY

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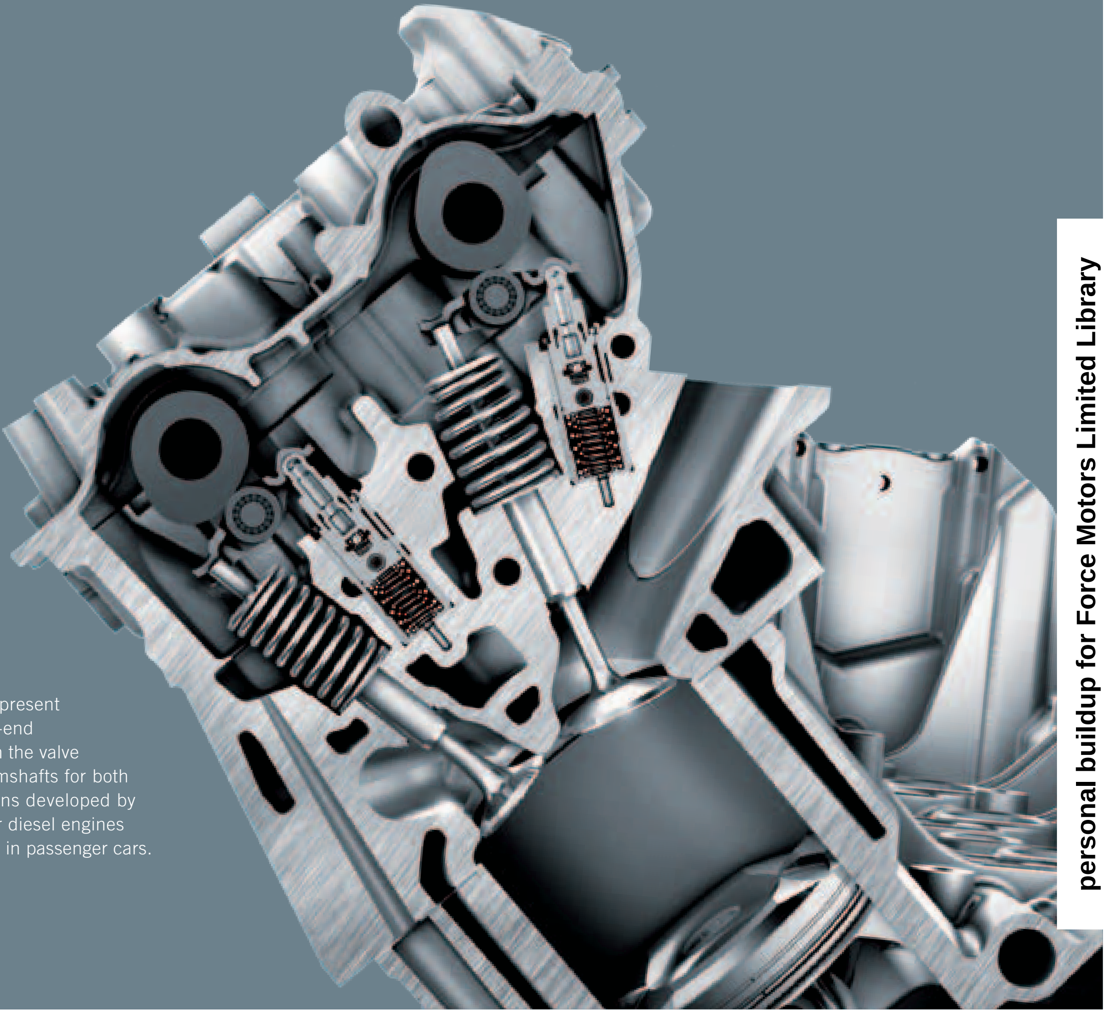

COVER STORY

HIGH-END ENGINE TECHNOLOGY

4, 10 I In the cover story of this issue, we present the latest examples of innovations in high-end engine technology. BorgWarner focuses on the valve train and presents concentric variable camshafts for both petrol and diesel engines. The steel pistons developed by Kolbenschmidt are relevant exclusively for diesel engines and are designed especially for application in passenger cars.

COVER FIGURE © [M] Saulius L I shutterstock
FIGURE ABOVE © Daimler

SAVING ACCEPTED

Dear Reader,

Until the circle to a successful product closes, many obstacles and often contradictory factors need to be overcome. This does not apply exclusively to the automotive sector, but our industry does have its special demands. The challenge of minimising costs through research, development and production is in conflict with the purely technical challenge of complying with emissions standards. Difficult to resolve, but for that very reason a key driving force behind the industry's high level of innovation.

Achieving the acceptance of the – by no means uncritical – end customer with cost-efficient and effective technologies is a balancing act. This is true of all vehicle classes and technical approaches.
A hybrid drive system is certainly perceived by the buyer as being economical, but from a cost perspective it still remains a problem child for the time being. New downsized engines are no doubt suitable for a wider field, but also not without their limitations. Customers have high demands regarding comfort and performance, and in addition to technical limits, costs quickly become a limiting factor in this case too. And in the higher vehicle classes, it remains to be seen whether car buyers will accept the image loss of having fewer cylinders.

The alternative is to optimise existing engines. From an engineering perspective, many things are still possible, and even sophisticated developments can be implemented cost-effectively on a wide scale, for example through a top-down strategy. Usually, it is the application of many different measures at the same time that leads to the necessary reduction in fuel consumption. It is then a matter of communicating this package to the end customer in comprehensible way.

The IAA will focus precisely on this issue: putting different concepts on the market. And I look forward to meeting you there (Hall 4.1, MTZ Stand E20) to discuss the numerous exciting approaches.

Yours,

RUBEN DANISCH, Vice Editor-in-Chief
Wiesbaden, 18 August 2011

CONCENTRIC CAMSHAFT SYSTEM FOR GASOLINE AND DIESEL ENGINES

BorgWarner and ThyssenKrupp Presta have jointly developed a system of phaser and adjustable concentric camshafts that are applicable to both diesel and gasoline engines. Comprehensive simulation work and experimental investigations on an engine dyno have proven considerable potential for reducing emissions and improving fuel consumption.

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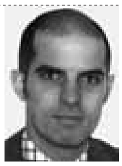

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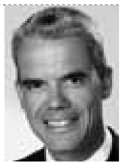

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POTENTIAL FOR REDUCTION OF EMISSIONS AND FUEL CONSUMPTION

Concentric camshafts have been in production for use on overhead valve engines, where they allow to vary valve overlap [1]. But this technology also offers potential for emission reduction and improved fuel economy on modern overhead camshaft gasoline and diesel engines. BorgWarner and ThyssenKrupp Presta commonly developed a whole family of so called Concentric-Cam systems, which consist of phaser technology of BorgWarner and assembled camshafts from ThyssenKrupp Presta. The functionality the system offers goes beyond what is available in the market today.

BASE COMPONENTS

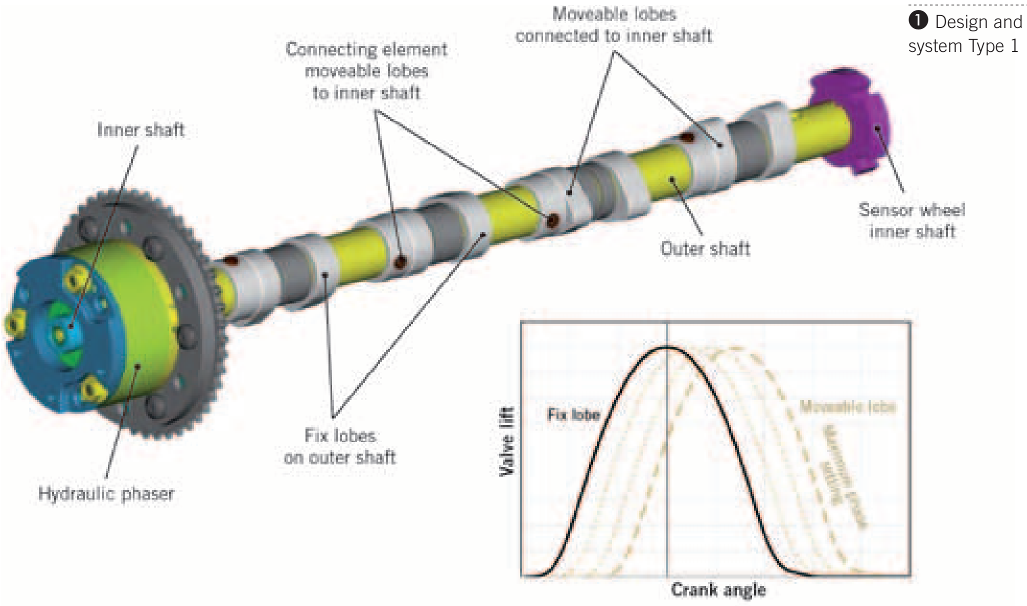
The described systems are based on BorgWarner's cam phaser and ThyssenKrupp's assembled camshaft technology. Both components have distinct characteristics that support the functionality of the system. In general, every BorgWarner phaser technology can be used for the Concentric-Cam: the conventional OPA (Oil Pressure Actuated) phaser, the CTA (Cam Torque Actuated) phaser or the TA (Torque Assisted) phaser. The OPA phaser operates with oil from the engine, the CTA phaser uses cam torque fluctuations to phase one camshaft with respect to the other with the benefit of faster actuation rates and very low oil consumption. The TA represents the synergy between the CTA and the OPA and is particularly well suited for the Concentric-Cam because it combines good applicability with fast actuation rates and low oil consumption.

The outer camshaft is assembled using Presta's knurling technology. Cam lobes are pressed on to the camshaft axially at defined positions and angles creating force closure and a form fit connection. Advantages of this process are reproducibility and high production quality. Other benefits are significant weight savings through application specific choice of materials, tight production tolerances as well as the possibility to integrate functions like oil separation. Even integrating camshaft and bearings into a preassembled ladder frame is possible [2, 3].

DESIGN AND FUNCTION

The cam phasers as well as the assembled camshafts are production proven and cost optimized components. What is novel is the concept of combining them to different versions of the Concentric-Cam. The different versions are similar in many aspects: the cam lobes are connected to the two concentric camshafts in a way that rotating one lobe with respect to the other is possible. The fixed lobes are assembled on the outer camshaft and the moveable lobes are pinned to the inner camshaft. Radial slots in the outer camshaft provide the necessary clearance to rotate the inner with respect to the outer cam lobes.

A concentric camshaft system Type 1 design is shown in ❶. The cam phaser rotor is connected to one, and the phaser housing to the other concentric camshaft. An alternative design called Type 2 is similar in many ways. However each of the camshafts is connected to at least one part of a split cam lobe. Acting on a common rocker arm (handoff principle), the Type 2 system allows adjusting the



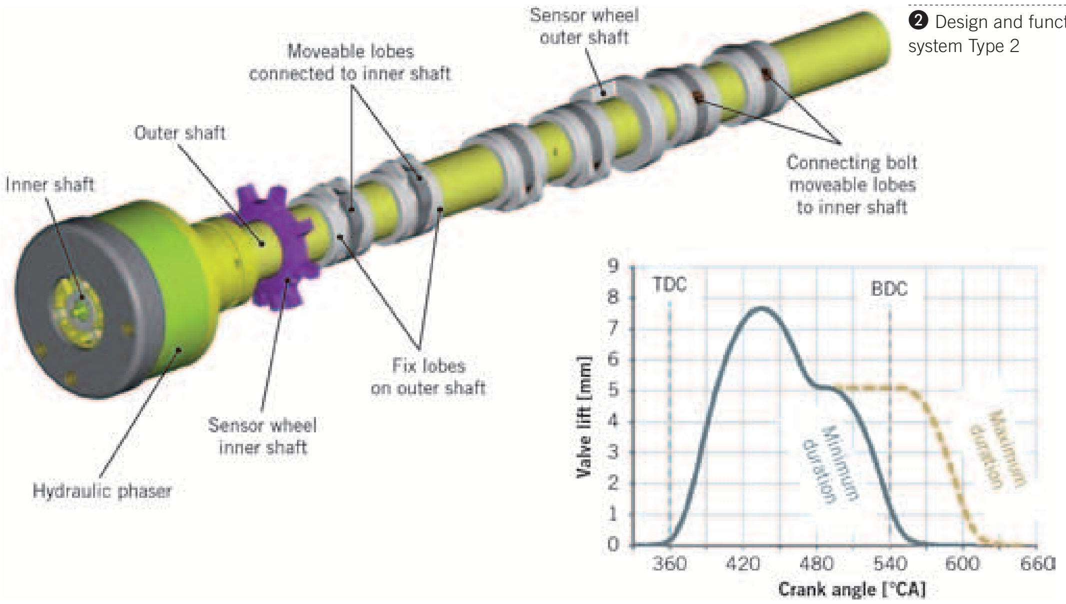
❶ Design and function of the concentric camshaft system Type 1

duration of the valve event. To avoid tilting of the rocker arm due to eccentric forces, one design option is to use two fixed outer and one rotatable inner cam lobe as shown in ❷. However, depending on the rocker arm design, a dual lobe solution can also be an option. ❸ shows a detailed view of a production feasible triple lobe design.

For the Type 2 system, valve train simulations and component testing showed that an adjusted cam lobe profile is required to achieve acceptable dynamics while fulfilling thermodynamic targets. Various cam lobe profiles were evaluated. A profile with desired characteristics regarding both gas exchange and durability was found. The resulting valve lift curves are shown in ②. All tests were completed without any noticeable valve train wear and confirmed the predicted good thermodynamic performance, especially at full load.

The valve lift curve of the Type 2 system is defined by a first section, in which a peak lift very similar to the base valve train is achieved, and a second section which defines the duration of the valve event. The relationship between peak valve lift and maximum achievable duration is variable, however with a certain dependency. A compromise between peak lift and duration must be found for each specific application. A reversal of the valve lift characteristic, with peak lift in the second half of the valve event and consequentially the ability to advance the valve opening, is also possible.

On diesel engines, slightly lower peak lift in combination with variable duration allows opening the intake valve slightly earlier without valve/piston collision. In combination with seat chamfers, swirl can be influenced, which can help reduce smoke in some areas of the engine map. One can



❷ Design and function of the concentric camshaft system Type 2 easily see that when applying Type 2, trade-offs between peak lift, valve clearance, swirl and flow must be re-evaluated. The valve lift curve shown in ② is especially beneficial for a diesel engine. Possible application strategies will be described in the following chapters. To maximize the benefits of both Type 1 and Type 2 concentric camshaft systems, both systems can be combined with a second cam phaser. These systems are then called Type 4 and Type 3 respectively. The second phaser allows adjusting absolute valve event phase in addition to the relative changes within the valve event created by the first phaser.


❸ Concentric camshaft system Type 2 – detail view of the cam lobes

CONCENTRIC CAMSHAFT SYSTEMS FOR GASOLINE ENGINES

One opportunity to apply Concentric-Cam for gasoline engines is the so called Valve-Event Modulated Boost (VEMB) concept. Its principle is based on the fact that the exhaust stroke can be divided into the blow-down and the scavenging phase. During blow-down phase, most of the kinetic energy is transferred into the exhaust system while the scavenging phase – at lower temperatures and pressures – is responsible for the pumping losses incurred during the exhaust stroke. While the kinetic energy can be well utilized by the turbo charger turbine, the energy exhausted during the scavenging phase is lost to the turbine. During this phase, it makes sense for exhaust flow to bypass the turbine and expand to a much lower temperature and pressure. In-cylinder pressure at exhaust valve closing, in-cylinder residual gas and of course pumping work can then be significantly reduced.

In the VEMB concept, the flow split between blow-down and scavenge phase is achieved through the use of an exhaust side concentric camshaft Type 1 system. Two exhaust valves of one cylinder are phased with respect to each other. The blowdown exhaust port is connected to the turbine inlet, the scavenge port to the three way catalyst. Depending on the base engine, a fuel consumption reduction of 2 to 10 % throughout the whole engine map can be achieved by means of reduced pumping work and lower residual gas fraction. By allowing the turbo charger turbine to be bypassed during engine cold start, VEMB can provide additional emission potential [4].

CONCENTRIC CAMSHAFT SYSTEMS FOR DIESEL ENGINES

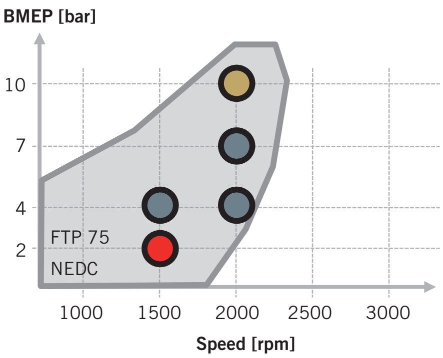
As described, Type 2 and Type 3 are especially beneficial for the diesel engine. Some of the effects achievable with a cam phaser and with Concentric-Cam (Type 1, 2 and 3) and also possible application strategies are summarized in ❹.

The Type 2 already shows significant potential for diesel engines, mainly through improving the NO_x/smoke trade-off but also providing a softer engine shut down. Greatly reduced smoke emissions also lead to shorter particulate filter regeneration intervals; this will lead to higher real world fuel economy, which can further be improved by the use of Type 3. Type 3, providing improved low end torque, is an enabler for downsizing and down speeding the engine without compromising transient performance.

❹ Application for diesel engines

TARGET	TECHNOLOGY				COMMENT
	CTA/TA CAM PHASER	CONCENTRIC-CAM SHAFTS			
		TYPE 1	TYPE 2	TYPE 3	
NO_x-/smoke mass tradeoff improvement			IV, EV	IV	Late intake valve closing combined with internal EGR
Swirl enhancement with less pumping losses	IV	IV		IV	Adjusted opening of one or both intake valves
Higher low end torque				IV+EV	Optimized scavenging More energy to the turbine through early exhaust valve opening
Faster engine transient response				IV+EV	Fast system response More energy to the turbine through early exhaust valve opening
Higher specific power			IV	IV	Low effective compression ratio combined with high pressure ratio boosting
Soot and NO_x after treatment support	IV, EV	IV, EV	IV+EV	IV, EV	Mass flow reduction (replacing a throttle body) combined with early exhaust valve opening
Soft engine start-stop (shut down shake)	IV	IV	IV	IV	Reduction of effective compression ratio during engine shut down

IV: Inlet Valve EV: Exhaust valve

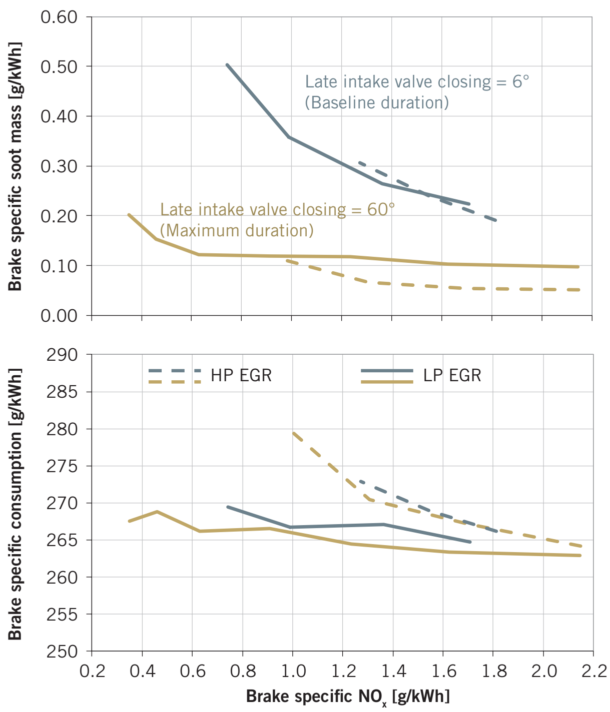


Point	$BSNO_x$	BSSoot	BSFC
1500/2	(Large coefficient of variation with late intake valve closing = 60°)		
1500/4	-24.5 %	-52 %	+1.3 %
2000/4	-23 %	-55 %	0 %
2000/7	-31 %	-20 %	+1.2 %
2000/10	-33 %	+5 %	+1.3 %

❺ Concentric camshaft system Type 2 for diesel engines: NO_x/smoke emissions and fuel consumption compared to the baseline when applying a "late intake valve closing" strategy (Atkinson)

In ❺, some key engine test results with the Type 2 system for a V6 diesel engine with 3.0 l displacement and a peak power of 115 kW are shown. The light duty truck engine is certified to meet the EPA 2007 US emission standards. A Concentric-Cam system was retrofitted on the intake side and a second, low pressure EGR loop was added to complement the stock high pressure EGR system. Apart from these modifications the engine hardware was left unchanged.

In principal, a concentric camshaft system adds a new degree of freedom to optimize emissions and fuel economy. In the following paragraphs, the potential shall be described in detail. Starting from the base intake event, duration was increased up to 60 in 20° increments. The engine was calibrated to run a so called Atkinson cycle. Keeping load, center of combustion and EGR rate constant, the timing and quantity of pilot and main injections as well as boost pressure were optimized. Engine operating points representative for the NEDC and FTP75 cycle were chosen. These points are listed in ⑤. Applying duration increases up to 60° at light to medium loads, significant improvements of the NO_x/soot mass tradeoff were achieved while maintaining fuel consumption nearly constant. Relative improvements compared to the baseline are also shown in ⑤. Below 2 bar BMEP however, combustion stability was compromised at maximum duration.



❻ Type 2 for diesel engines: engine test results varying high and low pressure EGR (operating point: n = 2000 rpm, BMEP = 4 bar)

At higher, less test cycle relevant load points (10 bar BMEP or more), NO_x could still be improved but at less smoke benefit. A different turbo charger would have allowed expanding the area of improvements to higher loads; however boosting hardware changes were not part of the work scope of this investigation.

In ❻, NO_x/soot mass tradeoff improvements at constant fuel consumption are shown, when applying low pressure instead of high pressure EGR at 2000 rpm and 4 bar BMEP. The emission benefits of late intake valve closing can therefore be found independent of the calibrated EGR rate and applied EGR technology. Parameter studies of various injection and boost related calibrations, not described in this report, also show clear synergies with late intake valve closing strategies [5, 6]. As one can see, a concentric camshaft technology now becomes a key building block on the path to lowest engine out emissions.

SUMMARY AND OUTLOOK

Based on production proven components, Concentric-Cam is a robust and cost effective technology with many different application opportunities for gasoline and diesel engines (passenger and commercial vehicles). Its ability to effectively integrate into a given cylinder head architecture can be considered another clear advantage over other variable valve train technologies. Through extensive simulations and engine testing, notable benefits in emissions and fuel economy were demonstrated.

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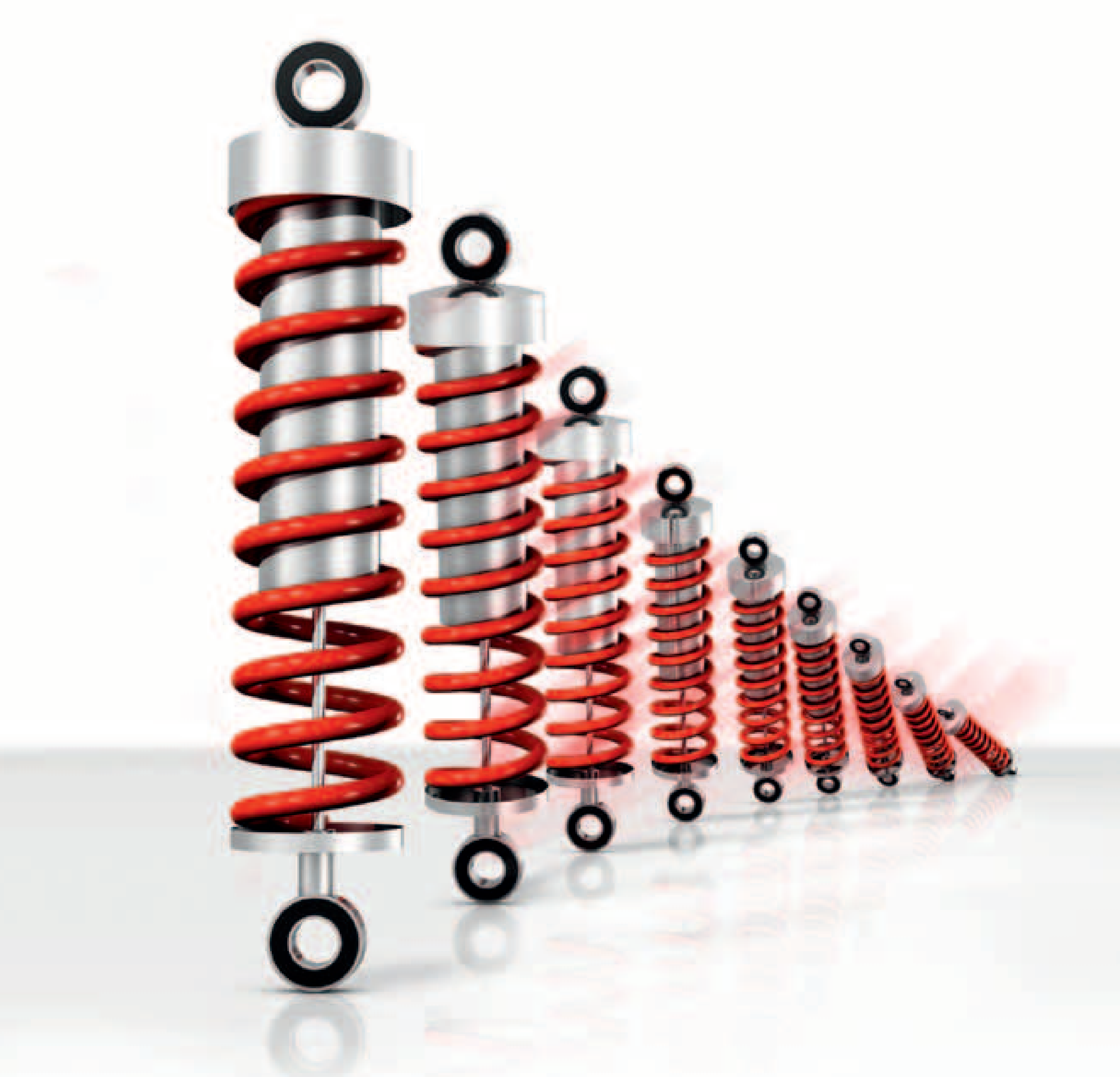

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STEEL PISTONS FOR PASSENGER CAR DIESEL ENGINES

Aluminium pistons have been used successfully for decades in passenger car vehicles. Yet rising thermal and mechanical loadings make the employment of steel as piston material increasingly attractive. In compliance with growing demands on loading capacity and functional performance KS Kolbenschmidt develops steel pistons for passenger car diesel engines.

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MOTIVATION

Demands placed on modern passenger car diesel engines have strongly increased in recent years. Downsizing concepts aimed at improving thermal and mechanical efficiency have experienced a rapid rise. As a direct consequence, specific engine performance has increased to more than 90 kW/l and peak cylinder pressures have climbed to more than 200 bar. The fatigue strength of today's aluminum alloy pistons is hardly sufficient to satisfy the resulting thermal and mechanical loadings. The time to introduce the higher strength steel piston material, combined with a robust piston design, is therefore fast approaching. This step has already been taken in the commercial vehicle sector some years ago [1].

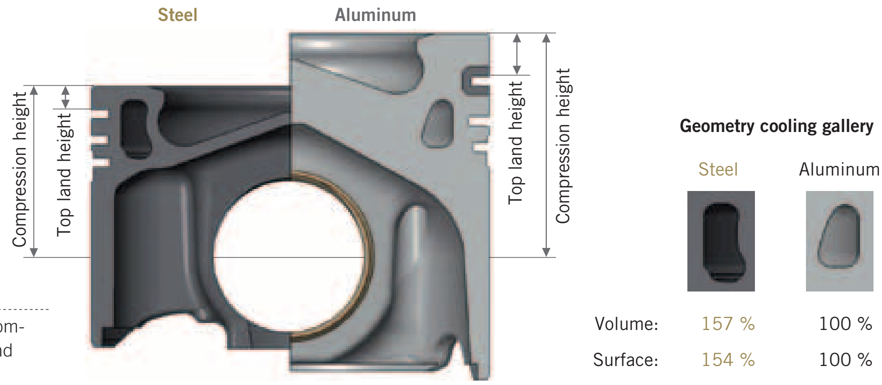
DESIGN LAYOUT

The steel piston patented by KS Kolbenschmidt consists of a one-piece forging. Using a special production process, the ring zone is shaped in such a way as to create an enclosed cooling gallery. The ring zone and piston skirt are then joined with each other. In order to achieve the same weight with steel as with today's aluminum alloys, the steel piston was conceived with low wall thicknesses, a large cooling gallery, and a low compression height.

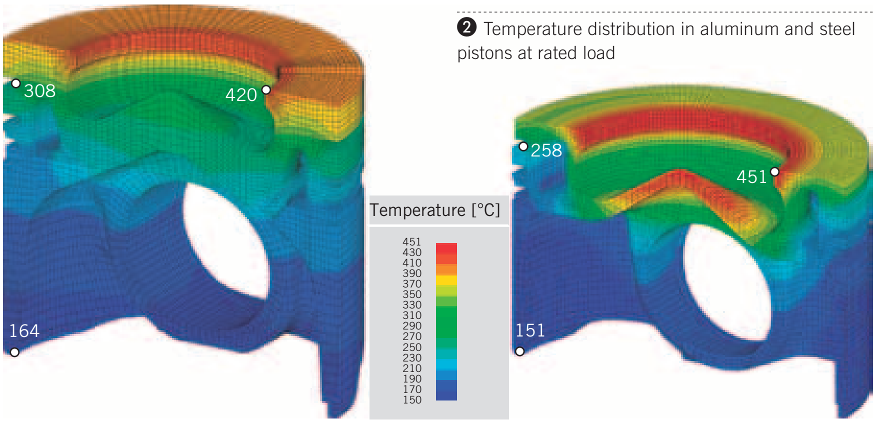
The compression height is determined by the necessary pin diameter, the connecting rod small end geometry and the combustion chamber bowl. It appears possible to reduce compression height by up to 30 % and top land height by up to 50 %, ❶. This allows the use of a longer connecting rod, which results in lower lateral forces with reduced friction at the piston skirt/cylinder interface. The compact design also allows a lower cylinder block height to be used in developing new engines. This not only means lower engine mass but also increased passive vehicle safety with respect to pedestrian protection.

The piston pin makes a significant contribution to the weight neutrality of the piston assembly. The length of the piston pin can be significantly reduced thanks to the 80 % higher permissible pin bore contact pressure achievable with steel. This compensates for a large part of the bare piston weight. An additional feature of the pin is a friction minimizing diamond-like carbon (DLC) coating.

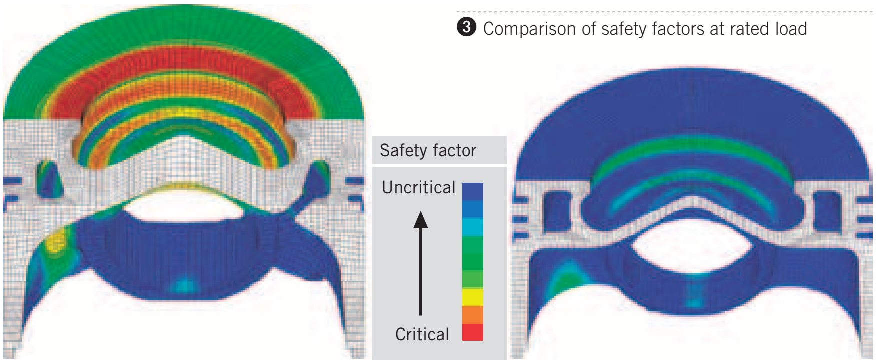
Piston cooling is highly important. Key factors in designing the cooling gallery include a small distance from the bowl rim as well as thermal shielding of the first ring groove. Compared to aluminum pistons the cooling gallery volume is 57 % larger, and



❶ Geometrical comparison of steel and aluminum pistons



❷ Temperature distribution in aluminum and steel pistons at rated load



❸ Comparison of safety factors at rated load

the effective gallery heat transfer surface 54 % larger, ①. Also important is the free inner cooling gallery height, which enables high heat flows during the piston stroke by convection (shaker effect). The design concept implemented by KS Kolbenschmidt removes the need for welding beads in the cooling gallery, which disrupt and therefore reduce heat transfer. The lower temperature level in the ring zone compared with aluminum pistons according to the analysis reduces ring groove carbonization as well as groove and piston ring wear over piston lifetime. The piston rings do not require special modification. The cooling oil flow must be adjusted in order to prevent the oil from overheating due to the elevated heat input. The material used is heat-treated steel 42CrMo4. This steel grade offers a very good compromise in terms of formability, joinability and machinability, tensile strength characteristics and scaling resistance for high specific engine outputs.

SIMULATION

Compared to aluminum, steel possesses a higher fatigue strength, which allows it to fulfill the demands placed on modern passenger car diesel engines with augmented power density and peak cylinder pressures of up to 250 bar [2]. The illustration in ❷ of the temperature distribution for both piston designs for identical engine performance demonstrates the influence of significantly lower thermal conductivity of steel. The larger cooling gallery in the steel piston shields the ring zone from the heat input into the combustion chamber bowl, such that the groove temperatures are more than 50 °C lower than with aluminum pistons. Temperature levels more than 30 °C higher arise in the bowl rim and bowl bottom.

A safety factor can be calculated by analysis of the load situation during a combustion cycle in connection with the temperature dependent strength characteristics of the respective material. The comparison in ❸ shows that the situation in the combustion chamber bowl area must be rated as critical for aluminum pistons. By contrast, the conditions for steel pistons are significantly less critical and offer reserves for additional performance improvement.

As a consequence of thermal expansion, an aluminum piston operates with a simultaneous load of the piston skirt on the thrust and anti-thrust sides over substantial parts of the engine operating map, i.e. the stroke movement occurs with interference fit between skirt and cylinder for the greatest portion of the combustion cycle. Increased assembly clearance is one measure for reducing frictional losses in this case [3]. With steel pistons the different material properties (thermal conductivity and expansion coefficient) result in lower or no overlap forces, so that friction losses only occur at the contacting side of the piston skirt. In connection with the minimised area and asymmetric design of the piston skirt surfaces, this effect leads to a 50 % decrease in average friction power at the observed partial load point, as shown in ❹.

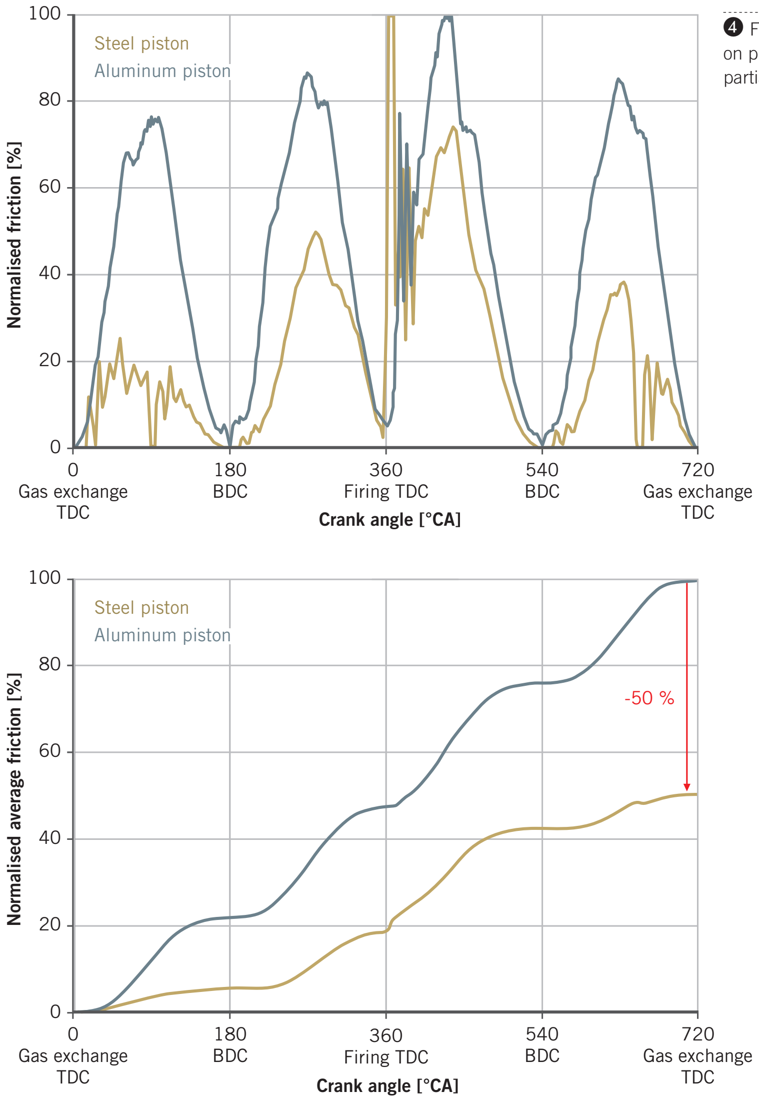
Due to the smaller assembly clearance the noise characteristics significantly improve at the operating point “cold idle”. The critical vibration excitation caused by the piston side change at FTDC causes an excitation level which is over 5 dB lower than that of the aluminum piston, shown for a representative point on the exterior wall of the cylinder in ❺. As a consequence of the less favorable warm clearance conditions at the operating point “partial load, warm”, careful piston design is necessary. With optimised skirt stiffness and support, an excitation level comparable to aluminum pistons can be achieved by using appropriate pin offset and skirt profile design.

ENGINE TEST

Various engine tests have been carried out with passenger car steel pistons on four-, six- and eight- cylinder engines in Euro 4 and Euro 5 applications. In addition to their basic functionality, steel pistons proved their operational stability in endurance tests with operating times of several hundred hours and peak cylinder pressures of up to 220 bar.

Initial piston temperature measurements were conducted on a V engine in Euro 4 application and with increased peak cylinder pressure of 190 bar. ❻ shows a comparison at rated power and speed of the temperature range measured at the bowl rim, in the first ring groove, and at the pin boss for aluminum and steel pistons respectively.

Bowl rim temperatures ranging from 360 to 420 °C are attained with aluminum pistons, whilst steel piston temperatures here range from 385 to 450 °C. Due to lower thermal conductivity of steel an



❹ Friction losses on piston skirt at partial load

approximately 30 °C higher temperature occurs at the bowl rim.

An approximately 50 °C lower temperature in the first ring groove is a characteristic feature of passenger car steel pistons. While aluminum pistons exhibit groove temperatures of 260 to 300 °C, the groove temperatures determined for steel pistons reach a significantly lower level of 220 to 245 °C as a result of longer heat conduction path between combustion bowl and ring zone, lower thermal conductivity of steel and a large cooling gallery with increased cooling oil flow.

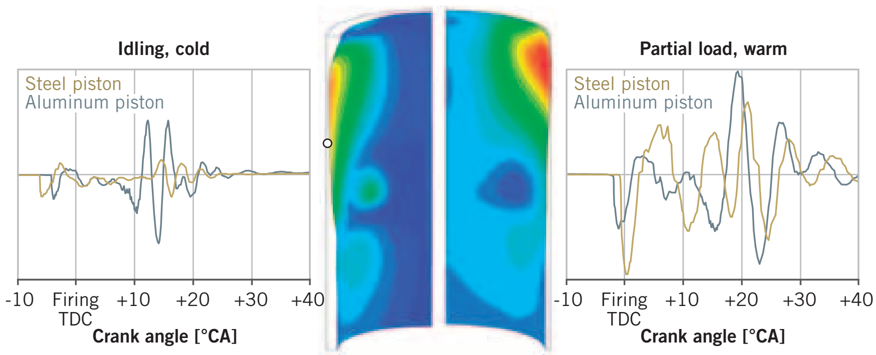
Pin boss temperatures measured for aluminum pistons are 230 to 250 °C. The significantly reduced compression height of steel pistons and the resulting lower distance between pin boss and combustion bowl lead to pin boss temperatures of 290 to 320 °C.

The influence of higher steel piston surface temperature on operative engine performance – especially with regard to emissions – was examined on an engine in Euro 5 application (pcp = 180 bar). The steel pistons were designed with the same bowl shape and compression ratio as the aluminum pistons. A longer connecting rod compensated for the approximately 10 mm shorter compression height.

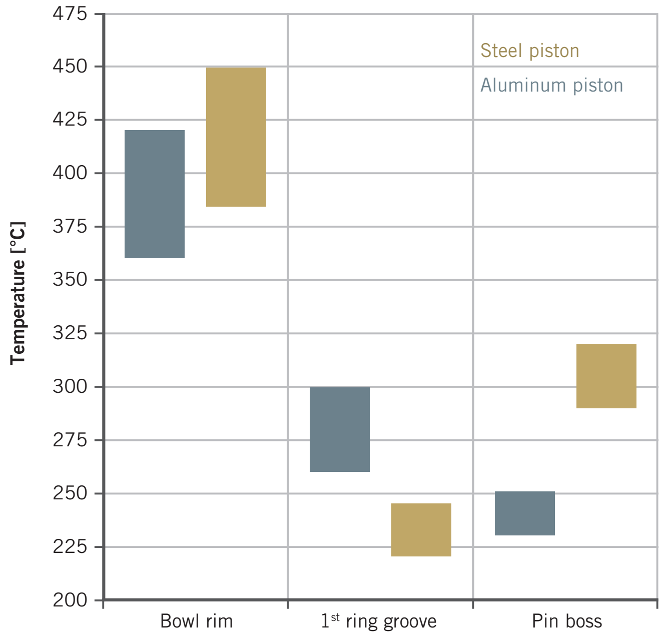
As also verified with other engines, a stable operating performance can already be achieved without making any modifications to the engine operating maps stored in the control unit. For the tests presented here the engine operating maps were adapted for steel piston usage in some operating points. ❼ shows the values determined for specific fuel consumption (bsfc) and for raw emission values of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxide (NO_x) and soot at a selected partial load point (n = 2000 rpm, bmep = 2 bar) as compared with aluminum pistons. The values achieved with aluminum pistons are set at 100 % as a baseline for comparison.

The higher surface temperatures of the steel piston have a positive effect on the HC, CO and soot emissions at partial load. This can be attributed to better fuel mixture preparation and more complete combustion. The reduction of HC emissions by 76 % at a constantly maintained EGR rate is significant, but the lowering of soot emissions by 50 % as well as the CO emissions by 23 % also demonstrate a clear advantage for the steel piston. Increased surface temperatures and improved fuel utilization however result in higher combustion temperatures, which lead to 29 % higher NO_x emissions. In combination with longer connecting rods, which reduce lateral forces and piston skirt friction, the improved fuel utilization also leads to an advantage in specific fuel consumption of up to 4 %.

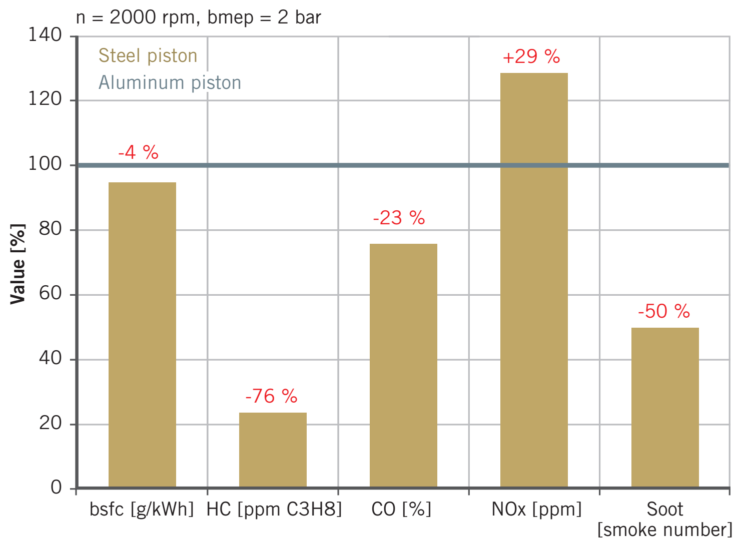
Measurements under full load (n = 4000 rpm, bmep = 18 bar) show that NO_x emissions are on the same level as



❺ Vibration excitation of the cylinder considering bore distortion



❻ Measured temperatures of aluminum and steel pistons



❼ Engine operating performance with aluminum and steel pistons (partial load)

for aluminum pistons when operating under the same boundary conditions as steel pistons (peak cylinder pressure, turbocharger speed). The cause for this is the dominant combustion temperature at full load as compared to the temperature on the piston surface. An exhaust temperature increase of only 1 %, caused by thermal flow restriction, results in an advantage for steel pistons in the order of 20 % with regard to soot emissions. HC and CO emissions only play a subordinate role under full load in the range of only a few ppm.

SUMMARY AND OUTLOOK

Steel pistons for passenger car diesel engines in the compact KS Kolbenschmidt design have proven clear advantages in fuel consumption and emission levels without compromising functional performance. Kolbenschmidt Pierburg believes that the higher loading capacity of steel opens up even further potential for a performance improvement and/or downsizing the engine, which is no longer achievable with aluminum pistons. It sees additional optimisation possibilities resulting from adjusting the compression ratio and bowl geometry of the steel material.

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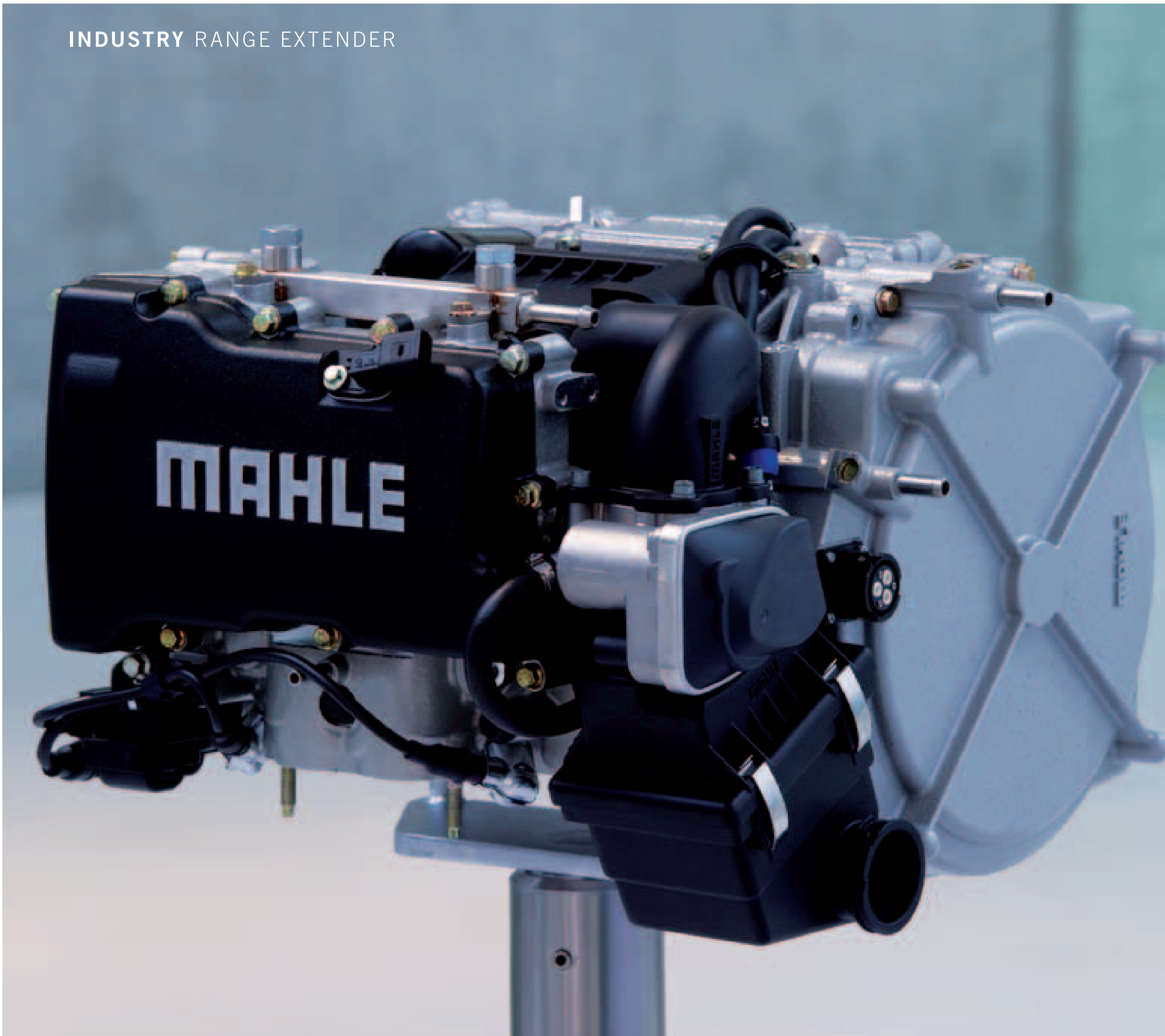

DEVELOPMENT OF AN EFFICIENT AND COMPACT RANGE EXTENDER ENGINE

Mahle Powertrain has developed a compact, two-cylinder, spark-ignition engine that is specifically designed to be used as a range extender. Drive-cycle simulations and engine tests indicate that a range-extended vehicle using this engine would achieve a significant reduction in fuel consumption and tail-pipe CO_2 levels.

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RANGE EXTENDER FOR ELECTRIC VEHICLES

At the end of 2009, on behalf of the Mahle Group, Mahle Powertrain began the development of a range extender engine to identify the requirements and challenges faced in the development of the components for such future engines. The range extender application places different demands upon engine components to those of a conventional powertrain. The use of the engine is decoupled from vehicle usage, and the engine may spend prolonged periods unused, even while the vehicle is moving.

Key features of the Mahle developed concept include the compact package for flexible integration into different automotive applications, the total-cost-optimized design with a view to mass production, to provide low noise and vibration emissions ("silent driving"), as well as the potential CO_2 emissions of less than 40 g/km over the European cycle.

CONCEPT DEVELOPMENT

A conventional compact class vehicle with typical performance characteristics was chosen as the basis for the development of the Mahle range extender concept. To enable a hypothetical electric version of this vehicle to be analysed, performance targets were set to enable the electrical components to be specified. The performance targets selected were:

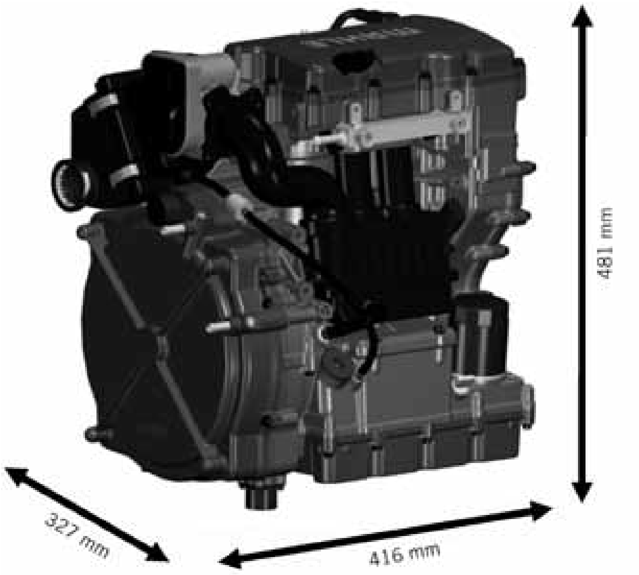
: electric driving range of 80 km to cover 70 % of typically daily usage
: charge sustaining speed of 120 km/h for the safe operation of the vehicle on motorways (maximum speed 160 km/h)
: similar or improved launch, acceleration and hill climbing capability to the reference vehicle [1].

This enabled the selection of a traction motor with a peak power output of 100 kW (55 kW continuous) and a 15 kWh battery pack.

Mahle Powertrain has an extensive database of fleet vehicle drive-data. This was used to identify the typical daily usage pattern of such passenger cars to enable the requirements for the range extender engine performance to be determined. It was concluded that 30 kW mechanical power output was required from the range extender engine. The key attributes for the range extender engine were identified as being low production cost, small package volume, good NVH attributes and reasonable fuel efficiency. A broad range of range extender engine concepts were developed and evaluated. As the best solution, in terms of the technical and commercial criteria identified, a two-cylinder, in-line, four-stroke gasoline engine concept with a swept volume of 0.9 l achieving 30 kW at 4000 rpm, was selected, ❶. The final

ENGINE	Inline two-cylinder, four-stroke gasoline
DISPLACEMENT	898 cm^3
RATED POWER	30 kW at 4000 rpm
TORQUE	72 Nm from 2000 to 4000 rpm
BORE x STROKE	83 x 83 mm
COMPRESSION RATIO	10:1
IGNITION TIMING	Cylinder 1: 0°, Cylinder 2: 180°
VALVETRAIN	Two valve SOHC head, rockers with roller followers
FUEL INJECTION	Multi-point fuel injection
ENGINE MANAGEMENT	Mahle flexible ECU
GENERATOR	38 kW permanent magnet synchronous generator (watercooled), 320 V nominal voltage
EMISSION AFTERTREATMENT	Three-way catalyst (close coupled)
EMISSIONS	Euro 5/6 capable (vehicle dependent)
POSITION	Variable between 0 and 90° (vertically)
DIMENSIONS (L x W x H)	416 x 327 x 481 mm (vertically)
WEIGHT (INCL. GENERATOR)	70 kg (dry)

❶ Specifications range extender



❷ Dimensions of range extender concept

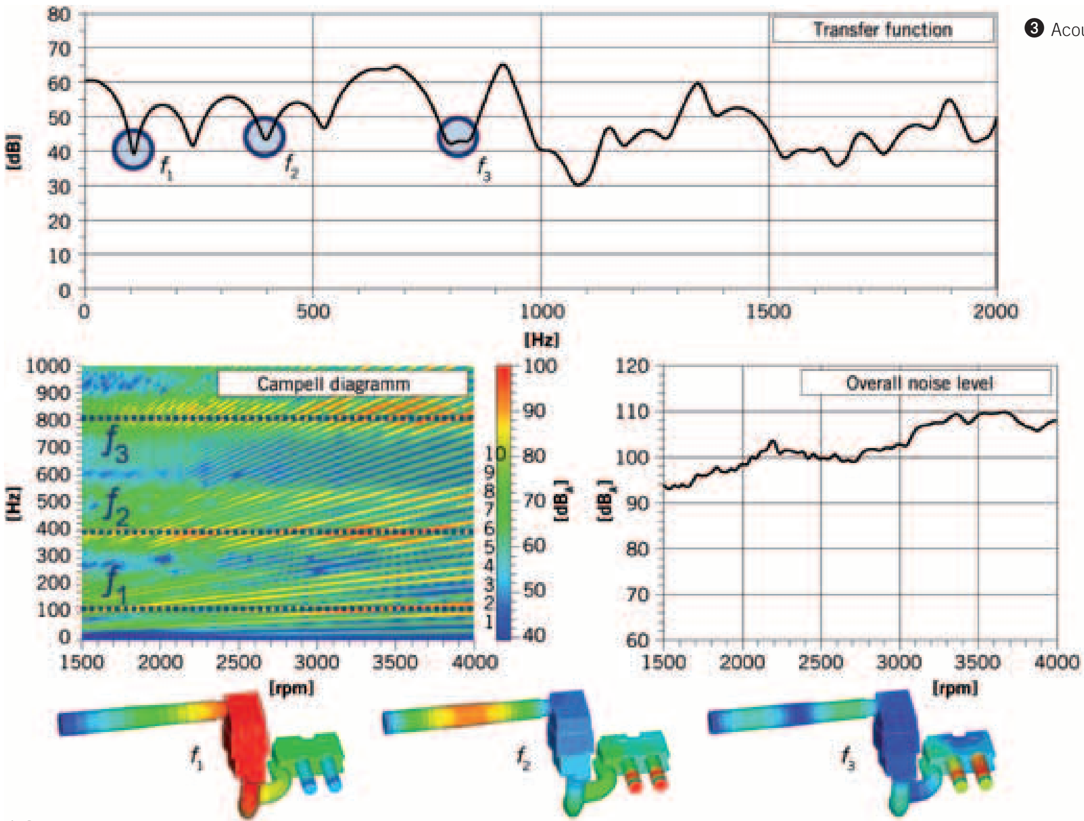
design, focussing on small package volume, ❷, included some interesting features, such as:

- the full integration of the generator into the crankcase with the rotor mounted directly to the crankshaft
- the two valve per-cylinder layout with valves actuated by a single overhead cam indirectly via rocker arms with roller followers
- an oil system enabling flexible installation angle, from vertical to horizontal mounting, which can also cope with periods of non-running when the vehicle is operated in a purely electric operation and optimized oil, oil filter module and bearing shells
- the intake system closely packaged to the engine and optimized for the limited engine speed range (2000 to 4000 rpm)
- the open deck cast aluminium crankcase with cast iron cylinder liners and Grafal coating with three-piece piston ring pack.

This study clearly demonstrates the significant benefits of developing a solution focused on the requirements of a range extender engine, as opposed to modifying a standard production engine.

INTAKE MANIFOLD OPTIMIZATION

A combined 1-D/3-D approach was used to optimize the inlet system to enable target engine power to be achieved, while at the same time minimizing the orifice noise generation, within the restrictive package targets set for the engine. A 1-D gas-dynamic simulation was used to derive optimal intake and exhaust geometries and valve timing in order to enable the target engine performance to be achieved. This 1-D model was also used to provide an excitation signal for a 3-D finite element model of the entire inlet system which was used for acoustic analysis. An Eigen mode and response analysis, from excitation (plenum entry) to evaluation (intake system entry) positions, was performed using a bespoke tool developed by Mahle Filter-



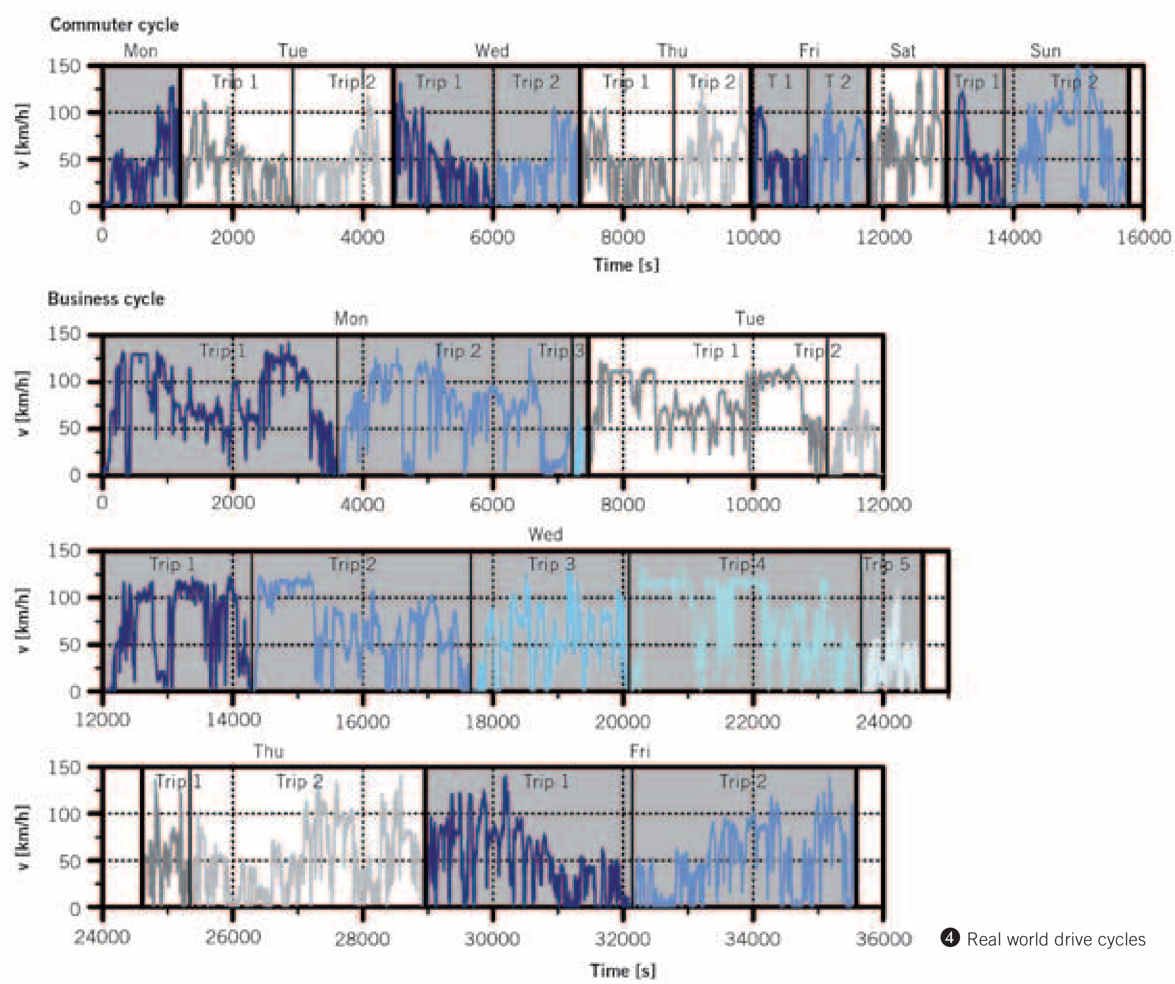
❸ Acoustic simulation

systems. The range extender presents a few specific issues, primarily related to the low number of cylinders, and relatively low operating speeds, which leads to low frequency NVH being of great significance. The first Eigen frequency must be damped or shifted. Low frequency issues correspond to duct length and strongly to air filter/damping volume. However, limited package targets with range extender engines often do not enable the implementation of sufficient damping volume in the air intake system. As an example, the inlet system acoustic analysis results shown in ❸ highlight some of the effects of a compact inlet system. The relatively high amplitude of the first natural frequency (f_1), at 107 Hz, is excited over a wide engine speed range. Increasing the volume of the air filter housing would reduce this natural frequency, or alternatively the response could be damped by the addition of a passive acoustic damper such as a Helmholtz resonator. Depending on the length of the intake system and the geometric design more resonances arise corresponding to higher frequencies, such as those apparent in ③ f_2 at 380 Hz and f_3 between 800 and 900 Hz, which specifically would have to be reduced due to the wide excitation range, without negatively impacting upon the power output or the package space requirements. The optimization of the intake system is by nature vehicle application dependent and ideally takes into account the whole operating range of the engine.

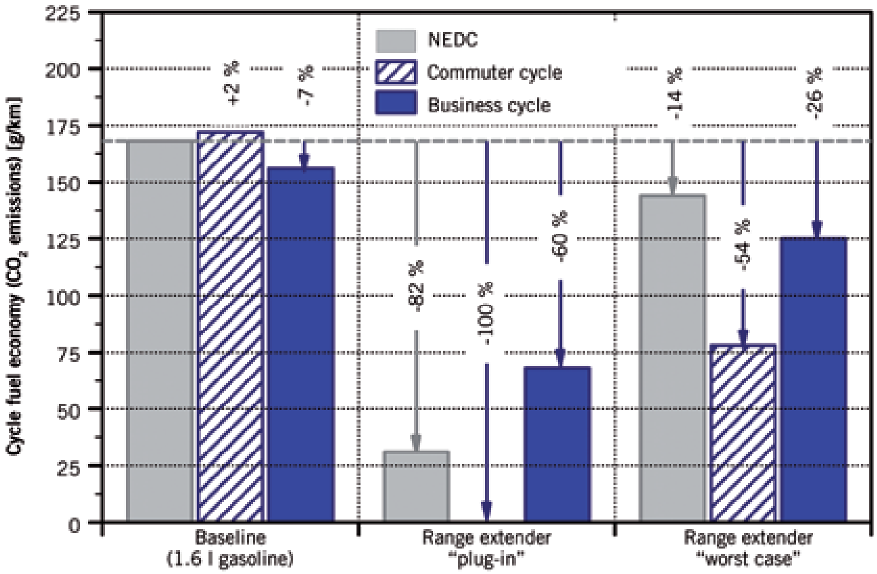
DRIVECYCLE SIMULATION

The vehicle model used to assess the power requirement of the range extender engine was further developed to provide an insight into the achievable fuel consumption of the hypothetical compact class range extended vehicle, with the Mahle range extender engine, during real operation. Two cycles have been generated, based on the fleet data held by Mahle Powertrain, these are intended to represent typical weekly usage patterns of two types of user. The first profile is characteristic for a private user and comprises mainly of short, urban journeys (commuter cycle), the second profile is more typical of business use and is comprised of a mix of short and long-haul trips on weekdays (business cycle). The speed profiles for both of these cycles are shown in ❹ (each trip is defined from ignition on to ignition off). The week long commuter cycle covers a range of 190 km with an average speed of just over 40 km/h, whilst the business cycle covers 610 km during the week, with an average speed of 62 km/h. In addition to the two weekly cycles, the NEDC (New European Drive Cycle), which is only 11 km long and takes 1180 s, was also simulated for comparison.

The European legislative test procedure for a plug-in hybrid involves performing two NEDC tests, one starting with a fully charged battery and the other one starting with the battery in the depleted state. The resulting declared fuel consumption is



❹ Real world drive cycles

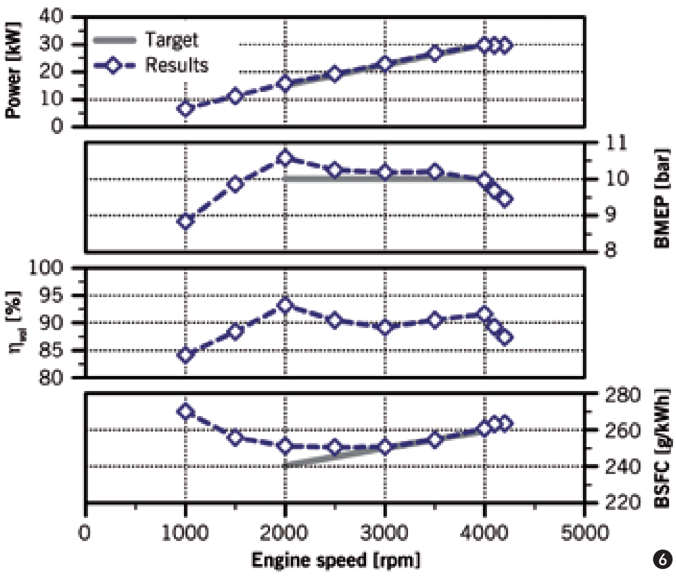


5 Cycle fuel economy results

then based on a weighted average of the results of these two tests, where the weighting factor applied is a function of the electric range capability of the vehicle [2]. A similar procedure exists for the US [3].

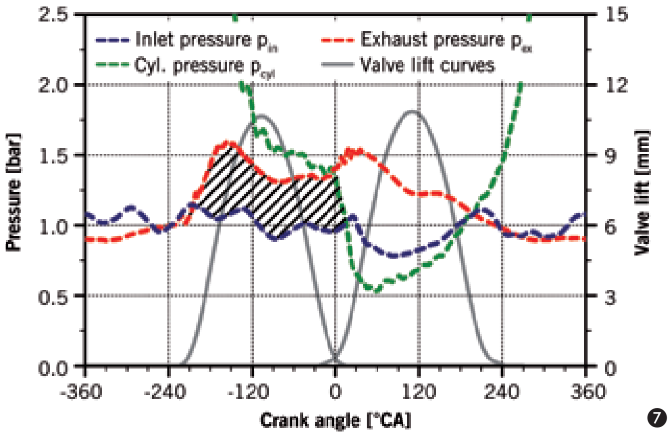
A control strategy for the range extender engine had to be employed to enable the analysis of the hypothetical extended-range electric vehicle fuel consumption performance over these cycles. A simplistic operating strategy has been adopted, whereby the range extender engine is activated when the battery state of charge (SOC) falls to a lower threshold value of 0.25 and the engine is deactivated when the battery SOC has reached 0.35. The battery is assumed to be fully charged at an SOC of 0.95. The engine is always operated at full-load and the power output of the engine is modulated, by varying the speed of the engine between 2000 and 4000 rpm, so that the battery charge rate never exceeds 1C. The two weekly cycles were both analysed for two recharging patterns, recharging overnight, every night and never recharging at night. For the first case it was assumed that the battery was restored to the fully charged state (0.95 SOC) for the start of every day. For the second case the battery SOC at the beginning of each day was assumed to be equal to that at the end of the previous day, the battery was set to the minimum state of charge (0.25 SOC) at the beginning of the week.

The fictional reference vehicle with a conventional 1.6 l gasoline engine, five speed manual transmission and an unladen weight of 1150 kg has been used as a baseline comparator for the simulations. The baseline vehicle achieves a tailpipe CO_2 emissions figure of 168 g/km for the NEDC, 172 g/km in the commuter cycle and 156 g/km in the business cycle. The resulting CO_2 values for all the vehicle and cycle combinations analysed are shown in 5. It can be seen that despite the two real cycles having a much more dynamic speed profile the resulting CO_2 values for the baseline vehicle are at a similarly low level, or below the NEDC baseline value by 7 %. This is brought about predominantly by two factors, firstly the lower proportion of idling in the real driving cycle (NEDC: 25 %, real cycles: < 10 %), secondly the combination of the gentle nature of the NEDC, and prescribed gear shift pattern, leads the engine in the baseline vehicle to operate at loads and speeds significantly below those of its optimum fuel consumption region, whereas the higher average speeds of the business cycle enables the operation of the engine in a better efficiency region of its operating map.



6 Test results

The simulations of the vehicle with the Mahle range extender powertrain, where



❼ Gas exchange analysis

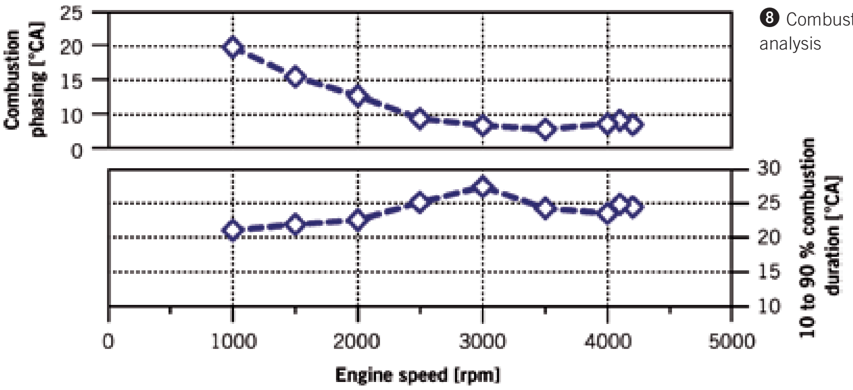
the battery is recharged every night (plug-in), show a reduction in CO_2 of between 60 and 100 %. In the NEDC test procedure, defined by the legislation [2] for a plug-in vehicle, the weighted CO_2 figure achieved is 31 g/km, which represents a reduction of over 80 % compared to the baseline vehicle on this cycle. The nature of the commuter cycle is such that the range extender vehicle can achieve all trips on pure electric operation. For the business cycle the range extender engine operates on four out of the five days that contain trips, but still a very significant saving is achieved, as the initial portion of each day can be achieved using pure electrical operation.

To examine the worst case recharging scenario for the range extended vehicle, all cycles were also simulated without any nightly recharging. In these simulations the vehicle began the week with fully depleted battery (SOC_{start} = 0.25). The results of this investigation are also shown in ⑤, and it can be seen that even when not recharged at all (worst case), the range extended vehicle still yields a significant CO_2 saving when compared to the baseline vehicle of between 14 and 54 % over the two real world cycles. This analysis clearly shows that the range extender concept has the possibility, in real world operation, of reducing the tailpipe CO_2 emissions by between 26 and 54 % compared to the baseline vehicle.

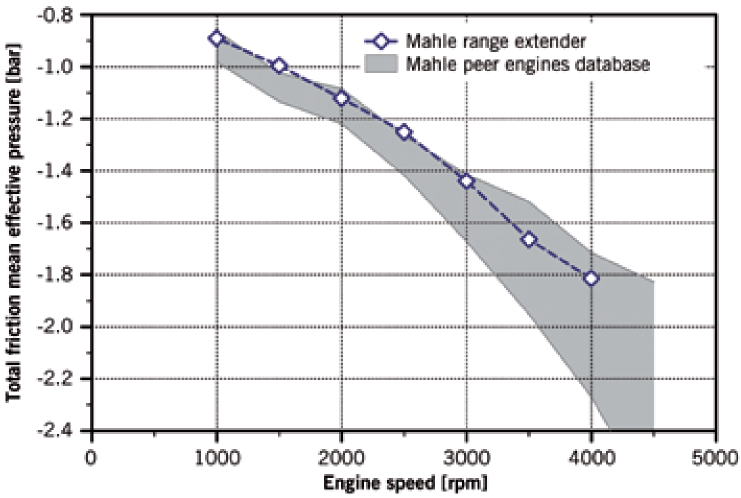
VALIDATION

In order to validate the engine concept and detail design of the Mahle range extender, a prototype has been constructed and tested. Engine testing has been conducted with the engine coupled to a conventional dynamometer, without the generator, to enable the performance and fuel consumption to be measured. As shown in ❻, the target values for performance have been achieved using the system geometries determined from the 1-D gas-dynamic simulation calculations performed at the design stage. In addition to the peak power output of 30 kW at 4000 rpm, the target of brake mean effective pressure of 10 bar BMEP throughout the entire operating speed range has also been met. It can also been seen that the torque curve is reasonably flat across the operating speed range, with the intake tuning focused on this operating range. The engine actually achieves a maximum volumetric efficiency η_{vol} of 93 % at 2000 rpm.

The measured fuel consumption, especially in the lower engine speed range, is slightly above the target values. One of the reasons for this is an increased engine oil system operating pressure of 4 bar absolute, which has been set above the intended operating pressure as a precautionary measure for the protection of prototype engines during initial testing. Analysis reveals that this leads the to an additional oil pump power consumption of 0.15 to 0.4 kW between 2000 and 4000 rpm, leading to an increase in fuel consumption of between 2.3 to 3.5 g/kWh. Detailed examination of the inlet and exhaust system pressures during gas exchange also indicate that the exhaust back pressure is too high, with values between 1.3 and 1.6 bar during the exhaust blow-down event, ❼. This is likely to be due to the high cell density of the three-way catalytic converter and the use of an exhaust system which has been optimized primarily for low noise. The next steps, as part of the vehicle integration, will include the optimization of the catalyst sizing for optimized cold start light-off emissions performance and reduced back pressure. The high exhaust pressure level during the exhaust event would be anticipated to give rise to a high level of trapped exhaust gas residuals, which would in turn lead to a reduced engine volumetric efficiency and also increased combustion duration. From the 10 to 90 % mass fraction burned duration measurements shown in ❽, it can be seen that the burn duration is reasonably short across most of the speed range of the engine, at around 22 to 24° CA. The only significant exception being at 3000 rpm, coinciding with minimum volumetric efficiency and thus likely to be where highest trapped residuals occur, where it can be seen that the 10 to 90 % mass fraction burned duration increases to almost 28° CA. The engine has fixed valve-event timings with low valve overlap. The short overlap period minimizes the reverse flow of the exhaust gas into the inlet system, which would lead to high trapped exhaust gas residual levels, and thus helps to mitigate the effect of the high exhaust system pressure on performance. Below 3000 rpm the engine ignition timing is limited by the onset of detonation. The ignition timing has been set to minimum advance for best torque (MBT) where achievable, otherwise it is at the detonation borderline timing minus 2°. The ignition timing of the engine is slightly limited by the onset of detonation at lower engine speeds and it can be seen in ⑧ that this also has the



❽ Combustion analysis



❾ Comparison of total motoring frictional losses with peer engines

slight effect of retarding the angle of 50 % mass fraction burned at lower engine speeds. A comparison of the total motoring frictional losses (motored engine frictional power losses and pumping losses) of the range extender engine with similar engines from the Mahle Powertrain database is shown in ❾. The Mahle range extender engine exhibits consistently good values of between -0.9 to -1.8 bar in the whole operating speed range, which implies a low engine friction level.

SUMMARY AND OUTLOOK

The range extender engine developed by Mahle Powertrain has been presented and it has been shown that the development of an efficient and compact drive for range extended electric vehicles places new requirements on the design and components of the engine and systems. The engine developed during this study was able to achieve the power target and provides a good basis for the integration in a demonstrator vehicle.

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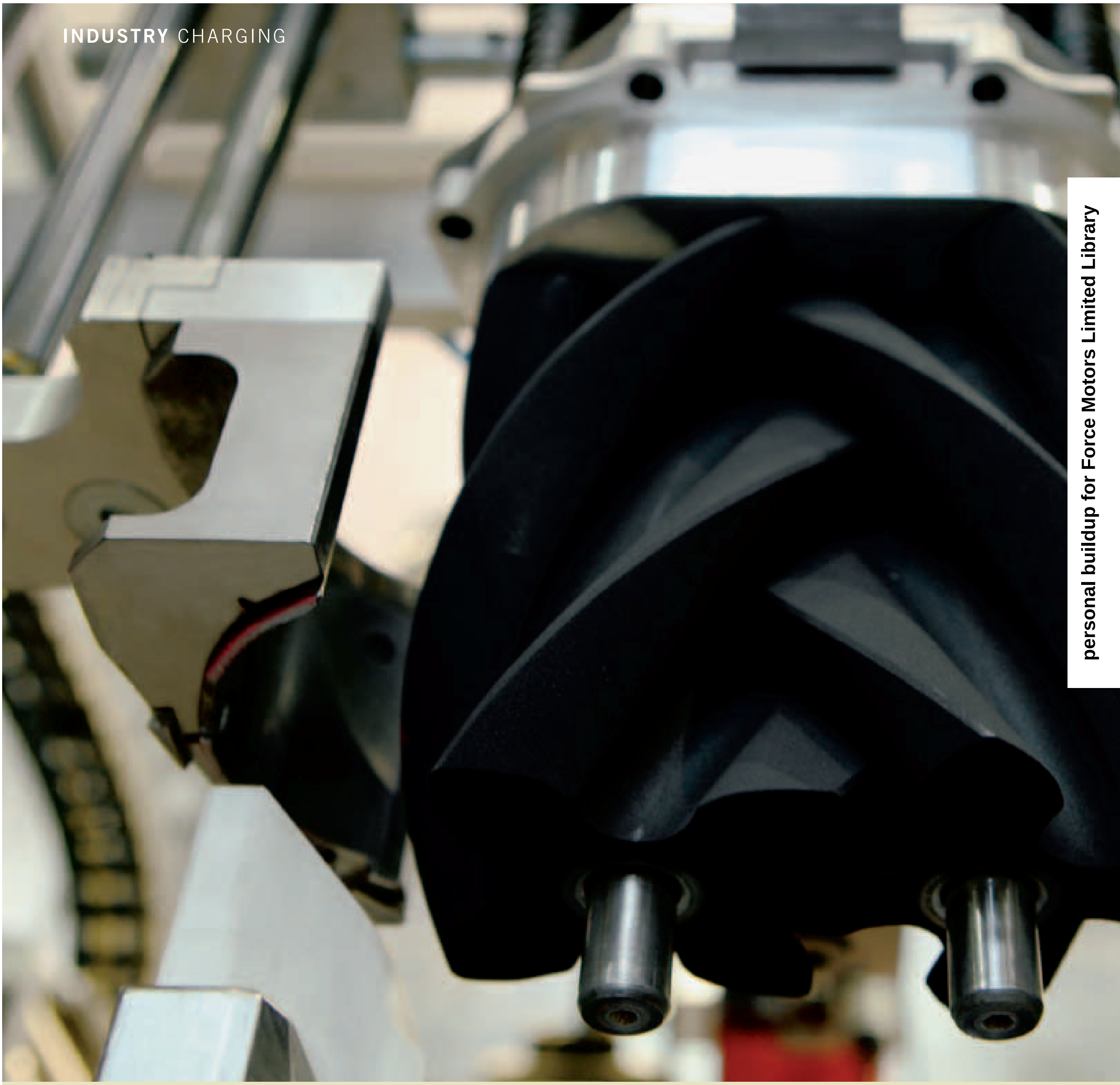

DEVELOPMENT POTENTIALS FOR SUPERCHARGERS

Eaton's supercharger helps vehicle manufacturers to downsize their combustion engines. Through its immediate boosting the supercharger improves fuel efficiency and reduces CO_2 emissions without compromising driving performance. In the following, Eaton describes further development of superchargers.

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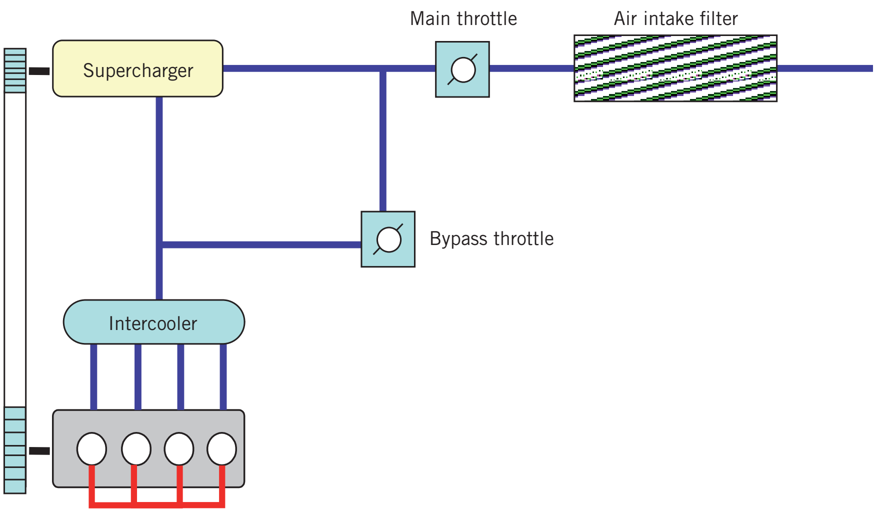
SUPERCHARGERS FOR DOWNSIZING

Since 1989 the Eaton Roots type supercharger is being used on many engine applications because of its immediate transient time-to-torque behaviour and reliability. Coming from relatively big engines which were only boosted for maximizing power output the supercharger design switched in an ecological direction enabling aggressive downsizing and thus improving fuel economy, reducing CO_2. The article will highlight supercharger operating strategies as well as four potential avenues of development.

SUPERCHARGER OPERATING STRATEGIES



❶ Recommended supercharger installation

Engine downsizing and boosting is a known trend; however, the choice has always been between supercharging and turbocharging to provide the airflow required to match the engine performance targets. In recent years, supercharger development has directly addressed some of the known issues, specifically with efficiency, while maintaining all of the key advantages such as boost response and reliability [1].

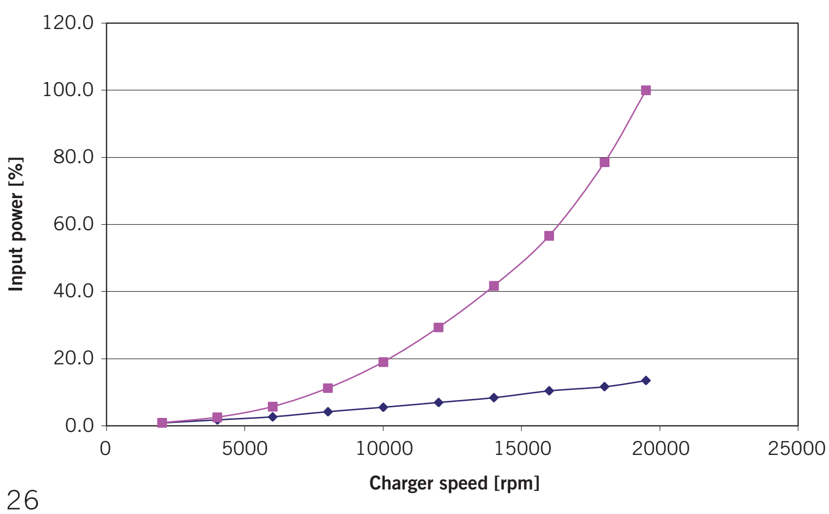
Pumping air it requires a significant amount of power regardless of the technology, however, the key is how to achieve the target airflow required for all operating conditions while achieving overall vehicle fuel consumption reductions. Boosting system sizing and control systems are critical to achieve the performance and fuel economy targets. The turbocharger system is driven by exhaust gas, while the supercharger is driven by the front engine accessory drive system. The supercharger typically rotates at a fixed ratio to the engine speed and offers many advantages, the greatest of which is boost response under all operating conditions. It does not rely on exhaust gas energy and will always be able to operate regardless of exhaust temperature and pressure.

The disadvantage of the supercharger system is not being able to recover some amount of heat energy from the exhaust system. However, for turbochargers, acquiring the heat energy is not free as typically believed. The majority of the turbocharger energy comes from a significant increase in exhaust pressure. Without an exhaust restriction in a supercharger system, the catalyst light off during engine warm up becomes very rapid and with the added benefit of being able to increase compression ratio or advance spark timing due to more complete combustion chamber scavenging. Other engine cycles such as Miller and Atkinson cycle may also be utilized to increase overall engine efficiency. The supercharger is also able to pump exhaust gas recirculation (EGR) to the benefit of both gasoline and diesel engines. These features can help to account for the lack of exhaust heat recovery and in many instances, provide benefit.

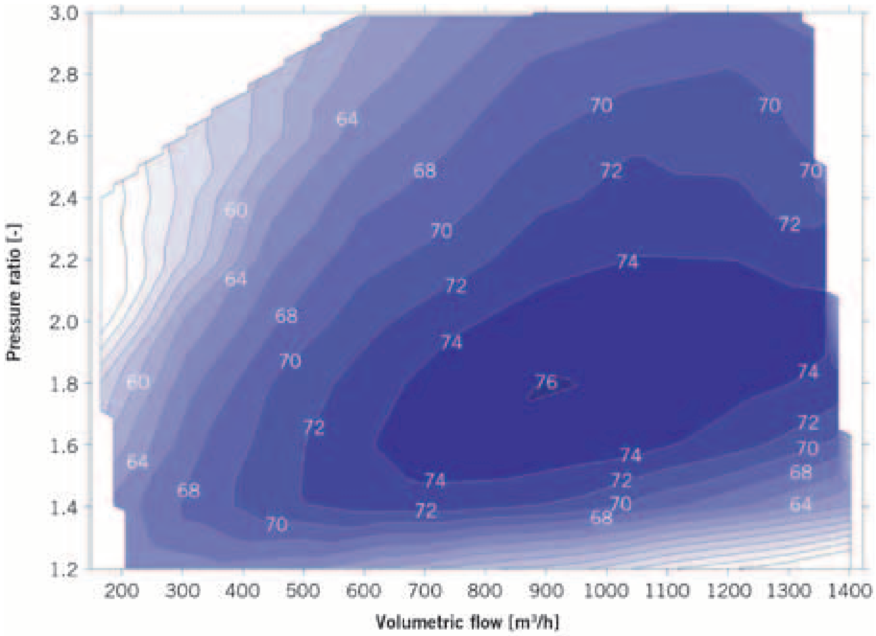
The advantages mentioned above will only end up in a competitive fuel consumption and best in class drivability when the internal combustion engine is optimized for the use of the supercharger [2, 3]. The recommended supercharger installation is to have the supercharger downstream of the main throttle which ensures that the supercharger inlet flow will be at sub atmospheric pressure depending on the throttle position, ❶. Instead of pumping excess air through the supercharger and bypassing it afterwards under atmospheric condition the air and bypass mass flow will be reduced and the work input reduces significantly down to the level of pure mechanical losses which are very low. At a typical highways speed depending on the supercharger size, the mechanical losses are between 0.1 to 0.3 kW, ❷.

OPTIMIZING SUPERCHARGER SYSTEM EFFICIENCY

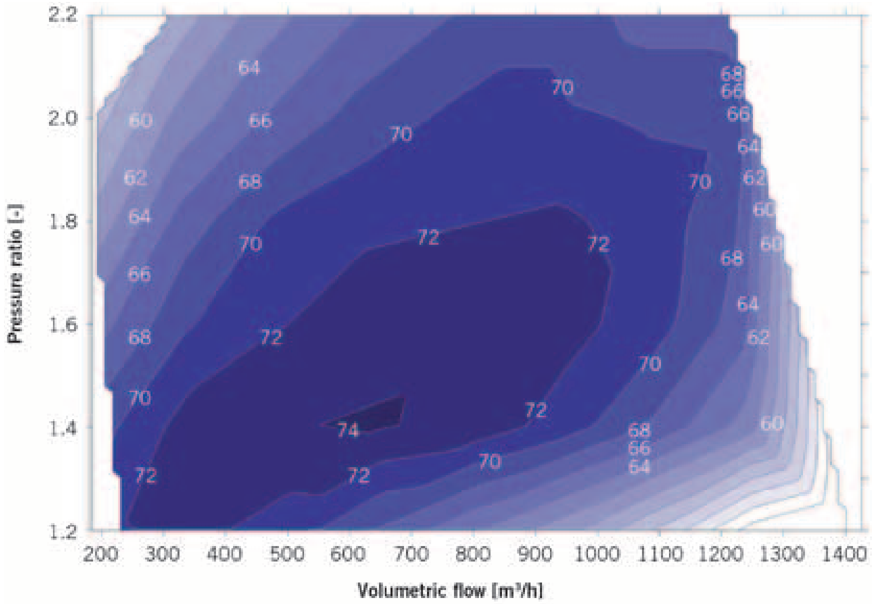
The positive and negative aspect of the Eaton supercharger is the fixed ratio between the engine and supercharger. This requires careful matching of the ratio as



❷ Supercharger input power



❸ RA-series: high efficiency at high speeds and pressure capability



❹ V-series: high efficiency at low speeds

well as the bypass system optimization. Typically the supercharger drive ratio is determined by the low speed torque target and has excess airflow at peak power. The trade off will occur based on the rpm for the peak torque and system efficiency at peak power. Excess airflow is wasted energy but more importantly, minimizing the pressure ratio across the supercharger is key for input power reduction.

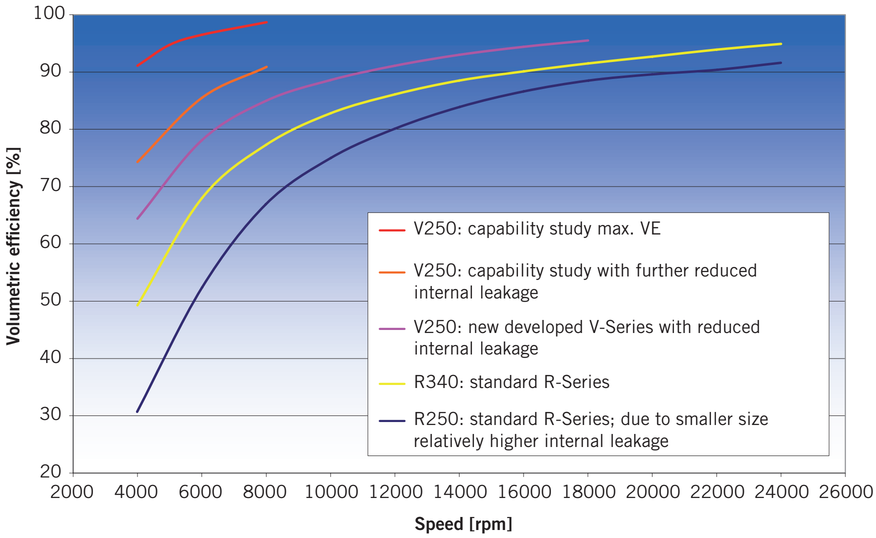
Bypass and throttle control strategy are critical in achieving minimum input power. There are many options to reduce the power throughout the fuel economy drive cycle. The first is operating the supercharger with a throttle upstream and the supercharger rotors spin in a decreased air density, ①. The second is utilizing the boost response to spin the engine slower throughout the drive cycle, which offsets any supercharger drive power with a significant reduction in engine friction power. The overall fuel efficiency of the engine and the emissions reduction can be summarized in four main development categories: improving thermodynamic efficiency, volumetric efficiency, mechanical efficiency, and operating strategies.

IMPROVING THERMODYNAMIC EFFICIENCY

The Eaton R-Series, also called Twin Vortices Series, provided the largest efficiency improvement over the previous generations. The peak efficiency values increased by more than 10 % and now on the same level of comparable flow size turbocharger compressors. This signalled a shift in supercharger main stream acceptance and lead to further developments of thermal efficiency. Next generation designs focus on improved aerodynamic enhancements that increase map width, pressure ratio capability, and location of peak efficiency, ❸ and ❹. Future targets for pressure ratio exceed 3.0:1 and will be accomplished through improved thermal efficiency. Keeping temperature limitations of all components equal, the only way to increase pressure capability is reducing the outlet air temperature through the thermal efficiency gains. Through the development of the Twin Vortices Series and next generation technology, the limits of supercharging have not been reached; they have only begun to be utilized. The technology continues to emerge and improve that demonstrates its ability to be very competitive in the future of boosting systems [4].

IMPROVING VOLUMETRIC EFFICIENCY

Relating to the fixed ratio between the engine and supercharger, the volumetric efficiency (VE) of the supercharger will shape the engine torque curve. The typical characteristic of the Eaton supercharger is an increasing volumetric efficiency versus rpm due to the fact of internal leakage becoming a significantly smaller portion of the total flow. One of the key targets for optimizing the supercharger for downsized engines is improving the volumetric efficiency at low speed. The improved low speed flow will result in a flatter torque curve, reduced bypass required at high engine speeds, and increased thermal efficiency. Achieving the target low speed torque, while also providing fast response, will allow even a greater degree of engine downspeeding.



❺ Optimization of volumetric efficiency at low speeds (pressure ratio 1.4)

The direction of the supercharger technology will continually improve the low speed volumetric efficiency, ❺. As mentioned previously, the supercharger ratio is selected to match the low speed torque target, therefore the increase in low speed volumetric efficiency decreases the drive ratio. For example a supercharger with 60 % VE and a 3.0 drive ratio could be replaced by a supercharger with 80 % VE and a 2.25 drive ratio. This directly reduces frictional losses and improves overall system efficiency. Also, a known benefit of increased volumetric efficiency is an increase in thermal efficiency.

IMPROVING MECHANICAL EFFICIENCY

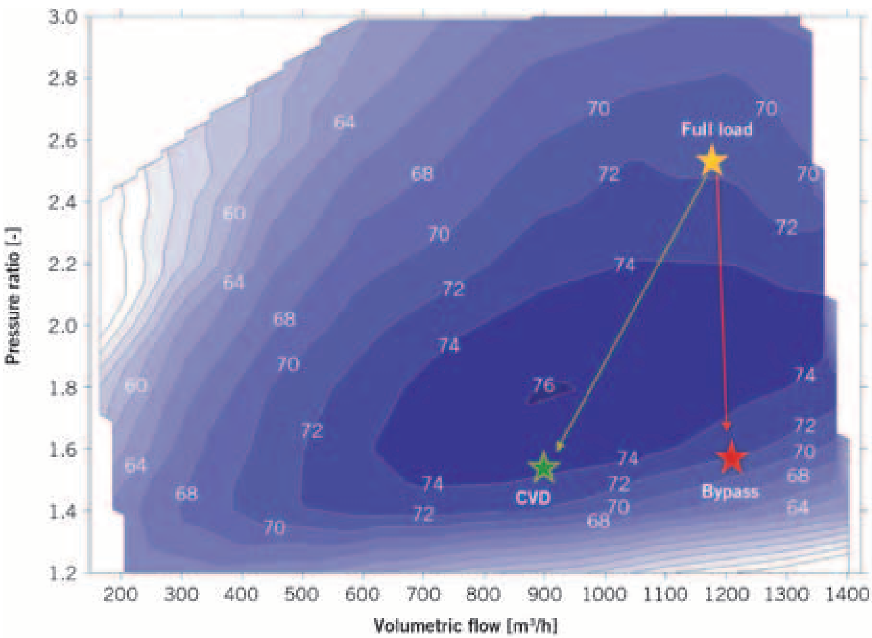
A common misconception is that superchargers have high parasitic frictional losses while they actually have very low mechanical friction. Current products all have ball bearing systems, PTFE low friction seals, a patented abradable coating of the rotors which allow non contact operation, high tooth count precision gears, and fully synthetic oil. This equals a 0.1 to 0.3 kW friction power at a typical engine cruise condition. The possible improvement in mechanical friction is small, however, still very important. The larger benefit of reduced friction is to allow the supercharger to operate in more efficient conditions.

Further development is currently underway on the PTFE sealing to make even higher supercharger speeds possible while reducing the friction. Purpose of this is to enhance the operating range of the supercharger which will open up the possibility of using a smaller unit with less weight and better package still delivering the same desired air flow. The system efficiency would increase due to less bypassing of excess air at high engine rpm because the unit would be operating in a flatter portion of the volumetric efficiency curve. Also advanced programs are changing the gear material to composite material for further mechanical efficiency and NVH improvement and going to even lower friction oil.

IMPROVING OPERATING STRATEGIES

The bypass valve is critical to supercharger operation in its current state of technology and allows the proper delivery of mass flow to the engine. Excess air is bypassed; however, it still requires power to pump the bypassed air. The ideal solution would involve no excess airflow and match supercharger airflow delivery exactly to engine requirements. There are many technologies aimed at reducing the losses associated with bypass, such as; operating in vacuum at part throttle, clutch, multi-speed drive, and continuously variable drive (CVD).

The supercharger clutch has typically been used on twin-sequential supercharger and turbocharger systems and is a protection for over speed. This allows a much smaller supercharger to be utilized only for the airflow required at low engine speeds, typically up to 3000 rpm engine speed. Other applications utilize a clutch purely for fuel economy savings. The amount of power that can be saved is seen in mechanical friction power chart which makes it application specific for the actual amount of fuel economy benefit. With the compound systems and standard applications, the target is to have minimal impact to the boost response of the vehicle due to clutch delay. The Eaton integrated clutch can engage the supercharger has the ability to bring the rotors from zero to operating speed in as



❻ Different operating points of bypass, multi-speed device and CVD little as 40 ms. The benefit with the internal clutch system is the inertia reduction during engagement and smaller impact to the engine to accelerate the inertia.

One step further is a multi-speed device or a continuously variable drive. Eaton has developed a two speed device in 2007 [5] and this unit was successfully tested on an engine. Eaton is currently developing the next generation multi-speed drive system. The multi-speed and variable drive system have two major targets; the first is a reduction of bypass losses at part throttle and the second is the ability to achieve high airflow rates at low engine speed. The major benefits of a multi-speed device will be the minimal increase in mechanical friction. With the CVD, the bypass has the potential to be eliminated. The operating condition on the supercharger map will be different between the standard bypass and CVD systems, ❻. The variable drive allows the direct matching of airflow need to airflow delivery without any excess pumping work. However, the challenge remains that variable drive system is the increased mechanical friction. The true viability of this technology remains with how much system efficiency can be gained vs. the added system complexity and cost [5].

CONCLUSION

The supercharger has continually been optimized to meet ecological goals such as fuel efficiency and emissions reduction. Eaton still works on the optimization of its mechanical booster and follows different development potentials by improving thermodynamic efficiency, volumetric efficiency, mechanical efficiency, and optimized operating strategies.

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THE TURBOCHARGED THETA GDI ENGINE OF HYUNDAI

Under the so-called Blue Drive strategy aiming at high fuel efficiency and low CO_2 emission, Hyundai developed the Theta turbocharged GDI 2.0 l engine to replace large-displacement engines. With a new conceptual design using the synergistic combination of various advanced technologies and rigorous optimization of the system, Theta turbo GDI engine has the same performance as 3.5 l naturally aspirated engines with significant improvement in fuel efficiency.

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CHALLENGES

Turbocharged gasoline direct-injection engines are now well accepted as the substitute for the large-displacement naturally aspirated engines for improved fuel efficiency through downsizing [1, 2, 3]. The fuel efficiency benefit largely depends on the degree of downsizing, but excessive downsizing in displacement typically results in deterioration of drivability due to the delayed response and limited performance of the engine. In addition, many downsizing applications fail to deliver the real-world fuel efficiency benefit, even though they offer significantly improved fuel efficiency in FTP (Federal Test Procedure) or NEDC (New European Driving Cycle) driving cycles. For these reasons, downsizing in displacement is often limited or the rated performance is sacrificed in many downsizing applications. Hyundai developed a 2.0 l turbocharged gasoline direct injection engine, the Theta turbo GDI engine, to replace the 3.5 l V6 naturally aspirated engines in the midsize sedan segment. The aim was to improve the fuel efficiency without compromising performance and drivability. Since the state-of-the-art 3.5 l V6 naturally aspirated engines on the market are rated very close to 200 kW in power, the specific power of the engine should be close to 100 kW/l. More importantly, responsive and smooth drivability with minimized NVH is critical for customers in this segment.

Since the engine is planned to be used globally, the performance and fuel-efficiency targets should be obtained with the globally available regular gasoline. These requirements impose a great challenge for engine development, and a completely new conceptual design and rigorous optimization were required to achieve the targets.

GENERAL SPECIFICATION

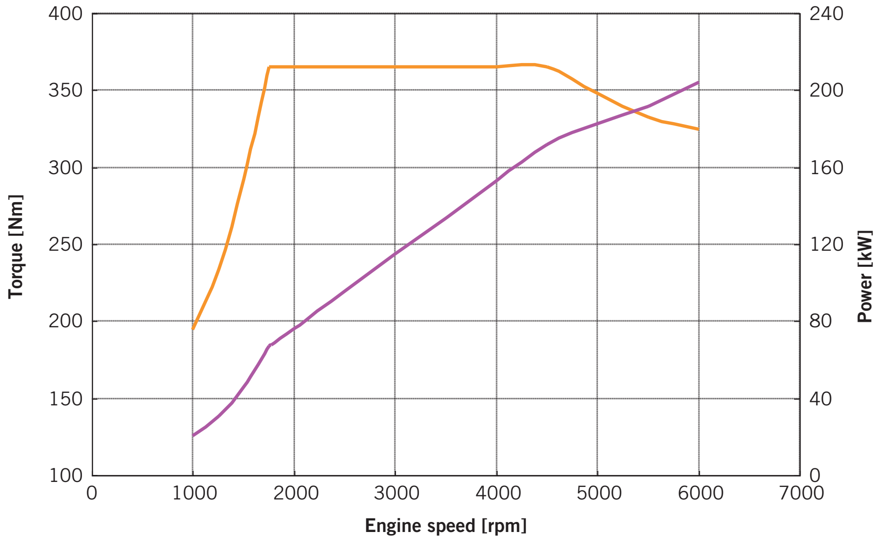
❶ summarizes the specifications of the engine. The engine is rated at 204 kW at 6000 rpm, which is 102 kW/l specific power, but more importantly the maximum torque of 365 Nm is achieved from 1750 to 4500 rpm as depicted in the performance curve, ❷. These performances are achieved with regular gasoline of research octane number (RON) 91. The fuel efficiency of the engine is maximized with the application of an intake and exhaust variable-valve-timing system and the motor-driven electrical waste-gate actuator. The engine is equipped with compact balancer shafts integrated into the oil pump, and various insulations are applied to minimize the vibration and noise generated from the engine.

PERFORMANCE DEVELOPMENT

In order to fulfil the requirement for both low- and high-speed performance, a completely new conceptual design had to be applied to the combustion system, turbocharger selection and intake and exhaust system including the intercooler design. ❸ shows the key technologies applied to the engine. It is common practice to apply a high-tumble flow intake port in the turbocharged gasoline direct injection combustion system in order to achieve improved mixing and fast combustion in low-speed

ENGINE TYPE	In-line four-cylinder (turbocharged)
VALVETRAIN	4-Valve DOHC
DISPLACEMENT	1998 cm³
BORE × STROKE	86 mm × 86 mm
C/R	9.5:1
POWER	204 kW at 6000 rpm
TORQUE	365 Nm at 1750 ~ 4500 rpm
FUEL	RON91
APPLIED TECHNOLOGIES	High-pressure direct injection system Intake / Exhaust variable valve timing Twin-scroll turbocharger Electrical motor-driven waste-gate actuator Intercooler with dual air guiding duct

❶ General specification of Theta turbo GDI 2.0 l

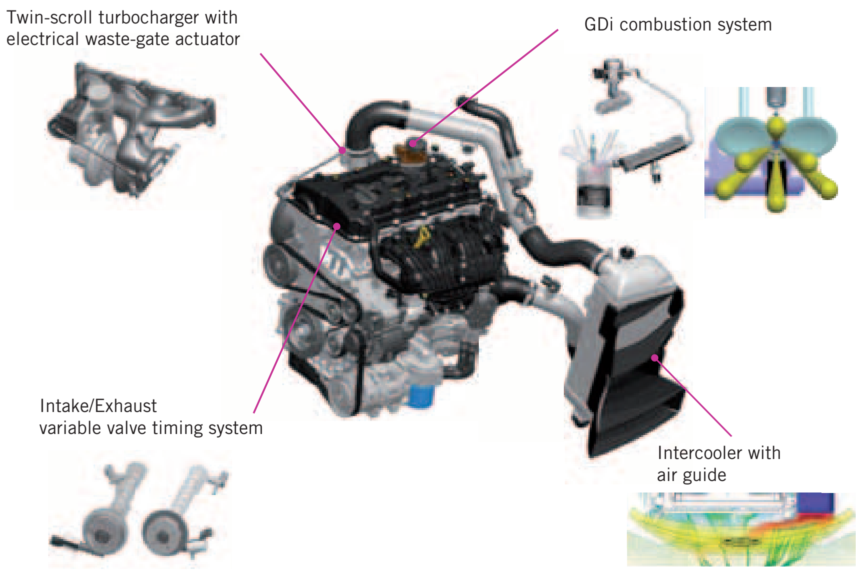


❷ WOT performance curve

regions [2, 3]. However, at high-engine speeds, such high tumble flow intake ports are imposing limits in the flow capacity, and the extreme turbulence level and fast combustion speed increases the ignition energy requirements to a significant level. The combustion chamber of the Theta turbo GDI engine has a wide angle of 47° between the intake and exhaust valves, and therefore can obtain high flow at high-engine speed. However, the conventional tumble port concept – which restricts the flow at the bottom side of the intake valve – does not create an effective tumble flow. In the transition from the port-injection to the direct-injection combustion system, the overall tumble has been increased by around 12 %, but the increase is still limited due to the wide valve angle. Therefore, in order to achieve the sufficient mixing between the directly injected fuel and fresh gas, the fuel flow direction of the multi-hole injectors has been optimized carefully. At the same time, the injected fuel momentum is transferred effectively to the fresh gas by avoiding any interference between the combustion chamber such as the intake valves, ③. The spacing between the injecting fuel flows is maximized in the given restriction to enhance the fresh air entrainment and therefore to enhance the mixing with the fresh gas. In this way, the inherent benefit of the large valve angles provides the potential to increase the performance at high speeds, while the low-speed performance and combustion stability were not compromised. In order to enhance the low-speed response of the engine, which is essential to replace large-displacement naturally aspirated engines, the twin-scroll turbocharger with a motor-driven electrical waste-gate actuator is used. The use of the twin-scroll turbocharger allows for the increase of scavenged air flow to spool up the turbine without the increased back-pressure at the exhaust port and therefore without any deterioration in the combustion quality. In addition, the exhaust pulses are more effectively transferred to the turbine with the smooth exhaust paths split to cylinders 1, 4 and 2, 3. In modern mid-size sedans, it is quite critical to reduce the aerodynamic drag of the vehicle to improve the fuel efficiency, and for this reason, the frontal opening area of the vehicle was minimized. However, in gasoline turbocharged engines, the effectiveness of the intercooler is critical for both performance and fuel efficiency. In order to achieve the required intercooler efficiency, a uniquely shaped dual air guiding duct is added to the vehicle, ❹. The dual air guiding duct increases the flow speed toward the intercooler by enlarging the effective area exposed to the incoming air stream. By adding the dual air guiding duct, the intake air temperature could be reduced up to 10 K, and it contributes significantly to achieve the high-speed performance and fuel efficiency targets. In addition, by inserting the intercooler in the vertical direction side-by-side with the engine radiator, ④, the length of the air passage from the compressor outlet to the intake manifold could be effectively minimized, which contributes to the fast response of the engine.

FUEL EFFICIENCY

When a significant degree of downsizing is applied, such as in the Theta turbo GDI engine, the thermal efficiency of the engine in higher load becomes more important compared to large-displacement engines. Therefore, the success of downsizing relies on the development of fuel efficiency in

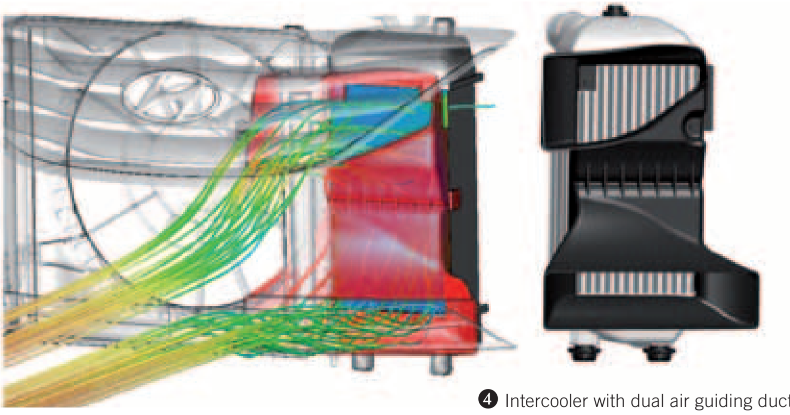


❸ Applied key technologies

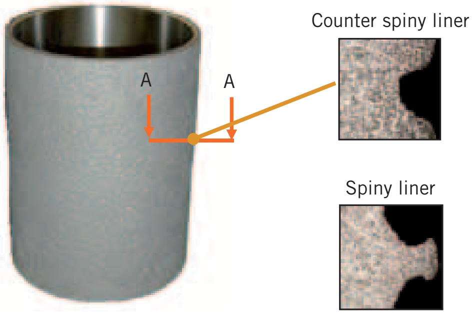
this operation region. However, in these higher loads, the intake pumping work by the throttle valve is not as critical as in low loads, and other factors become more important. The following paragraphs are a list of the main developments aimed at improving fuel efficiency in the higher-load operation region.

COMBUSTION IMPROVEMENT BY SPLIT INJECTION

The injection during the intake stroke is split into two separate injections in low-speed, mid-to-high-load regions to improve the combustion. The split injection reduces the effective penetration of the spray, and enhances the mixing of fuel and fresh gas. Since the fuel is injected under high momentum, the enhanced mixing of the fuel and the fresh gas improves the flow inside the combustion chamber, and hence improves combustion stability. Use of split injection improves the fuel efficiency up to 1 to 3 % in mid-to-high-load regions.



❹ Intercooler with dual air guiding duct



❺ Aluminium thermally sprayed counter spiny liner

APPLICATION OF ELECTRICAL WASTE-GATE ACTUATOR

In higher loads, exhaust pumping work tends to increase, especially in turbocharged engines. Since we could precisely control the position of the waste gate using an electrical motor-driven actuator, the waste gate can be carefully controlled to adjust the flow to the turbine to the minimal amount to generate the requested boost. In this way, the throttle valve could be opened as much as possible and the back pressure could be lowered to the minimal level to run the engine at a specific load. Therefore, by the careful control of the waste gate using an electrical motor-driven actuator, the exhaust pumping work can be reduced and the reduced back pressure improves the combustion quality as well.

OPTIMIZATION OF COMPRESSION RATIO

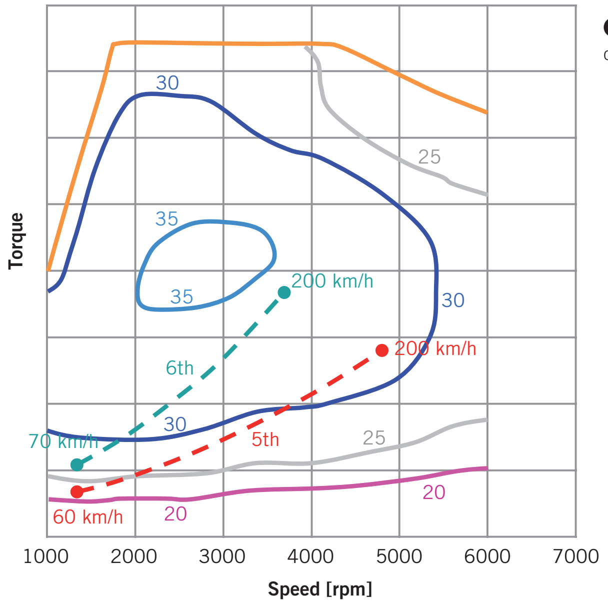
In regions where the fuel and air mixture could be ignited with the most effective timing, a higher compression ratio results in improved fuel efficiency. However, in the knock limited engine operating regions such as in low speed and high load conditions, it is often more beneficial to improve the combustion efficiency by advancing the ignition timing than to increase the compression ratio to higher values. In addition, when the engine has to be operated with a low-octane fuel, the increase in compression ratio does not necessarily result in improved fuel efficiency. The compression ratio of 9.5 is chosen by iterative experiments to produce the optimal fuel efficiency in various engine operating conditions.

HEAD AND BLOCK OPTIMIZATION FOR IMPROVED KNOCK TENDENCY

As described in the previous section, it is very important to improve the resistance to knock to improve efficiency in mid-to-high-load regions. First, the materials and the manufacturing methods for the engine head and block are optimized for improved heat transfer. The cast iron cylinder liner is thermally sprayed with aluminium to improve heat transfer to the aluminium block. The liner is cast into a high-pressure die cast open-deck aluminium block with high bonding strength, thanks to the innovative counter spiny liner, ❺. Using the counter spiny liner, the effective thickness of the cast iron liner could be increased by about 20 % while bore spacing is maintained. The machined inter-bore slotted passage for the coolant flow in the Siamese improves the heat transfer and contributes to minimize the bore distortion.

CYLINDER INDIVIDUAL FUEL INJECTION ADJUSTMENT

Unequal distribution of air fuel ratios in each cylinder leads to unbalanced combustion speeds and could cause early incurrence of knock combustion. In addition, when the twin-scroll turbocharger is applied, the engine inherently experiences unequal back pressure distribution between the cylinders 1, 4 and 2, 3 and this could disturb the equal distribution of the air mass to each cylinder. In order to reduce the differences in air fuel ratio in each cylinder, a careful measurement of air fuel ratio of each cylinder was performed and the fuel injection amounts of each cylinder were adjusted as the preconditioning of the cylinder air fuel ratio balancing. The cylinder air fuel ratio differences are then learned using the engine roughness differences during the life cycle of the engine operation to correct any difference from hardware dispersion and ageing. By



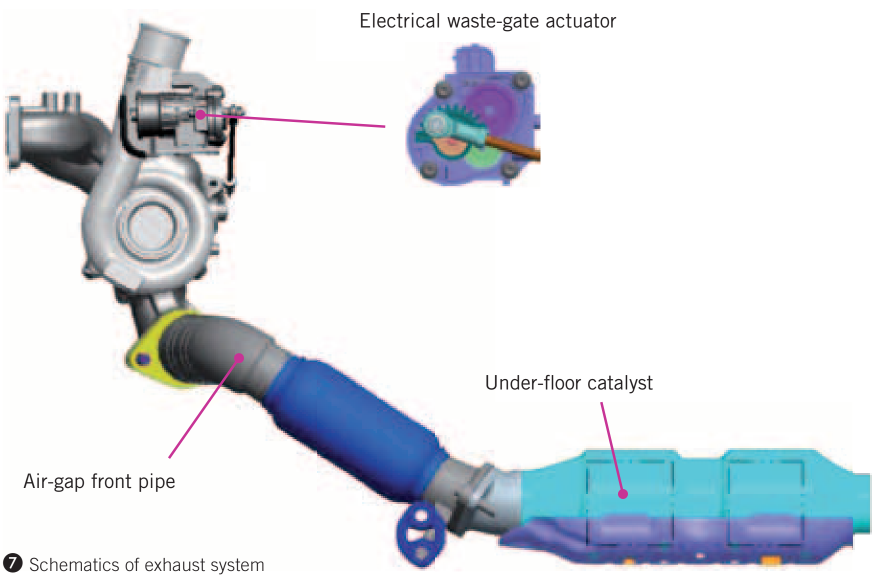
❻ Thermal efficiency of Theta turbo GDI 2.0 l

applying these treatments, the engine can remain in a smooth running condition and maintain as efficient combustion as possible during its life cycle.

❻ depicts the thermal efficiency map for the Theta turbo GDI engine. The engine shows competitive fuel efficiency in low-engine loads, but more importantly the engine has a wide region with the thermal efficiency higher than 30 % with the highest efficiency reaching more than 35 % in the mid-to-high-load regions, ⑥. The engine therefore not only provides significant improvement of the fuel efficiency in FTP or NEDC driving cycles, but also in the real world driving situations compared to the large-displacement engines it replaces. Even at very high cruising speeds, the engine stays in a very efficient region, and provides excellent high speed fuel efficiency.

EMISSIONS DEVELOPMENT

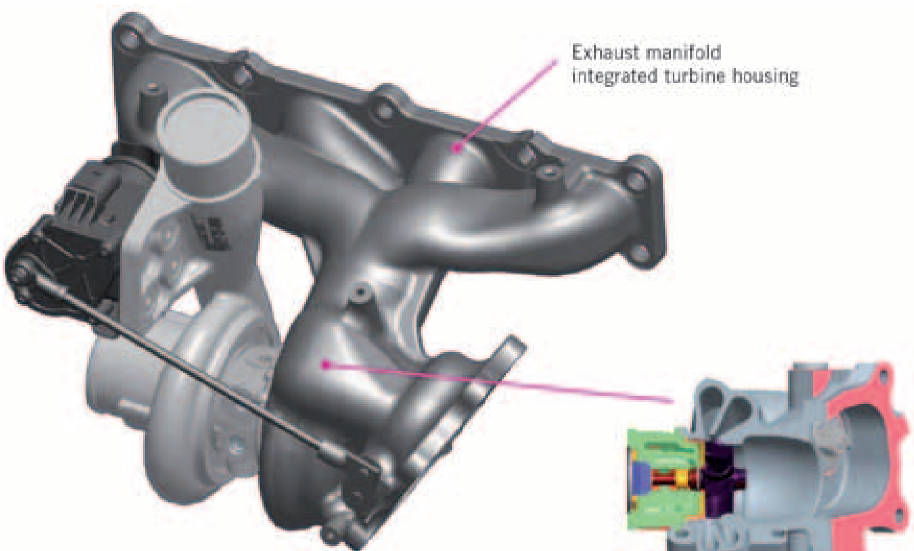
The engine is developed to satisfy the CARB LEV2 ULEV regulation. The main challenges are to maintain the low restriction at the exhaust to obtain high performance and fast response, and to heat up the catalyst promptly to activation temperature. The low restriction exhaust system requirement is very critical to satisfy the low-end performance and response of the engine. To satisfy this requirement, a simple single spinning-canned under-floor catalyst is used, ❼. In order to activate the under-floor catalyst that is located far from the turbine outlet, various measures are applied. Some of the examples include the use of an austenite stainless steel exhaust manifold integrated twin-scroll turbine housing, an electrical waste-gate actuator and the active use of catalyst heating combustion strategies. The exhaust manifold and the twin-scroll turbine housing are cast in one piece from the austenite stainless steel, ❽. In a twin-scroll turbine housing, the split wall has to be extended from the inlet of the exhaust manifold to the turbine wheel. For this reason, the shape of the core and the location of the rising in the shell mould have to be designed so that the melted stainless steel can flow into the heated mould without cavity formation. The one-piece austenite stainless steel casting reduced weight by 1.5 kg compared to the conventional two-piece assembly of exhaust manifold and turbine housing, and this helps to reduce the thermal mass at the exhaust. The electrical waste-gate actuator could be flexibly used to open up the waste-gate of the turbocharger to bypass the high temperature exhaust gases directly to the catalyst without going through the turbine wheel. When it is combined with the active catalyst heating combustion strategies which uses the split injections, the activation time of the catalyst could be reduced significantly. The engine operating conditions during warm-up and fully warmed-up phases are rigorously optimized using the design of experimental (DoE) techniques and automated operations of the engine dynamometer test cells to minimize the emissions and fuel consumption.



❼ Schematics of exhaust system

VEHICLE DEVELOPMENT

The first vehicle equipped with the Theta turbo GDI engine is the sixth-generation Sonata 2.0T. The U.S. EPA certified label fuel efficiency in city and highway driving are 22 MPG (miles per gallon) and 34 MPG respectively. These values are 10 to 20 % higher than the V6 3.5 l vehicles in the segment, while its 204 kW performance is class-leading. The vehicle is tuned to give a



❽ Twin-scroll turbocharger

smooth and responsive acceleration mated with the six-speed automatic transmission. This is possible with responsive and powerful engine hardware combined with accurate control of the electrical motor-driven throttle and waste-gate actuators, and it emulates the drivability of the large-displacement engines.

SUMMARY

The success of downsizing relies on matching the performance of large-displacement engines while achieving the fuel efficiency of smaller- displacement engines. With a new conceptual design using the synergistic combination of various advanced technologies and rigorous optimization of the system, the Theta turbo GDI engine matches the performance of 3.5 l engines with a significant improvement in fuel efficiency.

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THE NEW BMW SIX-CYLINDER DIESEL ENGINE

The new BMW six-cylinder diesel engine was developed with the aim of delivering further improvements in efficiency and dynamics. The modifications concerned saw an expansion to the basic equipment package shared by the four- and six-cylinder diesel engine variants in order to meet demands for efficient and flexible engine production with maximum exploitation of economies of scale through use of a high proportion of carry-over parts and conceptually identical or similar components.

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OBJECTIVES

The technical revision of the 3.0-l six-cylinder diesel engine presented in September 2008 achieved a further reduction in fuel consumption and emissions at the same time as an increase in power output and torque. Thermodynamic optimisation has resulted in significantly greater spontaneity in the throttle response. Engine weight savings and downsized dimensions have been designed to meet future package and pedestrian safety requirements. It has also been possible to make further sound improvements by reducing running noise to an even lower level.

The new six-cylinder diesel engine is the basic platform for the power variants in the BMW model series. The drive system sets new standards in the six-cylinder diesel engine segment and is designed to fulfil future market and customer requirements in the long term. Not only does it guarantee compliance with current emission limits, it is also optimally prepared to meet regulations and standards such as Euro 6.

CONCEPTUAL DESIGN

Offering high power density and low fuel consumption, the new, compact BMW six-cylinder diesel engine fits perfectly into the BMW diesel engine family. The fundamental structural design features that characterise this family are, on the one hand, a lightweight aluminium cylinder crankcase with heat-treated cylinder liners and a timing chain drive located on the flywheel end and, on the other hand, a standardised combustion chamber configuration with central nozzle position. Other typical features include the combined oil and vacuum pump in the oil sump, the uniform arrangement of assemblies such as the belt drive and the engine-resident location of the exhaust gas cleaning systems. The respective power output variants arise from the number of cylinders and the design of the injection system and turbocharger arrangement [1].

One particular focal point in the development of the new six-cylinder diesel engine was the increase in peak firing pressure to 185 bar at the same time as a reduction in engine weight. Another accomplishment was the optimised friction characteristics of the basic engine (pistons, rings and belt drive) thanks to a rearrangement of assemblies and a reduction in initial belt tension. Turbocharging performance has been enhanced by an even more instantaneous development of charge pressure and by the silencer in the charge-air line. The common-rail system with solenoid valve injectors delivers an injection pressure of 1800 bar. Finally, the acoustics-package has been expanded by the addition of a belt drive cover and soundproofing of the oil sump. Engine data is listed in ❶.

DESCRIPTION OF COMPONENTS

This section describes the fundamental component modifications by comparison with the previous model. The increase in peak firing pressure to 185 bar has necessarily affected the components of the basic engine. Weight savings were realised despite the increase in specific load.

CYLINDER CRANKCASE AND CRANKSHAFT DRIVE

The increase in firing pressure by 5 bar to 185 bar is an evolutionary development of the best 3.0-l straight-six engine on the market. Higher load demands required a market of the highly stressed zones in the cylinder crankcase. Essential modifications included the optimised bearing block connection to the skirt wall, ❷, and the increased preload of the main-bearing screws.

For the crankshaft, a central objective was to achieve a considerable reduction in mass. The completely new layout with four instead of the eight counterweights previously has saved 1300 g and has helped to realise a significant improvement in dynamic performance.

To cater for the increased engine power output achieved by the new crankshaft, it was necessary to adapt the torsional vibration damper accordingly, ❸. In the existing installation space, the viscous damper was equipped with an inertia ring having a greater mass moment of inertia. The big-end bearings are equipped with refined plain bearings that are less sensitive to dirt particle deposits and contribute to the more robust design of the overall crankshaft drive system.

PARAMETER		PREDECESSOR	NEW ENGINE
BASIC ENGINE DIMENSIONS			
DISPLACEMENT	[cm³]	2993	
BORE	[mm]	84	
STROKE	[mm]	90	
STROKE-TO-BORE RATIO	[-]	1.07	
CYLINDER VOLUME	[cm³]	499	
CONROD LENGTH	[mm]	138	
STROKE-TO-CONROD RATIO	[-]	0.326	
BLOCK HEIGHT	[mm]	289	
CYLINDER DISTANCE	[mm]	91	
MAIN BEARING			
DIAMETER	[mm]	55	
WIDTH	[mm]	25	
CONROD BEARING			
DIAMETER	[mm]	50	
WIDTH (PIN)	[mm]	24	
PISTON			
COMPRESSION HEIGHT	[mm]	47	
HEAD LAND HEIGHT	[mm]	9.12	
PISTON PIN			
DIAMETER	[mm]	32	
LENGTH	[mm]	64	
VALVES			
DIAMETER, INTAKE/EXHAUST	[mm]	27.2/24.6	
VALVE LIFT, INTAKE/EXHAUST	[mm]	7.5/8	
VALVE-SHAFT DIAMETER	[mm]	5	
COMPRESSION RATIO	[-]	16.5:1	
FULL LOAD VALUES			
POWER	[kW]	180	190
AT ENGINE SPEED	[rpm]	4000	
TORQUE	[Nm]	540	560
AT ENGINE SPEED	[rpm]	1750-3000	1500-3000

❶ Technical data

PISTONS

The existing ring carrier pistons underwent a series of detailed optimisation measures, which essentially involved modifications to the grinding pattern and ring set. The focus was on reducing the preload on the piston rings. Measures involving the cylinder barrel and raceway have achieved a considerable reduction in friction, which has helped to reduce also the fuel consumption of the new engine.

AIR DUCTING

For all vehicles equipped with the new six-cylinder diesel engine, the air ducting system, ❹, has been standardised with an arrangement in which the intake silencer is mounted on the engine directly – only the unfiltered air duct needs to be adapted to the specific vehicle. This modular design concept reduces application effort in development.

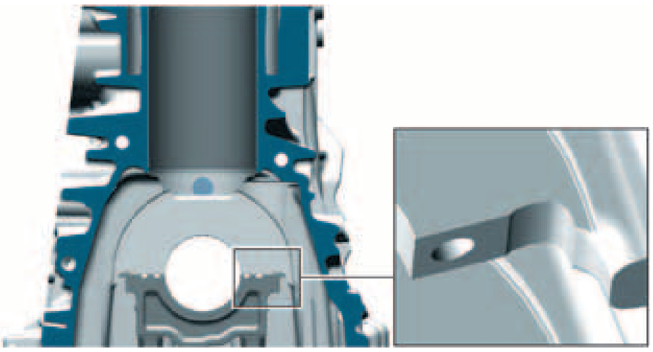
New calculations were carried out in order to optimise the flow of air to the air mass meter so that dispersions in the air cleaner elements and runtime-dependent variations in air cleaner throughflow caused by dirt do not result in malfunctions. Droning in the exhaust gas recirculation duct has been reduced by the side-mounted intake silencer arrangement. This measure has resulted in better noise characteristics than with the previous engine.

BELT DRIVE

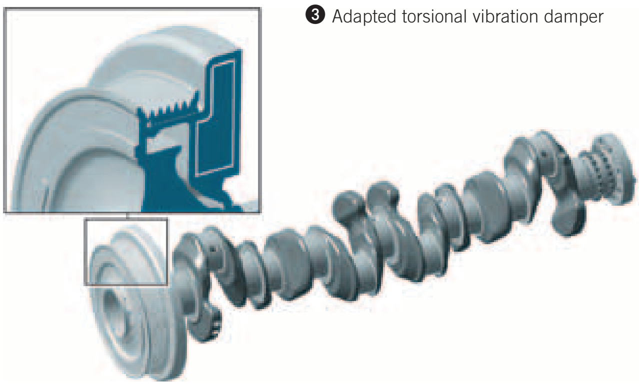
The revision of the six-cylinder engine also included a modified belt drive. The previous double-sided belt profile has been discontinued in favour of a single-sided profile and the air-conditioning compressor is now driven by the front side of the belt. Thanks to conceptual uniformity with the current four-cylinder engine, it is possible to make ideal use of the cost-saving benefits of the modular design principle. In vehicles requiring a hydraulic power-steering pump, the pumps for the four- and six-cylinder engines differ only in their size.

COMBUSTION

The proven combustion chamber configuration with side-mounted swirl duct and filling duct with shut-off valve has largely been carried over from the previous engine design [2]. However, the new turbocharger (see "Turbocharging") alters the pressure conditions on the charge air and exhaust sides. To improve cylinder filling under full throttle, the lift curves of the camshafts have therefore been adapted to the new pressure conditions.



❷ Optimised bearing block connection to the skirt wall



❸ Adapted torsional vibration damper

The solenoid-valve common-rail injection system, which has been upgraded to the latest generation, offers a maximum injection pressure of 1800 bar and features an eight-hole nozzle for the best use of air in interaction with the combustion bowl. An infinitely adjustable swirl flap has made it possible to achieve the very low nitrogen oxide and soot emissions required for compliance with Euro 5 and Euro 6.

TURBOCHARGING

Even though engine power output has been increased, the enhanced efficiency of the turbocharger and the optimised gas cycles made it possible to downsize the turbocharger significantly by comparison with the previous engine model, ❺. The reduced moment of inertia of the turbocharger rotor enables an even more instantaneous development of charge pressure. This has a positive effect mainly on standing start performance and responsiveness at low throttle and engine speed.

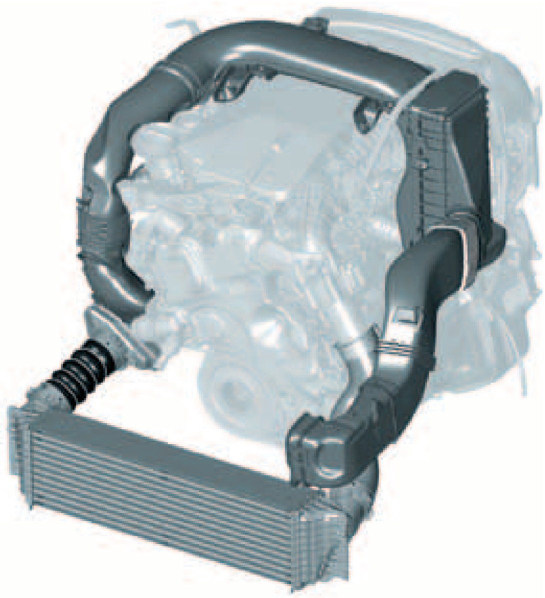
The introduction of a new bearing concept has improved standing start performance even further: The considerable reduction in friction losses lowers fuel consumption significantly, particularly in the important partial load range relevant to the customer. This improvement proves most beneficial during the warm-up phase before the engine oil has reached normal operating temperature.

A multi-chamber silencer is fitted to the compressor outlet. Thanks to reduced noise across a wide frequency range, it has been possible to broaden the operating range of the turbocharger without any negative impact on noise characteristics.

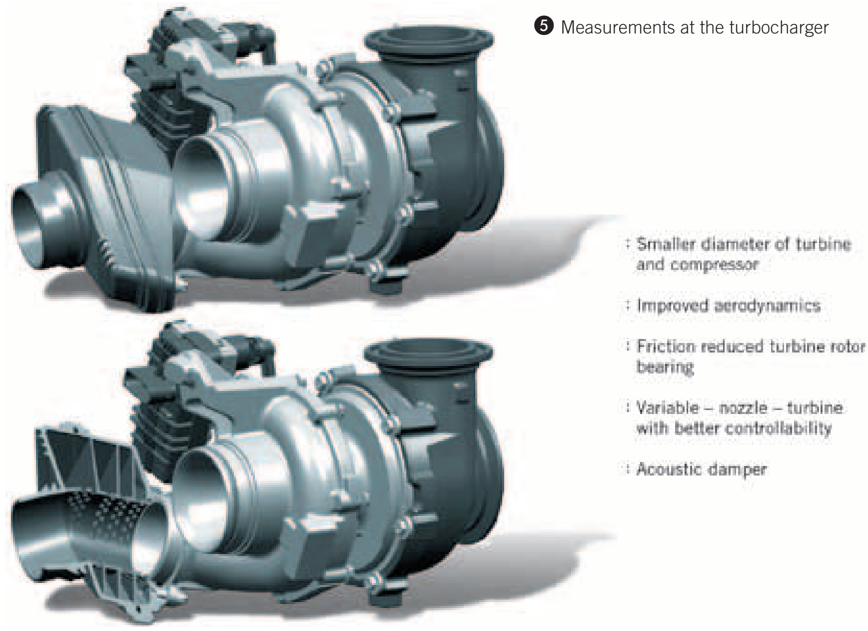
EXHAUST GAS RECIRCULATION

Another key aim in the development of the new six-cylinder engine was the further reduction in nitrogen oxide emissions. Not only does the engine comply with current Euro 5 limits, it also establishes the prerequisites for meeting future limits of Euro 6 in conjunction with a NO_x storage catalytic converter.

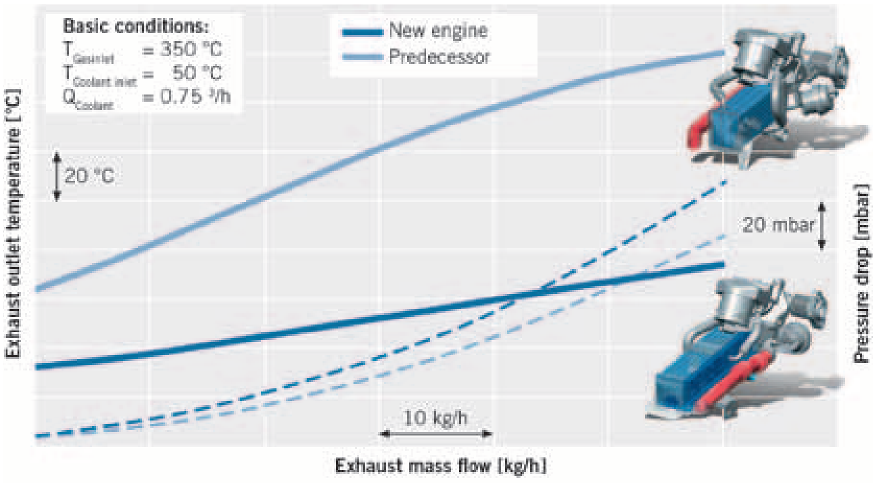
Along with the modification to the combustion process, optimisation of EGR cooling system is the most important parameter for lowering emissions. Cooling performance has been improved significantly, ❻, and the uncooled bypass at the EGR cooler has been refined. With these



❹ Air ducting



❺ Measurements at the turbocharger



❻ EGR cooling performance in comparison with the predecessor

measures, it has been possible to reduce nitrogen oxide emissions as well as HC and CO emissions to the extent that even heavy vehicles are able to meet Euro 5 limits on the basis of engine-internal measures alone [3].

EXHAUST GAS CLEANING

A compact arrangement located as close to the engine as possible is the basis by which all components of the exhaust gas cleaning system can offer good levels of efficiency.

During warm-up phases in particular, this arrangement minimises the cooling effect that components have on the exhaust flow when they are still cold [4].

In the Euro 5 version, a diesel oxidising catalytic converter and a maintenance-free particulate filter are fitted. Both components are housed in a common enclosure, ❼, immediately downstream of the turbocharger turbine. This arrangement is the same for all vehicle applications and national variants. The requirement for minimal exhaust backpressure has been fulfilled by means of a DPF cross-sectional area of 243 cm² in all vehicles.

To ensure that the Euro 6 variant produces even lower NO_x emissions, the oxidising catalytic converter has been replaced by a storage catalytic converter. This is dimensioned in such a way that the same enclosure can be used regardless of whether it is fitted in the Euro 5 or Euro 6. In order that the operating state of the exhaust gas cleaning system can be precisely determined, data supplied by special sensors, ⑦, in the digital engine management system are also taken into consideration to achieve an extremely accurate calculation of the soot mass and exhaust gas mass. This ensures that the necessary regeneration phases always take place at the right time, that no components are destroyed and that there is no possibility of an emission violation.

POWER AND TORQUE

The new six-cylinder engine delivers a nominal output of 190 kW at 4,000 rpm. The maximum torque of 560 Nm is available between 1500 and 3000 rpm. The specific power output of 63.4 kW/dm³ is the best specific power output ratio available in the single-turbo six-cylinder diesel engine segment. The full load curve in ❽ shows the improvements over the previous model. Particular importance was also placed on achieving a beefy torque characteristic. Maximum torque is available across a broad rpm range, which guarantees an agile response and is crucial to the engine's sporty performance.

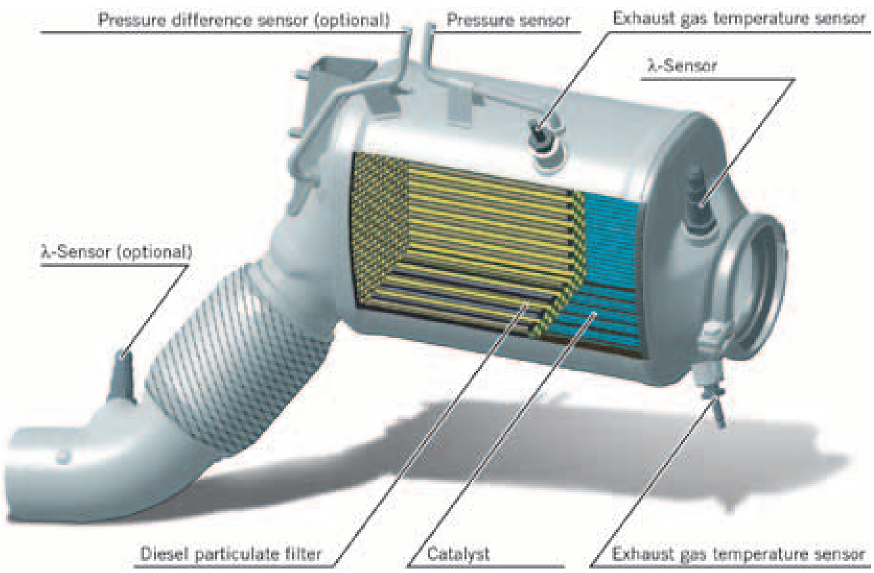
ECONOMY AND PERFORMANCE

The BMW 530d produces CO_2 emissions at a rate of 139 g per 100 km as determined in the New European Driving Cycle (NEDC), which is the lowest value for mid-luxury vehicles offering comparable performance. This outstanding accomplishment can be attributed to improved engine efficiency and the use of the automatic engine start/stop (MSA) function. Together, these measures have achieved a total reduction in fuel consumption of 13 %, ❾, calculated under standardised conditions by comparison with the previous model.

The use of a downsized exhaust turbocharger and the purposeful unthrottling of the intake and exhaust manifolds has significantly enhanced engine dynamics and improved its performance by 4.0 m four seconds after the start, ❿.

EMISSIONS

The new six-cylinder engine meets the emission requirements of Euro 5. A



❼ Sensors in the storage catalytic converter

Euro 6 version of the BMW 530d is also available as an option. Optimisation of the exhaust gas recirculation, injection system and turbocharging process has delivered another considerable reduction in raw emissions and establishes the optimum basis for compliance with even stricter limits in the future.

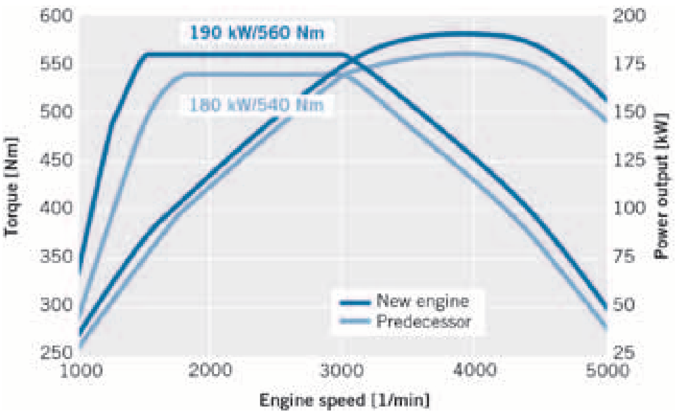
SUMMARY

The objective of any engine development must be to improve that which is already available and to realise optimisations without having to make sacrifices. Solutions to seemingly contradictory requirements, such as increased power output combined with lower fuel consumption and emissions, need to be found and put innovative engine developers to the test.

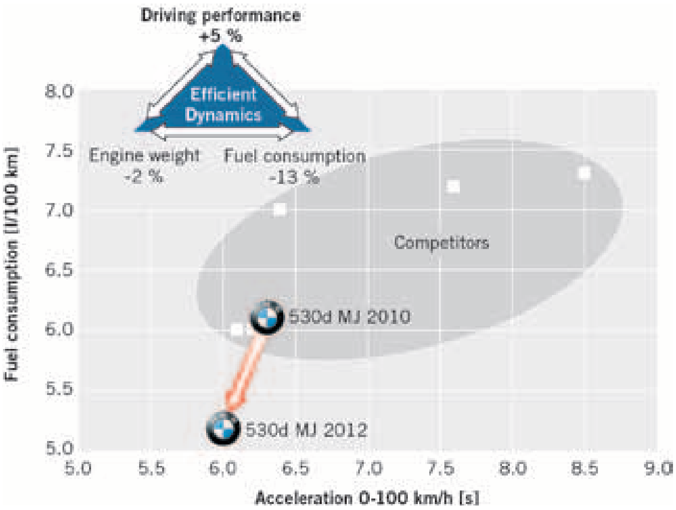
With the further-developed BMW six-cylinder diesel engine, the objectives set were achieved without compromise. It was possible to deliver another increase torque and power output, while savings on weight and fuel point forward to a future in which new standards for reducing and preventing emissions are set. All modifications were devised with consideration for the BMW production network and, within the BMW diesel engine family, with a view to the more extensive use of the four- and six-cylinder diesel engine basic equipment package in order that synergies could be realised in purchasing and production.

The individual measures were mainly designed to achieve greater load capacity of the basic engine unit, optimisation of turbocharger engineering, further development of the injection system and improved engine-internal cooling. Combustion and gas cycles were re-engineered and passive soundproofing measures were extended to improve comfort.

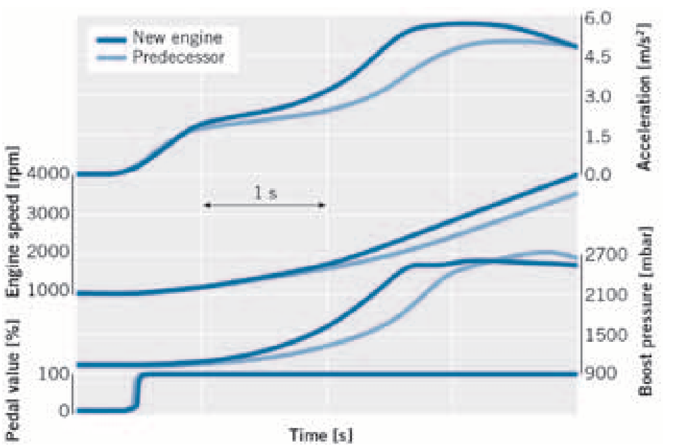
The revised six-cylinder engine is another characteristic and innovative member of the BMW diesel engine family that manages to comply with the strictest environmental requirements at the same time as delivering dynamic performance. With their state-of-the-art features, BMW diesel engines are optimally prepared for future automotive architectures and requirements of customers and the market.



8 Full load curve in comparison with the predecessor



9 Reduction in fuel consumption



10 Engine dynamics

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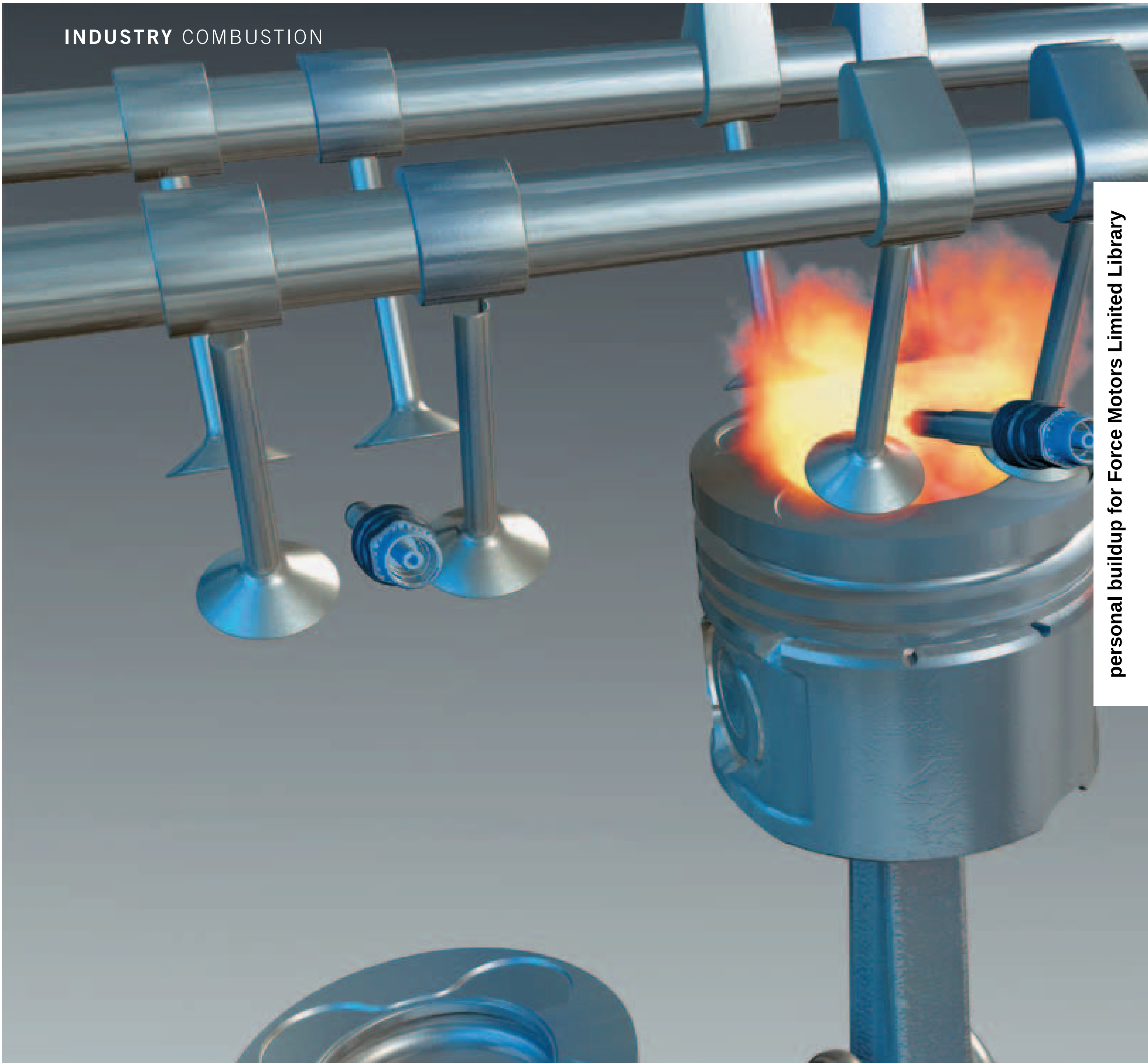

IN-CYLINDER PRESSURE SENSOR

Optimum combustion plays a key role in the reduction of engine-out emissions. Continental has developed a separate pressure sensor with integrated electronics for series-production engines that enables the pressure in the combustion chamber to be precisely determined for combustion control.

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❶ The Stand-Alone Pressure Sensor (SAPS)

IN-CYLINDER PRESSURE SENSOR OPTIMIZES COMBUSTION

Engine experts have always dreamt of controlling the combustion process from the inside. In-cylinder pressure sensors (ICPS) make this possible. The sensor gives feedback information from inside the cylinder throughout the process of combustion. This technology has been used for years during engine calibration campaigns to insure optimum combustion. However, the laboratory pressure transducer devices utilized are not only very expensive they also have a short lifetime on the engine. The challenge was to design a device that withstands in-cylinder combustion conditions over the engine life while delivering a sufficiently accurate pressure signal. After years of innovation, testing and improvement, Continental manufacturers a solution based on piezo electric technology with integrated electronics: the so-called Stand Alone Pressure Sensor (SAPS), ❶.

Cylinder pressure information is the best way for engine designers to reach the next step in the improvement of engine efficiency and enables controlling advanced combustion processes. Much information can be extracted from the in-cylinder pressure sensor signal such as fuel quality and quantity, oxygen quantity, combustion efficiency, torque delivered, and related pollutant production/emissions.

MEASURE RANGE	0 to 200 bar adjustable
CUT-OFF FREQUENCY	> 20 kHz
RESONANCE FREQUENCY	> 20 kHz
ACCURACY	2.5 % initial accuracy end of line incl. calibration; 3.5 % over lifetime
GEOMETRY	M8-M10 Design, compatible with wide range of length
TEMPERATURE RANGE	-40 up to +150 °C
SIGNAL OUTPUT	0 to 5 V or 3.3 V
ANALOG VOLTAGE	Linear/ratiometric
LINEARITY	< 0.2 %
BROAD BAND NOISE	< +/- 0.5 bar peak-peak
ROBUSTNESS	> 1000 thermal cycles -40 up to +150 °C
ADVANTAGES	: Robustness : Signal to noise ratio : Calibrated sensor : Very good thermal behavior : Large bandwith

❷ Key characteristics of the pressure sensor SAPS

CURRENT SITUATION

The diesel engine market is finally the first to adopt the use of cylinder pressure sensors. In-cylinder pressure measurement is part of an important proportion of new applications under development. The use of in-cylinder pressure sensors today mainly seeks to improve the control of air and fuel and to reduce overall system tolerances as well as advanced diagnosis feature for OBD (On-board diagnosis). The gasoline engine market has also been working hard on solutions integrating closed-loop combustion control based on in-cylinder pressure sensors. Auto ignition combustion (Controlled Auto Ignition – CAI) controlled by the cylinder pressure signal is the key to improved emissions and reduced consumption.

ASSOCIATED STRATEGIES

Integrating in-cylinder pressure sensors in a mass production engine is a first step into a vast choice of combustion improvement strategies with alternative combustion mode control being at the top of the list. Many manufacturers have invested years of research into alternative combustion modes that can drastically reduce emissions. The complex control of alternative combustion modes for diesel applications will probably need some experience to manage and optimize the transitions between different combustion modes for vehicle application use.

The in-cylinder pressure sensor can be used as the main information source to manage high and low pressure EGR systems (Exhaust Gas Recirculation) precisely and simultaneously. It can also improve the combustion in transient conditions and cold-start, resulting in a strong decrease of consumption and emissions. The overall engine system price can be reduced thanks to models based on the cylinder pressure information, from which, air, emissions, fuel quantity, and fuel quality can be deduced.

STAND ALONE PRESSURE SENSOR

In-cylinder pressure sensing is a key function for the next engine architectures. Of course a pressure sensing device can be integrated inside other components which have access to the combustion chamber, such as glow-plugs, spark plugs and injectors. Solutions of this type are more easily integrated in the engine. However, a stand-alone sensor has more advantages to offer. Separating the functions of pressure measurement from other functions leads to several benefits: the first one is linked to the product simplification which results in obvious cost reductions. The second advantage is that the SAPS will not need to be replaced if another component has a defect. Last but not least, the stand-alone concept limits possible interferences. Glow plugs, spark plugs and injectors all use a strong control signal for their primary function. Such high energy signals may disturb the pressure signal. The Continental stand-alone sensor can ensure that the in-cylinder pressure is correctly measured in every situation (engine start, glowing and spark events, fuel injection). Moreover, the SAPS gives greater flexibility for design and integration.

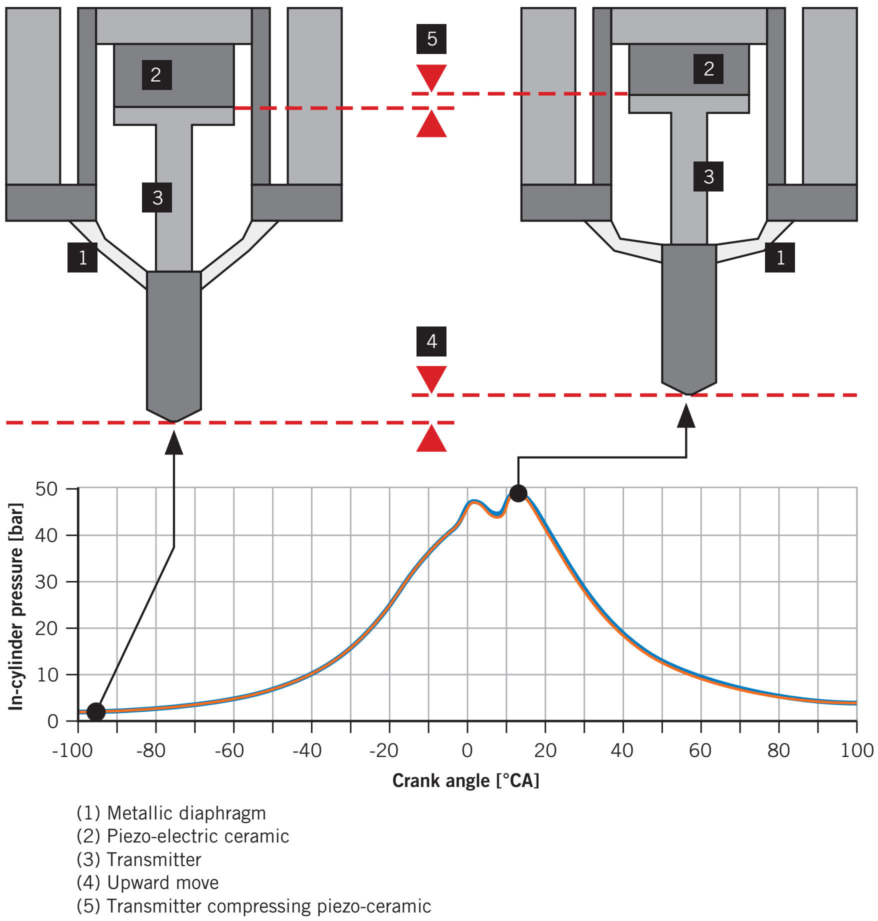
The ICPS design is compatible with any type of engine. This has been confirmed during a lot of engine integration expertise over the last few years. The sensor internal design can be easily adapted to most cylinder head designs (threads down to M8/100 mm). The ICPS connector type can match any customer requirement. ❷ gives an overview of key sensor characteristics.

SENSING PRINCIPLE

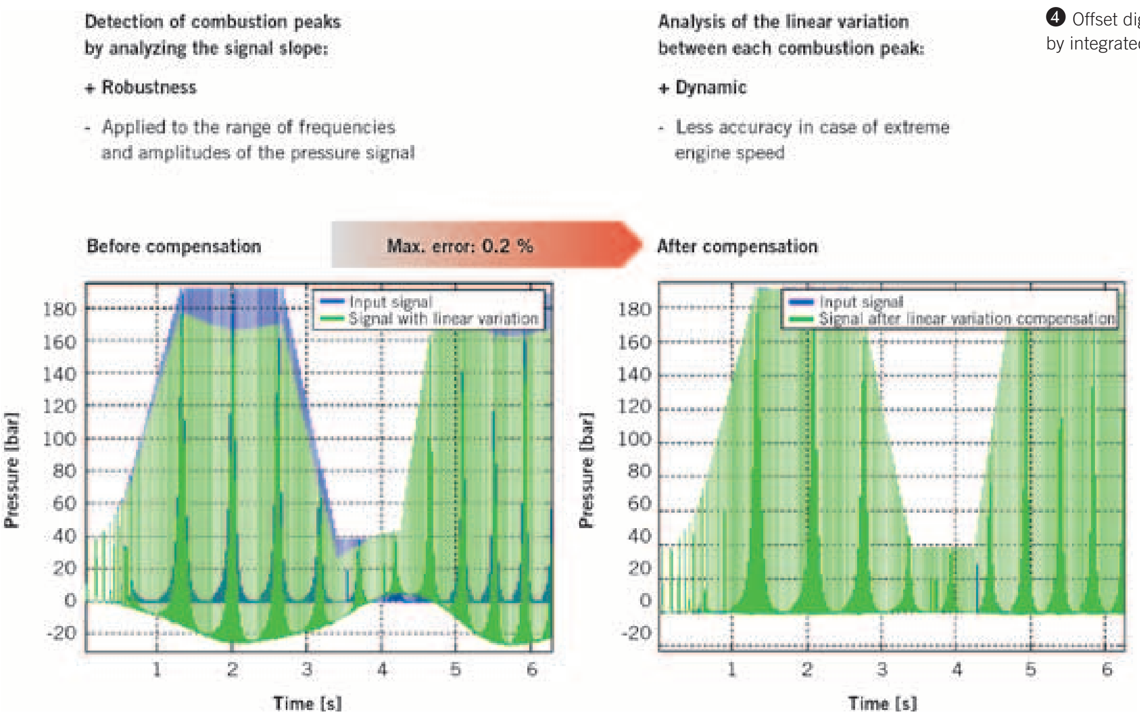
The ICPS sensing unit, ❸, combines a metallic diaphragm (1) facing the combustion chamber and a piezo-electric ceramic (2). The latter translates the micrometric diaphragm displacement into electrical charges. The in-cylinder pressure generates a force on the diaphragm and a part of this force is passed on to the piezo-ceramic by a "transmitter" (3). When the pressure rises, the diaphragm will move upward (4) pushing the transmitter and thus compressing the piezo-ceramic (5). The ratio of force reaching the piezo-ceramic is directly linked to the stiffness ratio between the diaphragm and the soft transmitter. As a result, the mechanical sensitivity of the sensing unit can easily be adjusted by design modifications. One of the key strengths of the ICPS sensing concept is that the diaphragm is tough enough to withstand pressure and temperature levels reached in the combustion chamber.

INTEGRATED ELECTRONICS

The ICPS is an intelligent sensor completed with control electronics. To get the best performance and wide customer compatibility Continental uses advanced



❸ Operating principle of the SAPS sensing unit



❹ Offset digital compensation by integrated electronics

integrated electronics, ❹. An ASIC was developed to fit the application needs of an external component placed in an overmolded body. It meets serial production requirements and low space constraints.

Whereas piezo-resistive technology is able perform absolute pressure measurement, Continental has chosen the piezoelectric technology to provide better signal-to-noise ratio and bandwidth. Continental has developed algorithms analyzing the piezo-electric signal in real time. Thus the signal output is kept within the specified range with minimal impact on sensor performance.

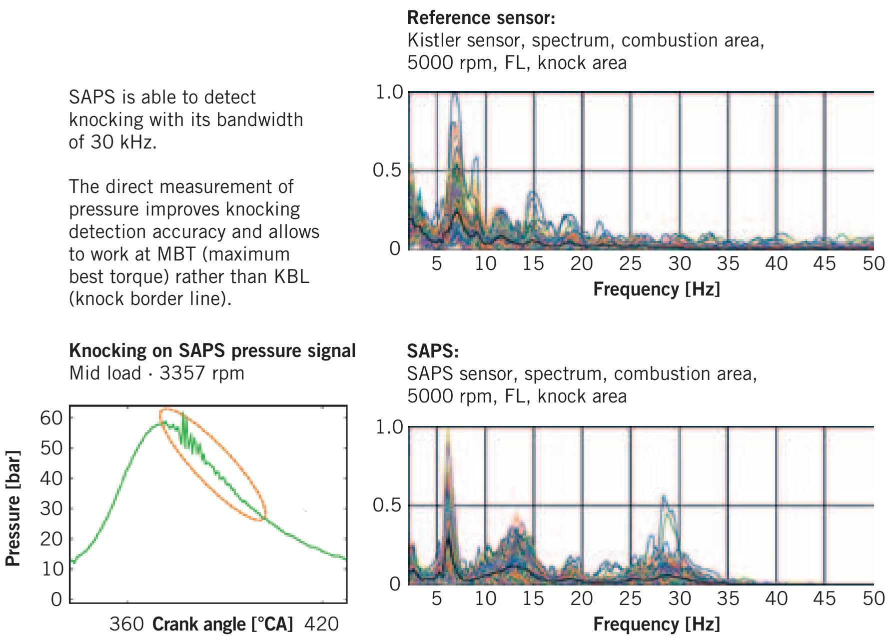
As the bandwidth is a key element of sensor capabilities, the ICPS goal is to provide a maximum usable signal output. It features > 20 kHz bandwidth, which allows knock detection, fuel injection detection, combustion and valve noise measurement, ❺. ICPS was designed to be compatible with any OEM configuration and engine type and design. The efficient sensor technology works with low current and low voltage. It does not require external conditioning or signal post-processing to deliver pressure information. Once connected to the ECU 5 V supply, it directly measures the pressure by delivering voltage output proportional to pressure level inside the cylinder.

ON-BOARD DIAGNOSIS

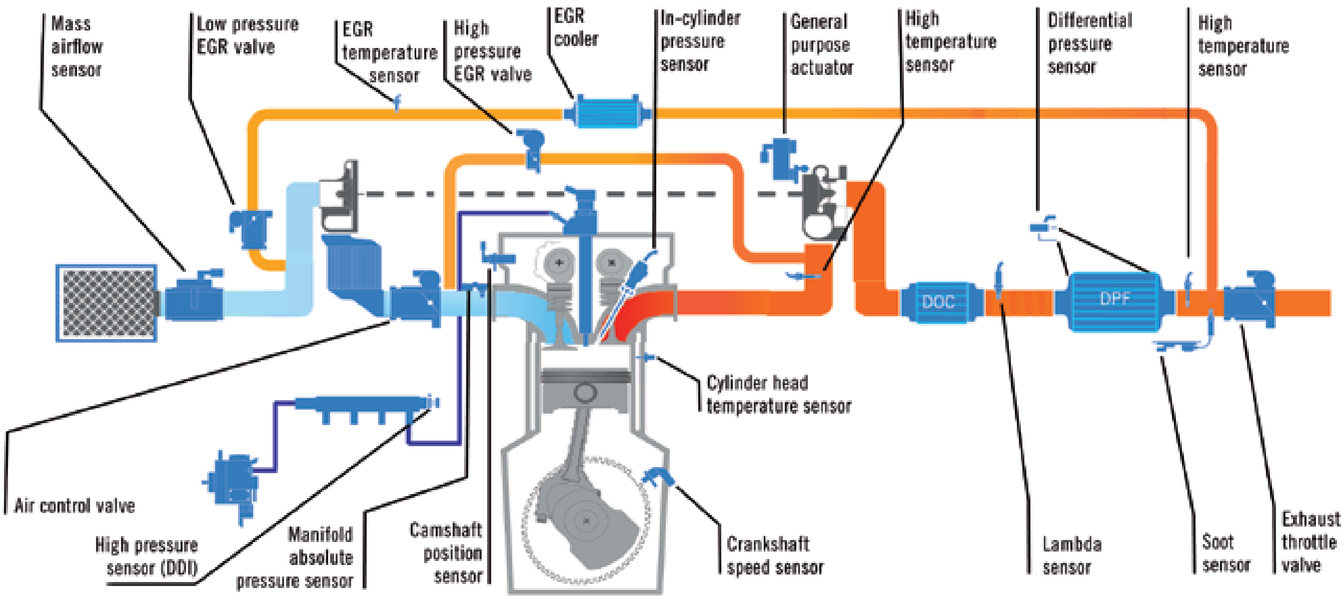
Standard diagnosis is integrated in the ICPS electronics to detect internal and external errors. In the case of a fault, the signal output switches to error band, allowing the ECU to detect and isolate the defective sensing. Furthermore, the in-cylinder pressure signal analysis of the ICPS allows detection of other engine components' drift or defect over lifetime.

CALIBRATION

Thanks to the ICPS's advanced electronics the sensor can be adapted to various sens-



❺ Knock detection is a use case of the SAPS



❻ Low pressure EGR standard configuration

ing unit characteristics. Continental has developed an air pressure test bench with up to 250 bar for sensor testing and calibration by adjusting sensor sensitivity (compared to a laboratory reference sensor) and a thermal correction factor. It is also possible to modify some post-processing features, to fit special customer requirements, during "end of line" calibration. The final pressure test checks that each sensor meets product specifications.

ENGINE CONTROL SYSTEM

Developing advanced combustion control and new engine technologies is mandatory to meet upcoming emissions regulations. The control parameters (injection, ignition) are conventionally derived from static characteristics. This causes a lack of robustness to environmental changes and production variability, impacting engine fuel economy and emissions. This problem can be solved by implementing closed-loop strategies using in-cylinder pressure sensors. The in-cylinder pressure measurement is used to compute the torque and the combustion phasing (CA50: crank angle at which 50 % of the heat from combustion has been released). Air and fuel are adjusted accordingly to achieve the desired targets. This strategy can be activated during steady state but also in transient phases or transition mode if there is an in-cylinder pressure sensor.

Based on in-cylinder pressure data the air flow into the cylinder can be modeled as well as NO_x emissions throughout the cycle. Therefore, advanced strategies will enable monitoring of engine emissions during operation. Pressure information is known to be a key for new HCCI (Homogeneous Charge Compression Ignition)/CAI engines. Considering new drivetrain technologies, engines of this type can be of great interest when used as range extenders for hybrid electric vehicles (HEV).

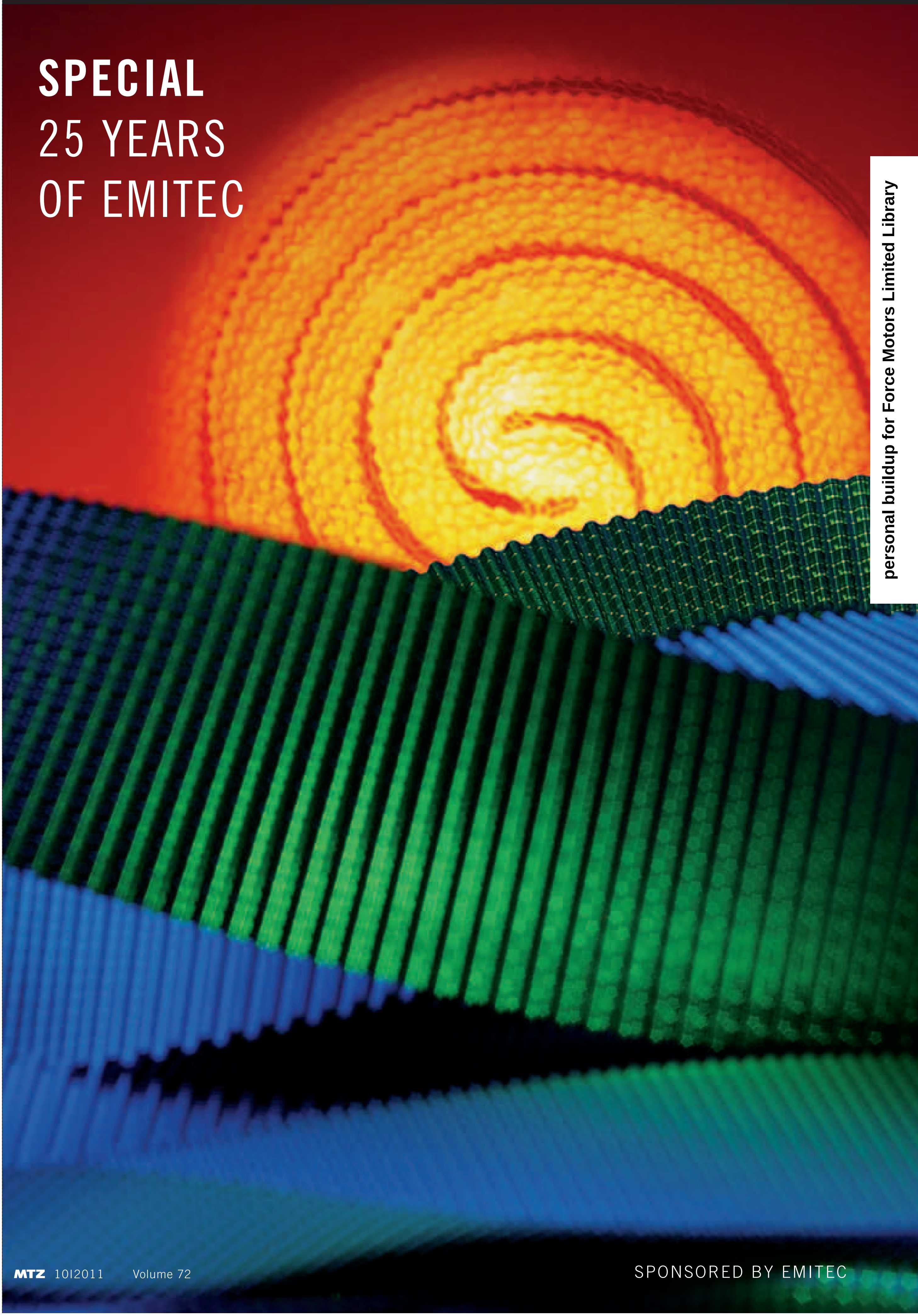
In addition, new OBD standards require greater control over time of vehicle robustness and pollutant emissions. The implementation of strategies to detect and compensate engine component drift is required. In case the control parameters (injection, ignition) come from open-loop strategies, engine component drifts turn into a direct and significant degradation of vehicle performance (fuel economy, noise, pollution). It is possible to address this problem through the development of an advanced combustion control loop. Examples include the LTC (Low Temperature Combustion) diesel engine application that allows a drastic reduction of NO_x emissions at the expense of combustion stability and sensitivity to system variability. The in-cylinder pressure measurement provides a direct track of the combustion quality (phasing and release of energy). The engine control parameters can therefore be adapted in real time to compensate faults, large tolerances and drifts. As an example a pressure based close-loop system will come back to optimal settings and will maintain a constant emissions level while simultaneously identifying a drift due to an injector fouling and triggering the raise of the OBD diagnostic flag.

Last but not least, the in-cylinder pressure information can also be used to replace other sensor data. For example, with the proper strategies based on in-cylinder pressure, camshaft and knock sensors can easily be removed, ❻.

OUTLOOK

Advanced control strategies for combustion are in validation on the vehicle in order to exploit the potential of these sensors. This is done in response to coming needs of the automotive engines, particularly in terms of robustness and diagnostics of combustion systems. Utilizing in-cylinder pressure measurement in mass production engines is the first step towards combustion engine performance improvement. The second step is to optimize ECU strategies managing the complete package of ICPS, ECU, and injection/ignition system. Continental's goal is to offer engine manufacturers an easy way to develop new engines that meet future requirements. The new engine control system using the full potential of in-cylinder pressure measurement is a result of pursuing this goal.

SPECIAL
25 YEARS OF EMITEC



EMITEC: 25 YEARS OF PIONEERING AND INVENTIVE SPIRIT

When Emitec was founded in 1986 engineers had already been trying to build stable metal substrate catalysts for years. Since then the company has stood for innovative engineering skills and 100 % quality in emission control.

Celebrating the 1,000,000th catalyst in 1990

It wasn't until 1978 before the development and production of metal substrate catalysts reached its first milestone. At that time the Siemens subsidiary Interatom succeeded in creating a reliable and durable joint between the metal foils and the jacket tube using a patented high-temperature brazing process. The final breakthrough came with a design patented in 1985 that involved winding the foils into an S-shape, which made it possible to build substrates with a greater diameter. This was accompanied by the development of inexpensive metal foils for temperatures up to 1200 °C.

When it became clear that these technical processes would be viable Interatom set up a "New Technologies" department in 1984 to industrialise the designs. The company soon received small orders for metal catalysts. One of the first customers was the prestigious marque BMW Alpina. Its director Burkard Bovensiepen was known for setting new standards when it came to building fascinating, fast and now also the most environmentally friendly cars. They were joined by a Canadian manufacturer of catalytic converters for stationary engines. The first automotive customer was Jaguar, which was looking for starting catalysts for their V12 engines. And so the second stage, finding satisfied customers, was achieved.

The first series-production metal substrates were still built by hand in small numbers at Interatom in Bensberg. Siemens was looking for a partner with experience in large-scale production and found one in the Anglo-German company Uni Cardan AG. The two partners founded Emitec GmbH as a 50/50 joint venture on 11 August 1986. Today after various company reorganisations Emitec is owned in equal parts by Continental AG and GKN plc. Within six months Emitec grew from a start-up with three founding members (Wolfgang Maus, Director, Rolf Hetzelberger, Technical Sales and Dorothee Groetzner, Secretary) into a company with 21 employees. One year later this figure rose to 64 because of a large number of new orders, including some from Alpina and Porsche (for main catalysts) and Mercedes. In 1987 Mercedes ordered 180,000 starting catalysts merely on the basis of satisfactory test samples because the carmaker had experienced major problems with catalyst substrates from another supplier.

Emitec started production in a hall rented from Uni Cardan in Lohmar. Like every start-up the company initially relied very much on improvisation and flexibility and its director and secretary would help out in production, whenever necessary. A growing number of orders meant that it was no longer possible to make units by hand and manufacturing moved up one step when the first semi-automatic production process was set up in 1988. In response to the company's bid for more business customers asked for lower prices first. The needs of a start-up for more orders before prices could come down seemed of no consequence. Emitec was intent on growing without outside assistance and was proud of not having to ask for further help from its shareholders after the initial capital injection. In 1990 the company opened its first production hall in Lohmar and combined the production facilities known as Vereinigte Hüttenwerke, which were located at various sites in Lohmar and Bensberg, under one roof. The automation of the production processes had progressed and the team's aspirations for the perfect production process came another step closer.

In the same year the company acquired Volkswagen as a customer and built the one millionth metal catalyst. In 1992 Emitec entered the North-American market after receiving an order from Chrysler. In 1993 engineers began to analyse different cell densities and foil thicknesses with the aim of optimising heating times and exhaust backpressure. The research carried out in a joint project with Toyota resulted in the supply of close-coupled catalysts to the carmaker. Emitec started a new trend with these catalysts. Metal catalysts with cell densities of 600 cpsi and foils that in some cases were only 0.02 mm thick turned out to be a perfect solution, especially in the US where they had to comply with LEV emission limits.

NEW CUSTOMERS, NEW PLANTS

When Chrysler recognised these advantages Emitec decided to build its first production site abroad. In 1995 the company opened a plant in Fountain Inn, South Carolina. The first product left the new fully automatic US production facility after nine months and another part of the team's hopes for the company came true. The

The three founding members (from left to right: Wolfgang Maus, Director, Dorothee Groetzner, Secretary, Rolf Hetzelberger, Technical Sales)

site was expanded after more large orders from BMW, Chrysler and Toyota and made a major contribution to revenues, which increased by 70 % to 149 million euros between 1996 and 1999. Emitec also had some other unexpected success during this period. Until that time most of its business was connected to models from the sports, luxury and high-performance sector. Completely out of the blue, Volkswagen placed an order for 700,000 close-coupled metal substrates for its small four-cylinder models, far more than Emitec's available capacity. Mr. Piëch made it clear that VW was not planning on slowing down its car production to suit the rate at which Emitec was able to supply substrates. The order came at the right time for the planned construction of a new factory.

Until 1996 Emitec had manufactured metal catalysts exclusively for petrol engines. The introduction of Euro 2 emission limits in 1996 meant that diesel engines now required oxidation catalysts and Emitec was ready to supply the right products. Towards the end of the millennium order volumes in Europe increased to such an extent that in 2001 Emitec built a new state-of-the-art production facility in Eisenach in the space of only six months to ease the pressure on the plant in Lohmar. Some 20 sites were surveyed across the world. Thuringia beat all competitors hands down. Productivity reached world-class levels within a short time and so fulfilled an objective the company had pursued for 15 years. The site is also home to one of the world's state-of-the-art emission test centres and in 2009 the world's most powerful all-wheel roller dynamometer for commercial vehicles with an overall output of 600 kW was installed. Emitec has always conducted high-quality research and development thanks to a small highly skilled team of engineers. The new test centre allows the company to perform all emission and durability tests in-house.

The properties of metal catalysts were substantially improved over the course of 25 years, for example, in 2004 when perforated metal foils (PE), which generate turbulent exhaust gas flow, were introduced in catalysts for Audi's RS models. Minimum pressure loss produced greater power output. A new foil structure (LS) with longitudinal grooves further intensified the turbulent cleaning process so that substrates could be made approximately 25 % smaller and lighter. This saves corresponding amounts of expensive precious metals for the coating. The heated metal catalyst is another unique development, which was first used by Alpina in 1995. In future they are going to play a very important role in optimising the heating and hence the efficiency of catalysts for combustion engines with a start-stop system or discontinuous operation (e.g. range extenders).

PRODUCTS FOR MOTORBIKES

It is a little known fact that Emitec is the world leader in catalytic converters for motorbikes. When the first emission limits for two-wheelers were announced in India a few years ago Emitec reacted by building a production facility in Pune. Since 2006 the company has supplied several hundred thousand emission control systems for two-stroke engines. The company operates further sites in China, Japan and South Korea.

Today Emitec is a medium-sized enterprise with approximately 1,000 employees. The company is expected to generate 180 million euros worth of revenue in 2011. The main customers are vehicle and engine manufacturers, which account for more than 90 % of turnover. The company particularly excels in process and product development with a sustainable outlook.

The market success of Emitec's products often comes years after they were first proposed but this also means that they are technically mature at the point of their launch. For instance, not one of the 150 million Metalit metal catalysts supplied to date has been responsible for a vehicle breakdown. Another secret of the company's success is a friendly working environment and its social commitments at local and political level. This has instilled a sense of community across company hierarchies, which prevails to this day. These progressive values ensure that Emitec will be able to face the challenges of the next 25 years.

"DETERMINATION FASCINATES ME"

A regularly updated ranking displayed in the company lobby reveals a great deal about Emitec. It shows how many employees have registered patents and acts as an incentive to all. CEO Wolfgang Maus headed the list for a long time. A few years ago he relinquished his top position, quite appropriately, to his development manager Rolf Brück.

4 QUESTIONS TO WOLFGANG MAUS

MTZ _ Emitec is a company driven by ideas. When do you feel most inspired?

MAUS _ Sudden inspiration or a brilliant idea in the shower tend to be the exception. Our ideas originate from processes. We're mainly concerned with the future and try to anticipate what the next evolutionary, or perhaps even revolutionary, step has to be. We then have to implement the resulting objective through components or products. It gives us great pleasure when we find a perfectly workable solution. These developments require engineering and scientific creativity.

Is there an invention that you would like to have thought of first?

Not so much in our field but I have the greatest respect for ground-breaking inventions, the systems of Konrad Zuse, for instance. And I would be very proud if I had discovered radio transmission or invented the light bulb. There are many great inventions but they, too, were developed in the course of processes and with clear aims. It's the determination that fascinates me.

What would you, as an entrepreneur, like to have more time for?

I would really like to broaden my knowledge of economics. I'm already doing that as much as time permits. I've noticed that there is a close relationship between economics and physics. Economics is easier to understand if you've already studied physics.

You have overseen 25 years of impressive company development. What is the most important insight you gained from that?

That's a little more complicated. On the one hand it depends on the entrepreneur, the driver, and on the other also on the opportunity of being able to pool critical intelligence and skills with your colleagues and partners. Each can complement and strengthen the other. Another important aspect is a positive attitude towards people and their qualities. We maintain a social environment that is based on honesty and social responsibility. This environment enhances staff performance. To make a long story short, we were able to bring together an excellent team.

Mr. Maus, thank you for talking to us.

INTERVIEW: Ruben Danisch
PHOTO: Emitec

CORPORATE CULTURE: HUMAN-CENTRIC AND PERFORMANCE-ORIENTED

Emitec's three founding members set up their company according to the maxim "Let's get stuck in" and this attitude prevailed when the first small administrative and production departments opened. The question of how to preserve spontaneity and performance as well as success orientation arose only as the company continued to grow. Seed capital was scarce and after its foundation and entry into the automotive sector Emitec intended to fund its targeted growth from its own resources.

Emitec has operated as an open system from the very beginning. All information was internally available, exhaustive communication was, and still is, every employee's duty. Employees were proud of the small initial success and felt that they had played a part in it. What would have been more natural than to banish the seemingly rigid corporate competencies, and not least the term itself, and ask each member of staff to take personal responsibility for Emitec as a whole. Just as in the early years everyone was expected to give their absolute best. Skilful improvisation accelerates routine practices as long as discipline remains the overriding force. Today all information still goes to where it is needed without having to pass through hierarchical decision-making levels. In brief, the management principle is based on a "neuro-

Celebrating the 100,000,000th catalyst in June 2008

nal network” that knows no taboos. The company demands complete openness. This also includes the red jackets that are worn by everyone, from the boss to the youngest apprentice, to give a sense of community.

Secondary virtues are an important part of Emitec’s culture and consequently truth is considered to be a subset of honesty. This interpretation stems from close interaction and discussions with politicians. Interaction and discussion are greatly cultivated in the “Lohmarer Forum”, which takes place at irregular intervals and is open to those living in the Lohmar region. Emitec invites various independent contributors to take up contemporary issues, pull apart all-too-comfortable half-truths and ideologies, examine the facts and provide an outlook to the future of the real world. The forum generates extraordinary interest and the venue is barely able to accommodate the audience. The presentations are followed by discussions, which would go on into the small hours if the management did not call time.

Of course, production is a top priority because it earns the money that pays for Emitec’s above-average investment in research and development. Then there are sales, administration and management. Development comes in a good second and is vital to the company’s continued existence.

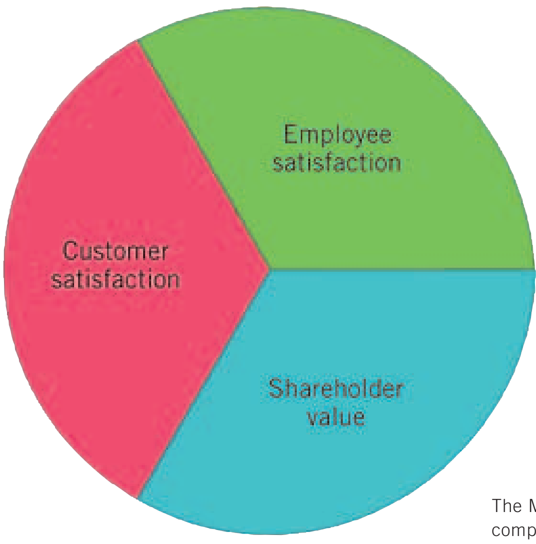
Emitec takes an honest approach to balancing the interests of its shareholders, customers and employees. This is redefined each year by the “Magic Circle”, which sets the company’s objectives and activities. Customers, employees and shareholders each receive one third of our company’s commitment. The “Magic Circle” is part of budget planning and budget fulfilment.

As every well functioning family we expect our employees to be totally committed to the corporate community, which will always support members of staff who experience problems, such as health issues, for example. Emitec pays flexible wages and salaries that contain bonus and penalty elements. This has proven to be the best and fairest solution during the company’s 25-year history.

Apart from the “Lohmarer Forum” Emitec organises a number of other schemes for those living near the company’s sites. We developed “research boxes” for nursery schools in Lohmar and Eisenach to help small children and their teachers understand technical and scientific issues. Emitec also runs technical and social projects in primary and secondary schools. Cooperation with universities, student scholarships, international placements for students or interns at the company’s branches and comprehensive apprenticeships are among our long-standing traditions. Emitec takes a clear view: Each site can survive only as long as there is young talent with special skills. Emitec does not rely on state education alone.

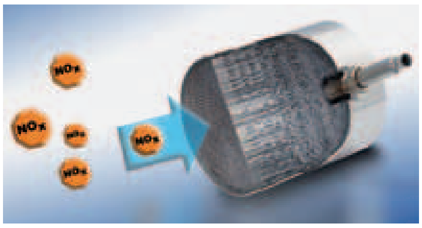
It is almost impossible to list every “living” aspect of Emitec’s culture. Many things have been an inherent feature of the company for many years and are no longer considered part of a special culture. The time for reflection comes whenever it looks as though things were better in the past. For instance, the advent of E-mail fundamentally changed our communication habits. Are we still sending information in a neuronal and targeted manner? Do colleagues still speak to each other or do they think it is easier to send an E-mail? Can regulations, instructions and corporate governance replace personal or group responsibility and decency?

Emitec will continue to avoid rigid structures wherever possible. The company is not going to change its beliefs. 25 years experience should help us to be honest, flexible, motivated and, if necessary, different. Every employee is proud of having helped to implement and fund Emitec’s global development through their work.



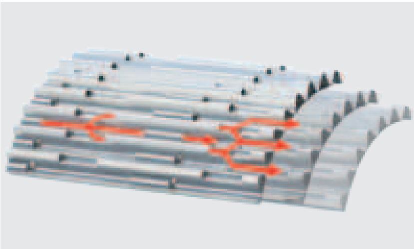
The Magic Circle defines the company’s objectives and activities

THE EMITEC PORTFOLIO AT A GLANCE



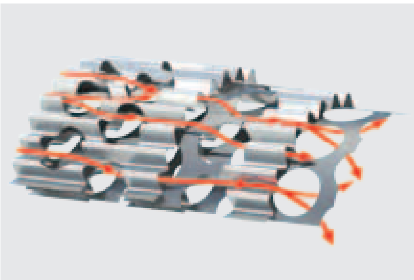
NO_x ADSORBER

: High cell density
: Increased mass transport
: Integrated NO_x sensor for optimised control



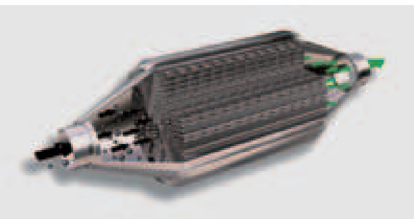
LS DESIGN

: Improved heat and mass transport
: Reduced weight/material
: Potential for volume reduction through high specific effectiveness



PE DESIGN

: Reduced weight/thermal mass
: Improved cold start behaviour
: Low pressure loss
: Improved flow distribution/ internal gas mixing



PM METALIT

: Partial-flow deep-bed filter with diffusive particle separation
: Continuous passive regeneration
: Blockage-free operation

SCRi SYSTEM

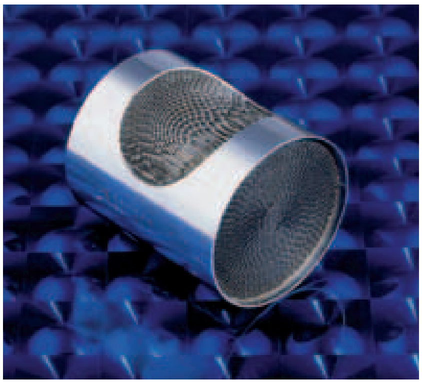
: Combination of particulate filtration and SCR
: Compact design through integrated function → reduced system volume
: Continuous operation with passive filter regeneration

COMPACT CATALYST

: Compact design for close-coupled installation
: Improved light-off behaviour
: Optimised temperature management
: Potential for volume reduction through greater effectiveness → cost potential

EMICAT

: Electrically heated catalyst with integrated heating function
: Energy-efficient, flexible temperature management
: Improved cold start and low-temperature effectiveness for DOC, SCR and TWC

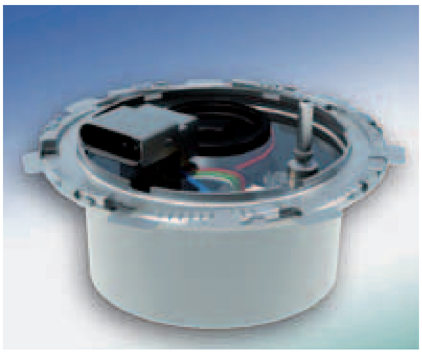


METALIT CATALYST SUBSTRATE

: Low heat capacity
: Large catalytic surface
: Low pressure loss
: High mechanical strength
: Various geometries available
: Applications: DOC, SCR, NO_x adsorbers, TWC

PRE-TURBOCHARGER CATALYST PTC

: Utilisation of high exhaust temperatures in front of turbine
: Turbulent flow – high specific effectiveness
: Potential for reduction of overall catalyst volume – cost savings



GEN 3 SCR DOSING SYSTEM

: Compact in-tank solution
: Highly integrated design, incl. heating, filters, sensors and actuators → only 1 electric and 1 hydraulic connection
: Variable injection pressure (5 to 9 bar)
: Integrated control unit, available as ECU or OEM version

AIRASSISTED SCR DOSING SYSTEM (UDA)

: External dosing system
: Integrated air mixing chamber
: Highly accurate volumetric dosing
: Excellent spray preparation and distribution
: Integrated control unit, available as ECU, retrofit or OEM version

AIRLESS SCR DOSING SYSTEM (UDL)

: External dosing system
: Spray preparation using high injection pressure (9 bar) and special nozzles
: Integrated heating via PTC
: External replaceable filter
: Integrated control unit, available as ECU, retrofit or OEM version

DME 60 SCR DOSING SYSTEM

: External dosing system for large engines
: Maximum delivery volume: 60 l/h
: Highly accurate volumetric dosing
: Use of multiple injectors possible

R&D IS ESSENTIAL EVEN IN DIFFICULT TIMES

Research and development is vital to Emitec. Without innovation the company would not have ventured forward or stood up to strong competition. Even during the crisis in 2009 and 2010 the company invested 18 % of its revenue in research and development despite a sharp downturn in sales.

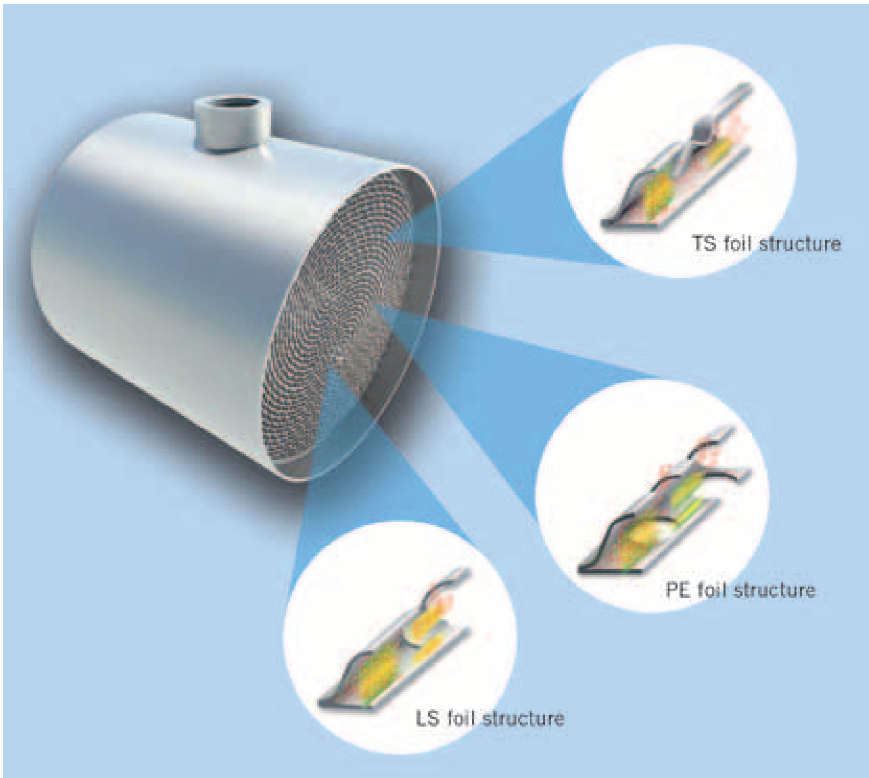
When Emitec GmbH was founded in 1986 credible innovations were the only way of convincing car manufacturers to abandon the tried and tested ceramic monoliths in favour of a newcomer who made metal substrate catalysts; especially one who as a start-up had as yet to produce specific applications. Emitec has been conducting high-quality research and development since its early days when the company had access to the materials research resources of Interatom.

The distinguishing features of Emitec's metal substrate catalysts are S-shaped foils that are stacked in alternate corrugated and flat layers and firmly attached to the jacket tube. The design prevents any embedding and durability problems during tough everyday conditions. It is sufficiently elastic to withstand temperature shocks and resistant to vibration stresses. Mercedes, Alpina and Porsche were among the first car manufacturers interested in the product and quickly established that its physical advantages also transferred into practice and that the S-shape was ten times more durable than other products. After the first sales success the company began to set up its own R&D facilities, including laboratories and dynamometers with sophisticated measurement technology.

SIMPLER HANDLING, SUPERIOR PERFORMANCE

The simple canning process carried out by exhaust system manufacturers has always been much easier with metal substrate catalysts than ceramic monoliths. The design and thin metal foils make metal substrates superior to thick-walled ceramic products. With the same diameter metal substrates cause far less performance and pressure loss and only marginally higher fuel consumption.

The advantages of low cell densities, that is, larger individual cell cross-sections, were already known. Pressure loss was reduced but so was catalytic performance because of a smaller catalytic surface. Was it possible to increase conversion rates with higher cell densities? And would this also make it possible to build cheaper and more compact catalytic converters? In 1993 Emitec started analysing substrates with cell densities of 400, 600, 800, 900, 1,200 and 1,600 cpsi (cells per square inch; one cell corresponds to one channel) at its test centre in Lohmar. Exhaust backpressure rose as expected but this was offset by thinner foils and shorter substrate lengths. The result was a significant increase in the conversion of a specified volume of pollutants so that the overall costs of the catalysts systems could be reduced despite stricter emission limits. Together with



Lambda sensor catalyst with TS, PE and LS foil structures

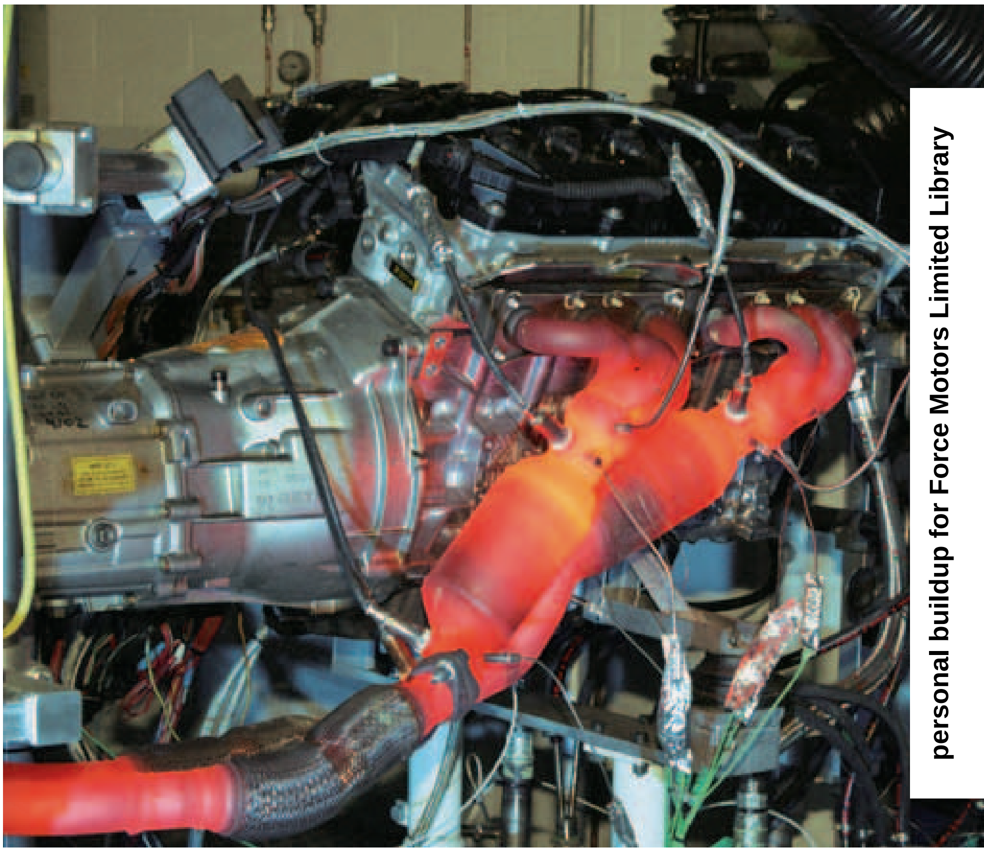
Toyota and Audi, Emitec started a new trend in catalyst technology.

After initial resistance the manufacturers of ceramic products followed suit. All profits were invested in strengthening R&D capacity. This was essential because the new catalysts with their high cell densities were far more susceptible to thermal and vibration stresses. The opening of a new test centre in Thuringia in 2000 made the company's highly specialised R&D work much easier. Special thanks goes to Emitec's partners in the steel industry, who were instrumental in the implementation of the very thin and corrosion-resistant steel foils.

THE FUTURE IS TURBULENT

After a decline in sales at the beginning of the new millennium, which was largely due to problems experienced by one of its biggest customers, Emitec bounced back with the invention of turbulence-generating honeycomb profiles. These new types of cell structures have been used in production vehicles since 2004 and convert the usual laminar flow inside the cells into turbulent flow. As a result, there is a much higher rate of gas exchange in catalysts with an LS structure between the wall flow that has already been catalysed and the core flow that still contains a high amount of pollutants. The PE structure with wall openings in the form of perforated foils was introduced at roughly the same time. It also promotes the cross-exchange of exhaust gas inside the catalyst and so improves conversion rates with substantially lower pressure loss. The investments in research and development have paid off. Without changing the size of the catalyst, the structures are able to cut emissions by at least an extra 25 %. Alternatively, the size of the catalyst can be reduced by 25 % saving 25 % of expensive precious metals while maintaining the same rate of conversion. To this day, Emitec's competitors have not been able to bring turbulent catalysts to the production stage.

Emitec has pursued a lead-user/fast-follower strategy from the very beginning. This involves the company working with interested vehicle manufacturers, the lead users, on the initial production of innovative technologies. Sophisticated R&D programmes ensure that even this small-scale production has zero defects in the field. Successful innovations speak for themselves. Other car manufacturers, the fast followers, are quick to take advantage of successfully tested innovations. This leads to the rapid implementation of large-scale production and the economies of scale that benefit everyone. Many automotive innovations were developed in R&D laboratories long before lawmakers introduced lower emission limits.



Engine test bench with red hot catalyst

The development of the electrically heated catalyst in 1988 is an important and elaborate example of R&D that was carried out to meet the requirements of US legislation. In 1995 Emitec supplied the first E-catalysts to Alpina and two years later BMW also used them for its twelve-cylinder 7 Series engines.

BEING FIRST AS A CORPORATE GOAL

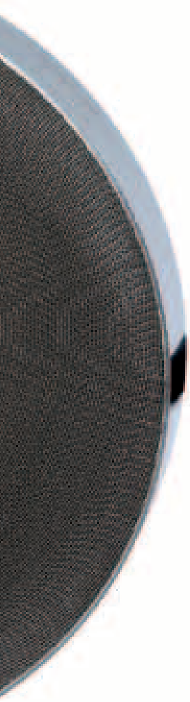
Lead users of Emitec's metal substrate products include such famous marques as Alpina, BMW, Bugatti, Ferrari, Toyota and Porsche with whom Emitec was able to exchange confidential information during the early development stage. As a more recent example, Volvo became the first manufacturer in 2006 to fit lambda sensor catalysts with a PE structure as standard. The lambda sensor in this turbulent metal substrate is no longer installed in front of the catalyst but in its centre where it is more effective and more protected. Then there is Volkswagen, which is equipping over one million four-cylinder diesel vehicles with highly effective turbulent oxidation catalysts.

Lead users also include commercial vehicle manufacturers. In 2004 MAN was the first to fit the unique PM-Metalit particulate filter as standard to control emissions from its D20 commercial vehicle engines. This was preceded by many years of joint R&D work. Small manufacturers can also become lead users, such as Hako-Werke GmbH, which were the first to use Emitec's SCRi technology (SCR system plus particulate filter) for its Multicar Fumo. This demonstrates that Emitec is usually one step ahead of lawmakers and competitors thanks to its targeted long-term research and development.

EMITEC'S MANY PATENTS ARE A SIGN OF INNOVATION AND SECURE THE MARKET

Emitec's over 2500 patents and strategic products demonstrate that car manufacturers derive much benefit from the company's great capacity for innovation.

Metalit S and SM: The breakthrough for Emitec's metal catalysts came first with S-winding and then SM-winding



When Emitec Gesellschaft für Emissionstechnologie mbH in Lohmar near Cologne started up with just three employees in 1986 innovative products were the only way of convincing car manufacturers to abandon tried and tested ceramic monoliths in favour of metal substrates.

Under normal driving conditions catalytic converters are subject to extreme temperature changes, vibrations and impacts. Coated metal substrates expand when heated and contract when cooled. Existing metal catalysts wound and soldered into a spiral shape were able to withstand vibrations but failed when exposed to temperature changes due to a lack of expansion compensation. Solderless, flexible bodies are unable to survive long-term vibration stress. Several other new designs for expanding structures, which were stabilised with nails or brackets, also all failed.

The breakthrough came with a high-temperature soldering process and a design by the development engineer Theodor Cyron, which used a coated, S-shaped winding form. This structure, which was registered as a patent in 1985, comprises flat and corrugated layers. Instead of the layers running parallel to the shell wall only the ends of each separate layer are joined to the wall. The resulting substrate combines great stability with high elasticity, which is essential for heat expansion. The initial production process (for S-winding) involved two winding mandrels. Over the years these were replaced by three mandrels (for SM-winding). In addition, four or more mandrels may be used when making substrates for commercial vehicles or stationary engines.

The patented S-winding and brazing processes were two milestones that marked the crucial breakthrough for the series application of metal substrate catalysts. Emitec's competitors were unable to establish themselves on the market. Initial failures had given metal substrates a bad name. By contrast, Emitec can be rightly proud of the fact that 25 years and some 150 million metal substrate catalysts later there hasn't been a single failure in the field among its end customers. The much-coveted zero-defect target was successfully put into practice.

In addition to many specific innovations that were registered as patents, such as new foil materials or extremely thin foils, which helped to significantly reduce catalyst costs, there are a number of other important milestones.

THE ELECTRICALLY HEATED CATALYST, STILL ONE OF A KIND

In the mid-eighties the introduction of ULEV limits in the US forced manufacturers to develop catalysts that met their stringent requirements. Everybody focused on developing heated catalysts because only catalysts that lit off quickly were able to comply with the strict ULEV limits. Existing catalysts took up to 10 minutes before achieving their full conversion capacity and even the highest subsequent conversion rates were unable to offset the emissions released up to that point. In 1991 Emitec sent newly developed heated

The Emicat heated catalyst and the PM-Metalit will revolutionise the market catalysts (registered as a patent in 1988) to CARB and EPA in California to prove that it was possible to meet even the stringent ULEV limits. Porsche used heated catalysts in its 944 model and demonstrated to the German Federal Environment Office (UBA) that the Euro 4 emission limits proposed for 2005 were attainable. In 1995 BMW Alpina became the first series manufacturer to fit the Emicat as standard. Two years later BMW AG also installed it in its 7 Series twelve-cylinder models and was able to reduce emissions well below statutory limits in the FTP 75 driving cycle. The BMW 750i still met emission targets even after 100,000 miles.

The installation of close-coupled catalysts avoided the greater complexity of heated catalysts. However, the Emicat is close to a global breakthrough because it is unlikely that future emission targets can be met without it. Toyota opted for close-coupled catalysts at an early stage and introduced the “manifold cat” (SM substrate with 600 cpsi, 30 µm foil thickness) worldwide. Early and comprehensive patent protection guaranteed rapid growth in revenue and the breakthrough as a major manufacturer.

THE TURBULENT PM-METALIT, THE SOOT FILTER SOLUTION

Emissions legislation is passed far too quickly compared to long development cycles. Compliance with the Clean Air Acts has become even more difficult since the introduction of emission limits in Europe. Diesel engines attracted a lot of customers because of their fuel economy and although they conformed to all emission regulations they suddenly came under fire because of the Clean Air Acts in Europe. This resulted in strong demand for particulate filters, which were regarded as a something of a panacea. Emitec had already developed its own product, the metal substrate diesel soot particulate filter (PM-Metalit) and was ready for production. In contrast to ceramic wall-flow particulate filters, the PM-Metalit is a system that removes soot on a continuous basis without requiring regular regeneration. It is maintenance-free for the lifetime of the vehicle. The next patented generation is already in place; the electrostatic particulate filter is particularly effective at eliminating nanoparticles.

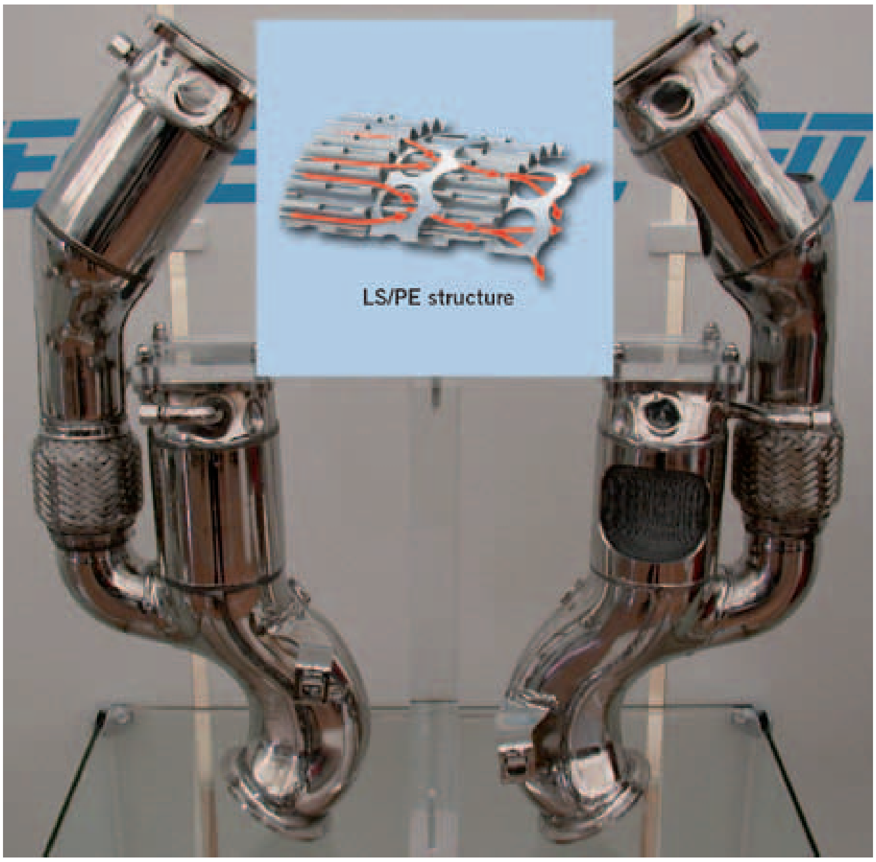
THE FUTURE IS TURBULENT

Turbulence-generating metal substrate foils represent another milestone in the history of catalytic converters. In accordance with the laws of the US physicist Osborne Reynolds (Reynolds number) the turbulent exhaust gas inflow changes to a laminar flow profile after the first few millimetres inside the catalyst. This means that pollutant molecules are very effectively converted in the inlet zone of the catalyst but far less so in the subsequent sections where the molecules come into contact with the catalytic coating only by slow-acting diffusion. Any increase in catalytic efficiency required to convert all pollutant molecules can only be achieved by a longer or larger catalyst. However, only the first few millimetres of these big and expensive catalysts are able to realise their full potential.

In 1989 Emitec patented its LS structure, which contains smaller transverse grooves in its longitudinally corrugated steel foils. While the grooves generate turbulence in the exhaust flow they also restrict the free cross-section. Other versions with cuts, grooves or holes proved difficult to coat. It took dogged persistence to solve every single problem.

In 2004, after two years of development, Audi was the first manufacturer in the world to introduce close-coupled catalytic converters with a PE structure in its RS sports cars. Perforations (PE) in the foils of the PE structure ensured that the entire catalyst cross-section was utilised. The substrates can therefore be made very light despite high exhaust flow rates and still deliver full cleaning performance with minimum pressure loss. In 2004 VW also introduced the PE structure in its highly compact W 12 engines. Racing and sports car manufacturers, including Ferrari, equip all their models with this foil structure because it causes minimum performance loss.

The next milestone was the series production of the LS structure, whose foils contain cuts and grooves so that a part of the wall projects into the centre of the cell



Despite its 1000 hp, the high-performance catalyst in the Bugatti Veyron is extremely compact thanks to turbulence-generating metal substrate foils channel. Compared to conventional catalysts LS metal substrate foils produce 25 % higher conversion rates. As a result, they can be made 25 % smaller and cheaper (through a 25 % saving in precious metals). A reduction in pressure loss and increased performance were the motivation behind using a combination of LS and PE structures in the Bugatti Veyron in 2005.

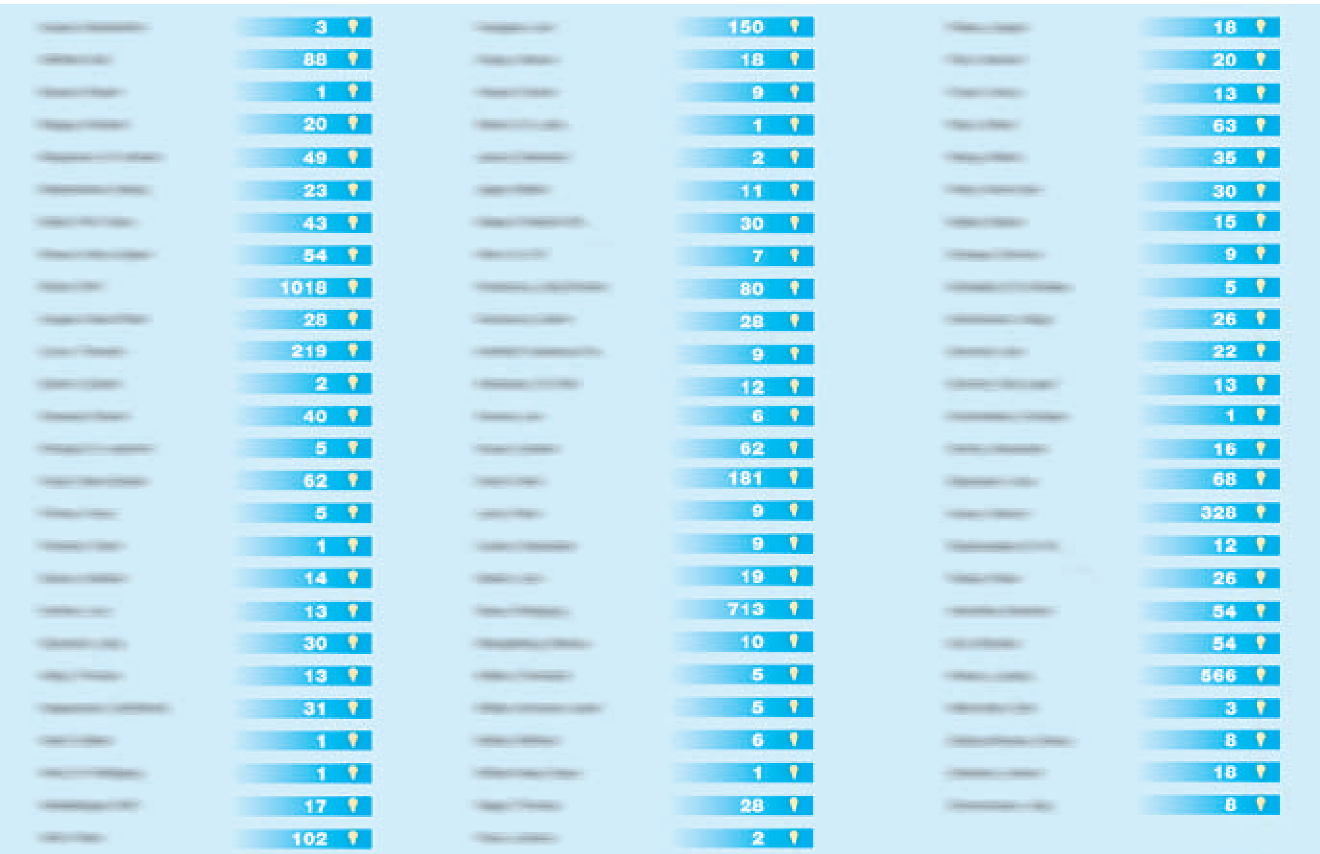
In 2006, 17 years after the first patent had been issued, the development of structured metal foils began to pay off with a 25 % increase in revenue. Production and coating developments took much longer than originally planned and only succeeded because structured metal catalysts had become standard in small and medium-sized vehicles. Special thanks must go to the coaters who made an important contribution to the breakthrough of turbulent catalysts.

EGR Metalit catalysts, compact catalysts (CompactCat), lambda sensor catalysts, NO_x adsorbers, pre-turbocharger catalysts and above all SCRi (selective catalytic reduction with an integrated particulate filter) are further highlights in the company's history that led to a large number of patents and set technical standards.

EXHAUST HEAT RECOVERY

Another recent successful innovation is the thermoelectric generator, a joint development by Emitec and BMW, which is able to convert exhaust heat into electrical energy. New processes to recover waste heat are currently being developed. Emission-reducing technology for trucks, ships, agricultural vehicles and construction and other machines is one area of innovation that has recently become the focus of attention. Last year Emitec opened a completely new, dedicated test centre with one of the world's most powerful roller dynamometers (up to 600 kW of braking power). In order to demonstrate that combustion engines have a sustainable future Emitec has carefully calculated and planned a process that allows fuel to be recycled from CO_2 and water (cf. "What Will Future Mobility Look Like?"). The company has registered relevant patents in this field as well.

Over the past quarter century Emitec has always placed great emphasis on above-average development management. Unique products and rapid growth are the result of correctly anticipating the components and systems required for future environmentally friendly mobility and of pursuing the appropriate R&D and patent strategies. Emitec once again received a special award from TOP100 for being among the best 100 innovative medium-sized companies. Hard work is part of the game; innovative projects usually take 2 to 5 years to come to fruition. Initial market success generally requires another 2 years and large-scale series production at least another 3 years. Emitec spent 8 years on the basic research for the above-mentioned turbulent catalyst before production started. A series of specific patents forms a major part of these long development periods. Emitec will continue to do things differently in future and improve on existing products.



Emitec employees and the number of patent applications (names changed for legal reasons)

WHAT WILL FUTURE MOBILITY LOOK LIKE?

When Emitec was founded there was still uncertainty as to whether catalytic converter technology would become the standard or whether emission limits could be met by improvements in engine technology alone. This question has since been answered. So, now that zero-emission electric vehicles are advocated as a solution to all our problems does Emitec still have a future?

INCREASINGLY CLEANER EMISSIONS

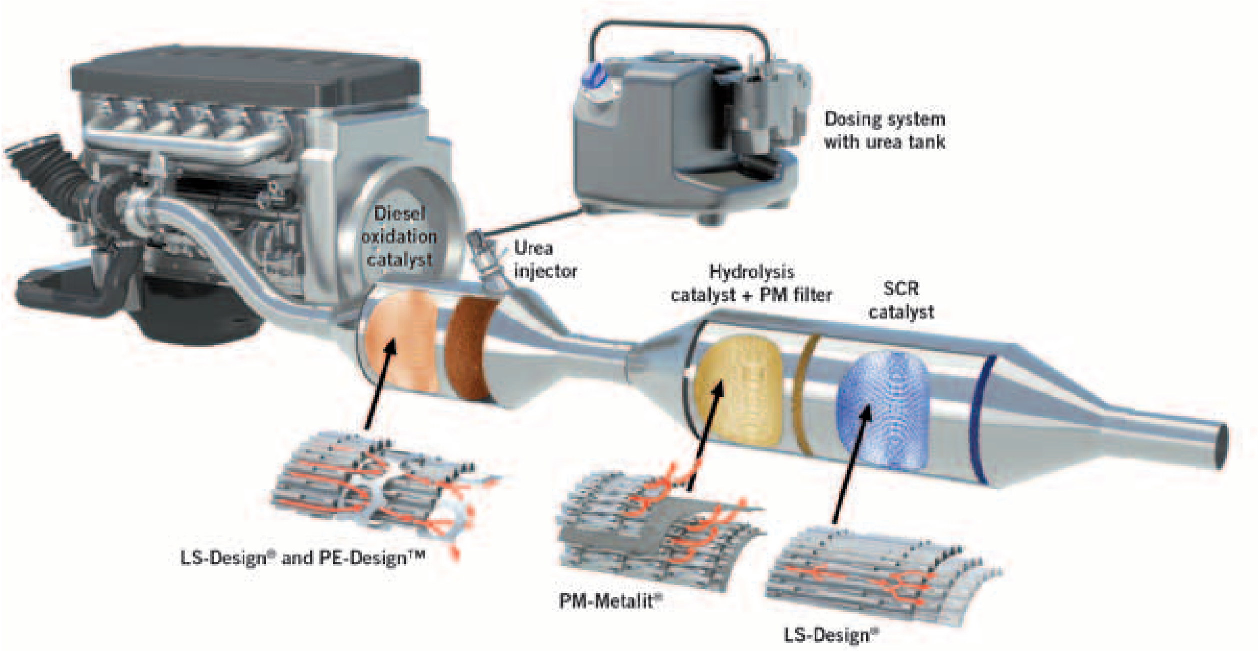
Twenty years ago when the sceptics denounced the motor vehicle as a great air polluter Emitec's engineers instead set out to prove that the vilified combustion engine would one day be able to clean the ambient air. Many of their contemporaries considered this to be an illusory concept. However, our tradition of innovation, our engineering skills and the pioneering spirit of our customers and suppliers turned this sophisticated vision into reality. Today, we manufacture exhaust aftertreatment systems for combustion engines, metal honeycombs for catalytic converters, $DeNO_x$ SCR systems, and particulate filters for a full range of combustion engines and applications. All of our products actively protect the environment. As strange as it may seem, vehicle emissions, with the exception of nitrogen oxides, are now cleaner than the intake air in urban areas thanks largely to Emitec's designs and innovative products. Cars with combustion engines have become a mobile device for partial air purification.

What will future mobility look like? Will we all be driving electric vehicles in 10 to 15 years' time? Over the past few decades cars in Germany have steadily become more environmentally friendly. All newly registered passenger cars now conform to the strict Euro 5 emission standard and some particularly exemplary models meet the even more demanding Euro 6 limits. A five-seater Polo BlueMotion with a diesel engine does 85 mpg in the standard cycle, which corresponds to 87 g of CO_2 per km. Many other cars produce emissions that are well below the EU limit of 130 g/km that will apply from 2015.

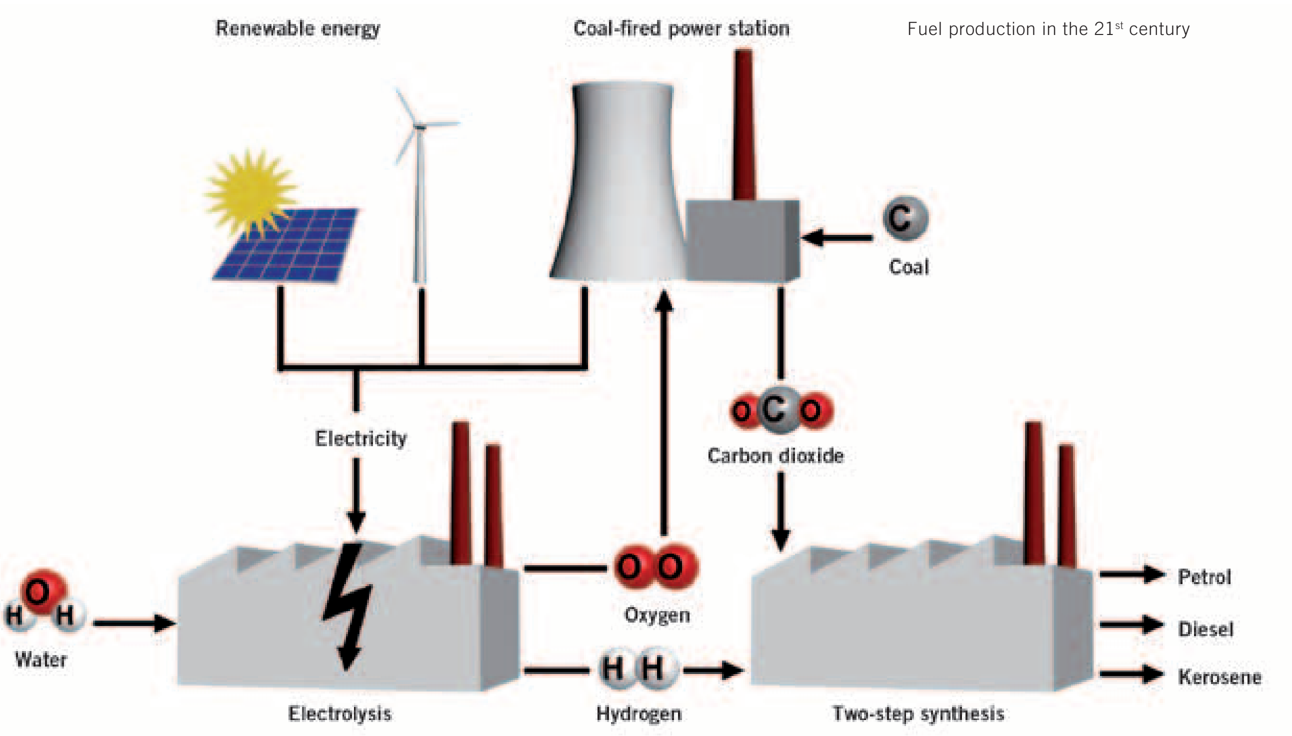
Progress in engine technology, lightweight construction and other improvements will continue to cut fuel consumption and CO_2 emissions. Conventional petrol and diesel engines are likely to see reductions of up to 30 %. Hybridisation is going to save another 10 %.

ARE ELECTRIC VEHICLES THE SILVER BULLET FOR A CLEAN ENVIRONMENT?

The public debate around electric vehicles frequently ignores the fact that they are emission-free only at local level. The actual emissions of these vehicles depend directly on power station emissions, which vary according to the power plant mix of each country. At present an electric vehicle in



Combustion engines will clean the environment



Fuel production in the 21st century

Germany typically emits 130 g/km of CO_2, which is significantly more than a Polo BlueMotion or many other production cars.

The decommissioning of nuclear power stations in Germany, some of which will be taken off the grid immediately or closed down early, and a rapid growth in electric vehicles would result in a supply gap that cannot be plugged by the so-called renewable sources. An extreme example drawn up by Emitec's experts illustrates this point: If every passenger car in Germany was an electric vehicle this would increase the power requirement by 37 % based on consumption figures from 2009. This raises the question as to which primary source should be used to generate this extra power in view of the fact that it takes a long time to build new power stations and that there is going to be less capacity following the decommissioning of nuclear power stations.

COMBUSTION ENGINES STILL HAVE PLENTY OF POTENTIAL FOR THE FUTURE

The challenges facing electric vehicles are just one reason why petrol and diesel engines still have a great future. Combustion engines will be given another boost by various developments relating to mild hybrid drives, which are based on a combination of conventional engines and electric motors. Start/stop functions and other improvements to the powertrain, such as more efficient gearboxes, are going to reduce fuel consumption significantly. If the enormous development expenditure and the subsidies that are being ploughed into electric vehicles were instead invested in advances in combustion engine technology it would be possible to save a much greater amount of energy across the entire vehicle fleet in a much shorter space of time.

FUEL AVAILABILITY IS NO PROBLEM

Crude oil reserves are finite regardless of how many new sources are found. In light of this fact it is safe to assume that in the long term the increasing scarcity of crude oil is going to push up the price of petrol and diesel from fossil sources. Green activists are not alone in calling for the protection of finite resources by placing strong restrictions on crude oil-based transport. This leading environmental trend would in the long term deprive Emitec of its business in exhaust aftertreatment.

In response to claims by the relevant sections of the scientific community that fuel is a finite resource, Emitec has developed a process that recycles the combustion product CO_2 to produce synthetic petrol and diesel using water and energy. Depending on the cost of the energy used in this process petrol could be produced for 61 Euro cents per litre. This would refute the claims that fuel supplies are unsustainable and that fuel prices inevitably have to rise because of impending shortages. CO_2 recycling would also address concerns about this so-called greenhouse gas and make it difficult for politicians to argue in favour of levying tax on it.

Ecological and economic trends are often politically motivated. The real world, however, is subject to the laws of physics. Emission prevention and health promotion unite ecology and economics. Voters and politicians will have to take heed. Emitec's engineers and scientists will make their contribution and take a key role in shaping this process. Mobility continues to be a basic human need. We are already working on sustainable future solutions to make cars with combustion engines even more efficient, cleaner and more environmentally friendly. Emitec is well equipped for the future. We are pleased to see that there are still many tasks ahead and many problems left to solve. We are ready.

GROWTH FROM WITHIN

After a quarter century it is impossible to imagine the automotive industry without Emitec. There are two major success factors behind the company's growth from within: profitable innovative strength and networking. "Me too" was never an option. Emitec has always sought to find a unique position through its innovative technologies. This is done in open and close cooperation with all its global customers and partners. Today emissions technology for mobility in all its forms, from two-wheelers, cars and trucks to off-highway applications, would be inconceivable without Emitec.
I would like to congratulate Wolfgang Maus and his colleagues on their success and wish them a prosperous future.

PROF. DR.-ING. PETER GUTZMER
Director of Technical Product Development and
Deputy Chairman of Schaeffler Automotive, Schaeffler GmbH

ENVIRONMENTAL PROTECTION AS A GUIDING PRINCIPLE

From its foundation 25 years ago to the present day Emitec has taken up the cause of promoting environmental protection in automotive engineering and made it the guiding principle of its corporate philosophy.
The company made a major contribution to emission reduction in the automotive sector through the development of metal substrate catalysts. In the early years, metal catalysts were primarily used in petrol engines to ensure optimum emission control. Today all VW diesel engines are equipped with Emitec's catalysts and comply with the most stringent emission standards. In addition to catalyst technology, Emitec also supplies other innovative high-performance products that remove soot and nitrogen oxide.
Volkswagen looks forward to more of the development dynamics and innovative strength that typify Emitec and wishes the company continued success and all the best for the future.

PROF. DR.-ING. JENS HADLER
Director of Volkswagen AG Powertrain Development

KEEPING AN EYE ON THE OVERALL SITUATION

Since the foundation of Emitec Gesellschaft für Emissionstechnologie in 1986 I have had the opportunity to maintain a close personal connection and working relationship with the company.
I have always been impressed by the foresightful and forward-looking manner in which Emitec conducts its developments. The company not only focuses on the specific object of the development but also gives careful consideration to the overall situation. The collaboration with technical universities resulted in valuable exchanges. I would like to extend my best wishes to Emitec and Wolfgang Maus's committed and excellent team and congratulate them on their company's anniversary. May they continue to develop many more innovative ideas.

PROF. HANS PETER LENZ
Austrian Society of Automotive Engineers (ÖVK), Vienna

INNOVATION WITH HEART AND MIND

I have known Emitec for almost 20 years. As engine and vehicle development engineer at BMW I have come to know and appreciate the company's excellent innovative strength and good working relationship.
I have particularly fond memories of our joint projects on the electrically heated catalyst Emicat for our twelve-cylinder engines or the close-coupled catalysts for our straight six-cylinder engines. They were groundbreaking technologies in the mid-nineties. Working together with enthusiastic and skilled employees enabled us to achieve something that was thought to be impossible at the time. Emitec is a driving force behind technological competition to this day. The company's deep-rooted innovative strength is a crucial factor in this. That's why Emitec will continue to be successful over the next 25 years – innovation with heart and mind.

DR. JOHANNES LIEBL
Editor of ATZ / MTZ

CREATIVE IMAGINATION AND GREAT COURAGE

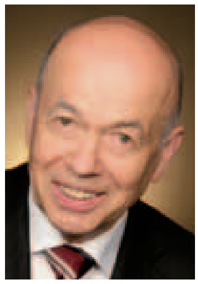
DR.-ING. KARLHEINZ RADERMACHER
former Director of R&D at BMW AG

Predicting the rise in environmental awareness 25 years ago and founding a company to make metal catalyst substrates instead of the tried and tested thermally stable ceramics shows creative imagination and great courage. Building up a company over the course of 25 years to supply a wide range of emission technology products, employing 1,000 people at four production sites, counting every major carmaker and agricultural and construction machinery manufacturer among your customers and leading the world with a number of products demonstrates exemplary leadership skills and decision-making.

The courage and imagination to lead and decide is the mark of an entrepreneur. 25 years of Emitec are an impressive example of successful commercial activity. It is with great pleasure and respect that I congratulate the management and workforce on Emitec's anniversary and wish them sound judgement and a sure hand in all their decisions in future.

A GLOBAL COMPANY

More than almost any other company Emitec has relied on numerous innovations in exhaust aftertreatment systems for petrol and diesel engines to develop into a global company. Since starting out with a core product, the metal catalyst, the company has moved on to supplying systems that meet the most stringent emission limits, including components for NO_x and particulate reduction. This success is down to many innovations, including the patents registered by CEO Wolfgang Maus and his staff, which cover the correlation between materials, construction and production relating to vehicles, machines and large engines. In addition to making traditional products, the company is also looking into processing CO_2 produced by the combustion process. Perhaps this will lead to another interesting product in a few years. I'm always pleased to find an article by Emitec in MTZ and wish the company all the best for the future.



PROF. DR.-ING. ULRICH SEIFFERT
Centre for Traffic at TU Braunschweig

COMMITTED TO SUSTAINABILITY

Emissions from passenger cars in Germany have dropped significantly during the past two decades. Compared to 1990 they fell by around 97 %. This is also thanks to Emitec whom I wish to congratulate on their 25th anniversary. Committed to sustainability from the beginning, the company's products have been reducing vehicle emissions year after year and ensure greater acceptance of the most popular mode of transport in the world, the car. The success of Emitec, which was founded 100 years after the invention of the automobile, is a piece of automotive history itself. We are proud to have Emitec as a member of the German Association of the Automotive Industry.

MATTHIAS WISSMANN
President of the German Association of the Automotive Industry (VDA)

SUSTAINABLE VISION

Congratulations dear Emitec GmbH. You have been delivering outstanding technological achievements for a quarter century. Your company and your team have consistently won us over with innovative dynamics and sustainable vision. You take a creative and positive approach to things and combine high tech with successful business and clear customer focus. I am sure that Emitec GmbH will continue to actively shape the future. I wish you all the best and lasting success.

BERNHARD PFALZGRAF
Director of Automation and Measurement Engineering,
Neckarsulm Test Facility, Audi AG

PEER REVIEW ATZ | MTZ

PEER REVIEW PROCESS FOR RESEARCH ARTICLES IN ATZ AND MTZ

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In the ATZ | MTZ Peer Review Process, once the editors has received an article, it is reviewed by two experts from the Advisory Board. If these experts do not reach a unanimous agreement, a member of the Steering Committee acts as an arbitrator. Following the experts' recommended corrections and subsequent editing by the author, the article is accepted.

In 2008, the peer review process utilized by ATZ and MTZ was presented by the WKM (Wissenschaftliche Gesellschaft für Kraftfahrzeug- und Motorentechnik e. V. / German Professional Association for Automotive and Motor Engineering) to the DFG (Deutsche Forschungsgemeinschaft / German Research Foundation) for official recognition.

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MODELS FOR LIFETIME ESTIMATION OF CAST IRON COMPONENTS

Within the research project "TMF lifetime models for cast iron", funded by the Research Association for Combustion Engines e. V. (FVV), models for lifetime estimation of thermo-mechanically loaded components were developed at Fraunhofer Institute for Mechanics of Materials IWM. The material model comprises a viscoplastic constitutive model to compute reliable stress and strain fields for cast iron materials and a mechanism-based model for micro crack growth for lifetime prediction.

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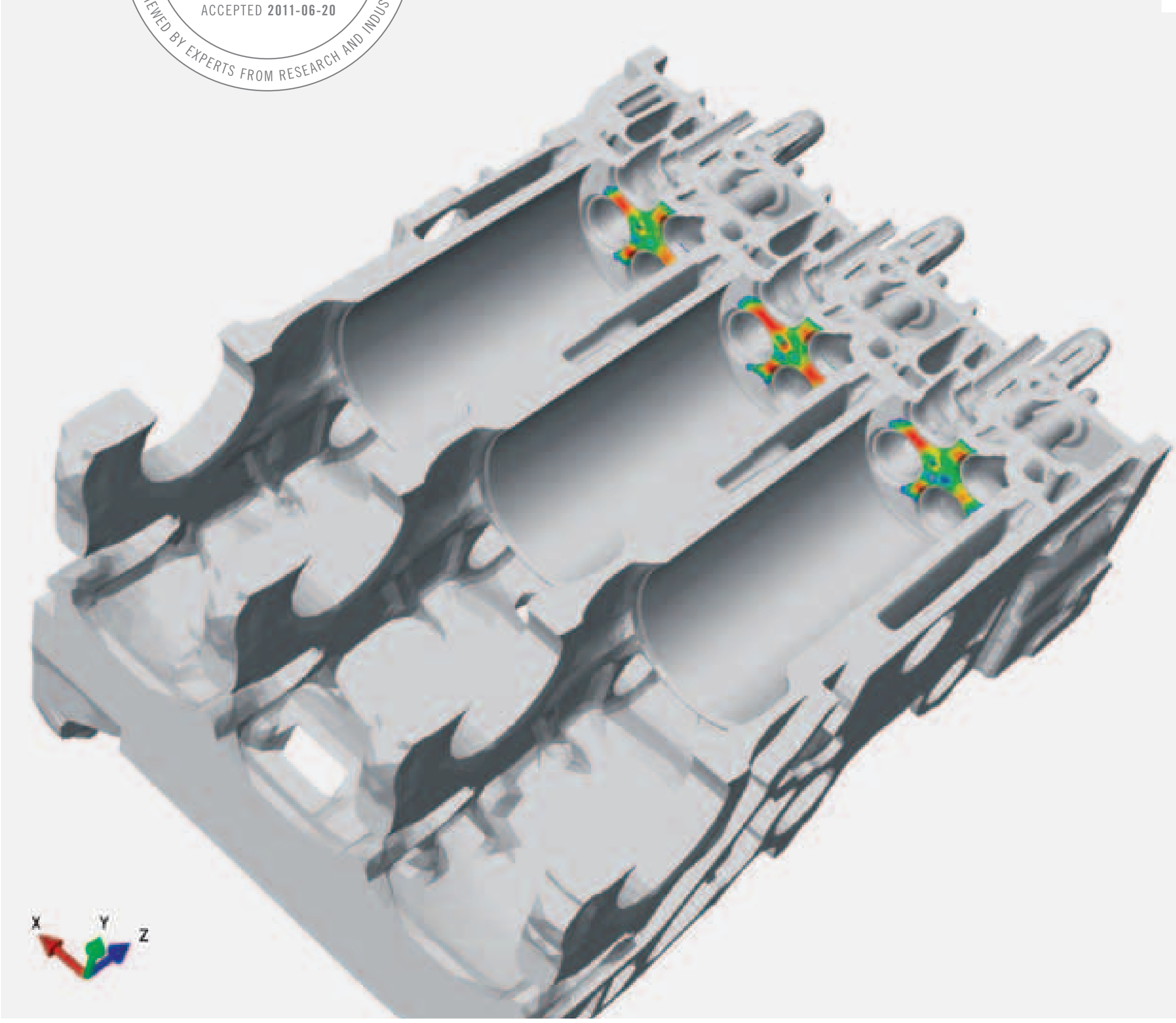


1 INTRODUCTION

Nowadays, cast iron is used in many fields of the automobile, utility vehicle and engine development. The advantage of this class of materials is mainly given by the competitive production of complex components. Further arguments for their application are a good dry-running capability and a high damping capacity of mechanical vibrations.

During service the components often underlie severe thermal loading cycles. Thermal gradients within the assembly and mechanical fixation constrain the thermal expansion and thus, lead to thermomechanical fatigue.

In the experimental part of the research project, uniaxial fatigue tests were conducted. In the theoretical part, the parameters of the models were determined based on the test data and the models were implemented into the finite element software Abaqus/Standard. To test the functionality in large scale finite element calculations, the implemented model was applied to a finite element submodel of a six-cylinder in-line engine of Ford Otosan.

2 EXPERIMENTAL MATERIAL CHARACTERIZATION

In [1], the materials EN GJS700, EN GJV450 and EN GJL250 have been characterized under realistic service conditions. To this end, quasi static tension and compression tests, relaxation tests as well as isothermal complex low-cycle fatigue (CLCF) and thermomechanical fatigue (TMF) tests were conducted at round specimens with a diameter of 7 mm in the temperature range from 20 to 500 °C. The CLCF tests compose of a non-periodic and a periodic part. In the non-periodic part, ❶ (a), hold times in tension and compression (each 1800 s) and different strain rates (0.1 %/s and 0.001 %/s) are applied. In the following periodic part, the specimen is loaded at constant strain amplitude and strain rate until failure of the specimen. Hence, effects like creep, relaxation, strain rate dependency as well as cyclic hardening or softening can be measured within one isothermal fatigue test. Using these tests, the parameters of the models introduced in the next sections can be determined. The isothermal tests were complemented by TMF tests with fully constraint total strains. The temperature history in the TMF loading cycles is shown in ① (b). The measured stresses in the CLCF and TMF tests are shown together with the model predictions in the next section.

3 DEFORMATION MODEL FOR CAST IRON MATERIALS

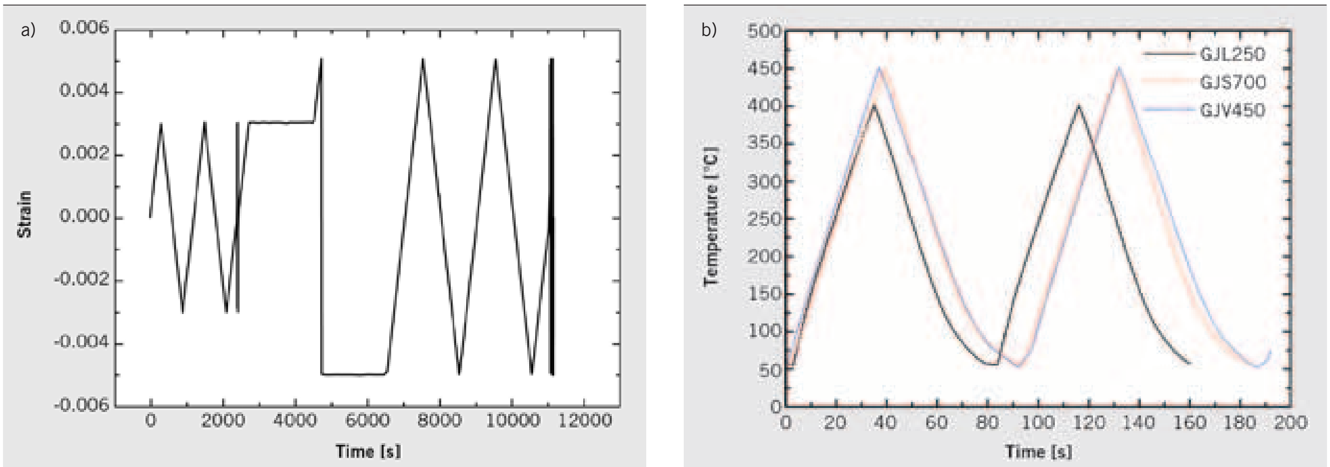
To compute reliable stress and strain fields in finite element simulation of components, material models are required that are able to accurately describe the underlying material behaviour.

The Chaboche model [2, 3] describes the essential phenomena of time and temperature dependent cyclic plasticity of metals, namely strain rate dependency, creep, relaxation, recovery and hardening effects. In cast iron materials a tension/compression asymmetry is observed due to graphite inclusions, which mainly depends on the shape, the size and the volume fraction of the graphite. To describe the asymmetry, the Chaboche model was combined with Gurson's micromechanical model [4, 5]. The Gurson model assumes spherical voids in a plastically incompressible matrix, where the shape of the voids does not change. Due to the growth (tension) and shrinkage (compression) of existing and the nucleation of new pores, the tension/compression asymmetry of cast iron materials can be described well. In the following the rate equations of the deformation model are given.

The total strain rate is

EQ. 1
$$\dot{\varepsilon}_{kl} = \dot{\varepsilon}_{kl}^{el} + \dot{\varepsilon}_{kl}^{vp} + \dot{\varepsilon}_{kl}^{th}$$

where $\dot{\varepsilon}_{kl}^{el}$ is the elastic, $\dot{\varepsilon}_{kl}^{vp}$ is the viscoplastic and $\dot{\varepsilon}_{kl}^{th}$ is the thermal strain rate.

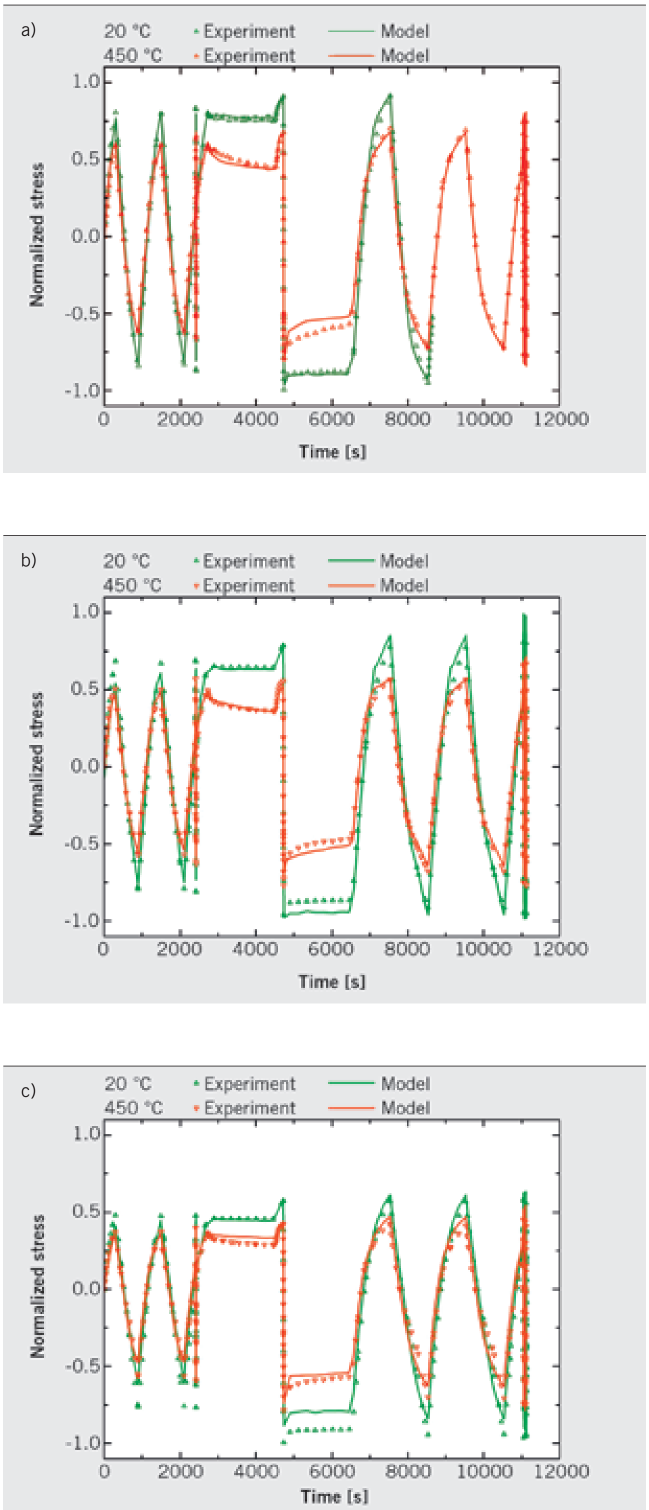


❶ (a) Applied strain history in non-periodic part of CLCF tests, (b) applied temperature history in TMF tests

The stress rate is

EQ. 2

$$\dot{\sigma}_{ij} = C'_{ijkl}\dot{\varepsilon}^{el}_{kl} + \left(\frac{\partial C'_{ijkl}}{\partial f}\dot{f} + \frac{\partial C'_{ijkl}}{\partial T}\dot{T}\right)C'^{-1}_{klmn}\sigma_{mn}$$



❷ Measured and calculated stress response in CLCF tests, (a) EN GJS700, (b) EN GJV450, (c) EN GJL250

The effective elasticity tensor C'_{ijkl} depends on the porosity f induced by the graphite inclusions and the temperature T. To compute the thermal strain rate, the differential coefficient of thermal expansion α^{th} is used.

EQ. 3

$$\dot{\varepsilon}^{th}_{ij} = \alpha^{th}\dot{T}\delta_{ij}$$

δ_{ij} is the second order identity tensor.

The total viscoplastic strain rate composes additively of a hydrostatic $\dot{\varepsilon}_p$ and a deviatoric $\dot{\varepsilon}_q$ viscoplastic multiplier and the respective flow direction.

EQ. 4

$$\dot{\varepsilon}^{vp}_{ij} = \dot{\lambda}\frac{\partial\phi}{\partial\sigma_{ij}} = \dot{\lambda}\left(\frac{\partial\phi}{\partial\beta_{eq}}\frac{\partial\beta_{eq}}{\partial\sigma_{ij}} + \frac{\partial\phi}{\partial\beta_h}\frac{\partial\beta_h}{\partial\sigma_{ij}}\right) = \dot{\varepsilon}_q\frac{\partial\beta_{eq}}{\partial\sigma_{ij}} - \dot{\varepsilon}_p\frac{\partial\beta_h}{\partial\sigma_{ij}}$$

ϕ is the yield function and $\beta_{ij} = \sigma_{ij} - (1-f)\alpha_{ij}$ is the relative stress with the relative von Mises equivalent stress β_{eq} and the hydrostatic portion β_h. α_{ij} is the backstress tensor which allows the description of hardening under cyclic loading conditions (kinematic hardening). The yield function is:

EQ. 5

$$\phi = \left(\frac{\beta_{eq}}{\sigma_y}\right)^2 + 2q_1 f^* cos\left(\frac{3}{2}q_2\frac{\beta_h}{\sigma_y}\right) - \left(1 + q_3 f^{*2}\right)$$

The parameters $q_1 = 1.5$, $q_2 = 1$ und $q_3 = q_1^2$ were proposed by Tvergaard [6] and Tvergaard and Needleman [7]. σ_y is the matrix flow stress and f^* is the effective porosity that takes an accelerated damage in the material into account as soon as a critical void volume fraction f_C is reached.

EQ. 6

$$f^* = \begin{cases} f & if\ f \le f_C \\ f_C + \frac{1/q_1 - f_C}{f_F - f_C}(f - f_c) & else \end{cases}$$

f_F is the porosity at failure. The evolution equation is additively composed of the growth $\dot{f}^{gr}$ of existing and the nucleation $\dot{f}^{\varepsilon}_{nuc}$ (strain controlled) and $\dot{f}^{\sigma}_{nuc}$ (stress controlled) of new voids [8].

EQ. 7

$$\dot{f} = \dot{f}^{gr} + \dot{f}^{\varepsilon}_{nuc} + \dot{f}^{\sigma}_{nuc}$$

EQ. 8

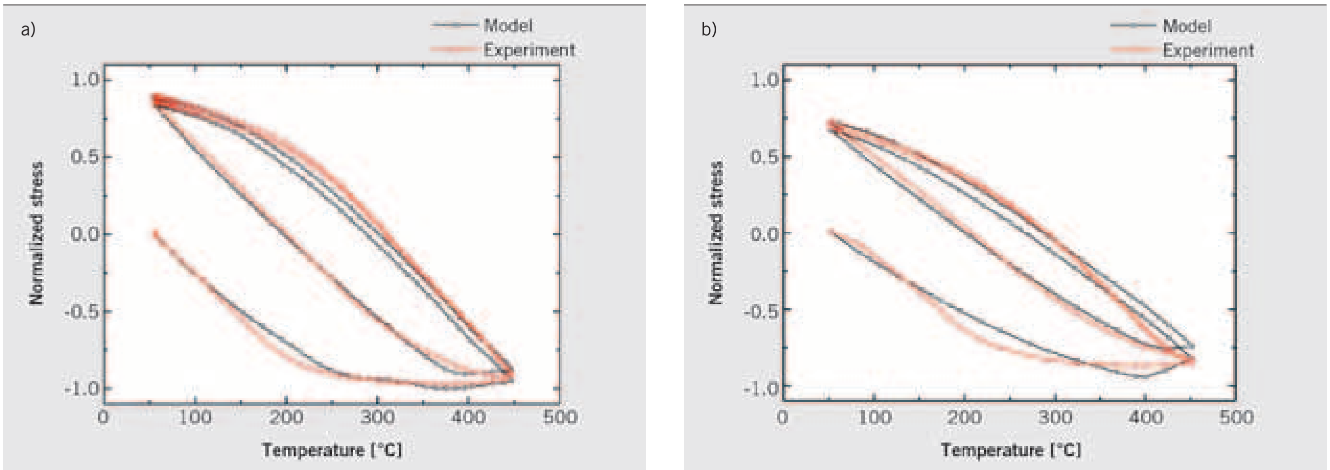
$$\dot{f}^{gr} = (1-f)\dot{\varepsilon}^{vp}_{kk}$$

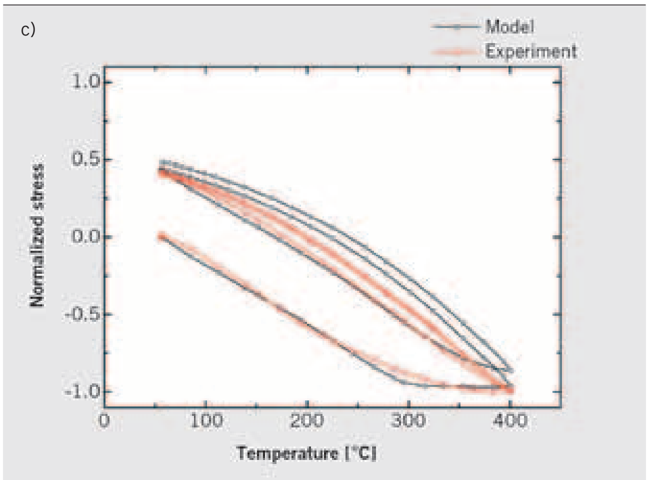
EQ. 9

$$\dot{f}^{\varepsilon}_{nuc} = \frac{f^{\varepsilon}_N}{s^{\varepsilon}_N\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{\frac{1}{3}\varepsilon_p - \varepsilon_N}{s^{\varepsilon}_N}\right)^2\right)\frac{\dot{\varepsilon}_p}{3}$$

EQ. 10

$$\dot{f}^{\sigma}_{nuc} = \frac{f^s_N}{s^s_N\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{-\frac{1}{3}\sigma_{kk} - \sigma_N}{s^s_N}\right)^2\right)\frac{\dot{\sigma}_{kk}}{3}$$





❸ Measured and predicted stress-temperature hysteresis in TMF tests, (a) EN GJS700, (b) EN GJV450, (c) EN GJL250

f_N is the volume fraction of the graphite inclusions, at which voids can nucleate. The nucleation law is a normal distribution around the mean value ε_N and σ_N and the standard deviation s_N^e and s_N^s, respectively.

Assuming the equivalence of micro- and macroscopic work [9], the viscoplastic equivalent strain rate in the matrix material is:

EQ. 11
$$\dot{\varepsilon}_M^{vp} = \frac{\beta_{ij}\,\dot{\varepsilon}_{ij}^{vp}}{(1-f)\,\sigma_y}$$

The dependency on the applied strain rate and isotropic hardening are account for the matrix flow stress [2, 3].

EQ. 12
$$\sigma_y = \sigma_0 + Q_\infty (1-\exp(-b\varepsilon_M^{vp})) + K(\dot{\varepsilon}_M^{vp})^{1/n}$$

σ_0 is the initial yield stress, Q_∞ and b are hardening parameters and K and n control the time dependent material behaviour.

The backstress is additively decomposed into two backstresses [2, 3]. The evolution equation of the backstresses is:

EQ. 13
$$\dot{\alpha}_{ij}^{(k)} = \frac{2}{3}C^{(k)}\,\dot{\varepsilon}_{ij}^{vp} - \gamma^{(k)}\dot{\varepsilon}^{vp}\alpha_{ij}^{(k)} - R^{(k)}\,\alpha_{ij}^{(k)} + \frac{\partial C^{(k)}}{\partial T}\frac{1}{C^{(k)}}\dot{T}\,\alpha_{ij}^{(k)},\quad k=1,2$$

EQ. 14
$$\gamma^{(1)} = \gamma_\infty^{(1)} + (\gamma_0^{(1)} - \gamma_\infty^{(1)})e^{-\omega^{(1)}\|\varepsilon^{vp}\|},\ \|\varepsilon^{vp}\| = \sqrt{\frac{2}{3}\varepsilon_{ij}^{vp}\,\varepsilon_{ij}^{vp}},$$
$$\gamma^{(2)} = \gamma_\infty^{(2)} + (\gamma_0^{(2)} - \gamma_\infty^{(2)})e^{-\omega^{(2)}\varepsilon'^{vp}},\ \dot{\varepsilon}'^{vp} = \sqrt{\frac{2}{3}\dot{\varepsilon}'^{vp}_{ij}\,\dot{\varepsilon}'^{vp}_{ij}}$$

$C^{(k)}$, $\gamma_\infty^{(k)}$, $\gamma_0^{(k)}$, $\omega^{(k)}$ and $R^{(k)}$ are parameter to describe the hardening behaviour.

The effective elasticity tensor is computed via the effective compression and shear modulus, κ' and G'. Following Mori-Tanaka, one obtains for spherical voids:

EQ. 15
$$C'_{ijkl} = 2G' II_{ijkl} + \left(\kappa' - \frac{2}{3}G'\right)\delta_{ij}\delta_{kl},$$
$$\kappa' = \kappa\left(1 - \frac{f^*}{1-\alpha(1-f^*)}\right) \text{ with } \alpha = \frac{3\kappa}{3\kappa+4G},$$
$$G' = G\left(1 - \frac{f^*}{1-\beta(1-f^*)}\right) \text{ with } \beta = \frac{6(\kappa+2G)}{5(3\kappa+4G)}$$

II_{ijkl} is the fourth order unity tensor.

The temperature dependent parameters of the model, that are determined on basis of the isothermal experimental data, are:

: the thermoelastic parameter G, κ and α^{th},
: the viscosity parameter K and n,
: the parameter for isotropic hardening Q_∞ and b,
: the parameter for kinematic hardening and softening $C^{(k)}$, $\gamma_\infty^{(k)}$, $\gamma_0^{(k)}$, $\omega^{(k)}$ and $R^{(k)}$ and
: the initial yield stress σ_0.

In ❷ (a) to (c), the experimentally measured and numerically computed normalized stresses of the three materials are plotted for 20 and 450 °C. Due to the lamellar shape of the graphite inclusions, EN GJL250 shows a strong tension-compression asymmetry even at small strains. Although the lamellar shape of the graphite inclusions deviates from the model assumption of spherical pores, this asymmetry can be described well with the stress controlled nucleation criterion.

With the model parameters, determined based on the isothermal experiments, the stress response in TMF tests with fully constraint total strains is predicted. ❸ (a) to (c) illustrates the TMF hysteresis obtained with the model and measured in the experiments. The model predictions agree well with the experimental results. The material parameters were adjusted using the software Fitit that was developed at the Fraunhofer IWM in Freiburg as well as the finite element Software Abaqus/Standard.

4 MODEL FOR LIFETIME ESTIMATION

Under LCF and TMF conditions, micro cracks develop in an early stage of the lifetime, so that the lifetime of components is mainly determined by the growth and coalescence of these cracks. A mechanism-based model for short cracks was developed based on the assumption that the cyclic crack tip opening displacement $\Delta CTOD$ correlates with the crack advance per cycle *da/dN* via the proportionality constant β.

EQ. 16	$\frac{da}{dN} = \beta \Delta CTOD$

For athermal loading cycles of arbitrary shape and elastic-viscoplastic materials, the damage parameter D_{TMF} was developed. For a semicircular surface crack $\Delta CTOD$ is given by:

EQ. 17	$\Delta CTOD = \frac{1}{2} D_{TMF} a$ $D_{TMF} = \frac{Z_D}{\sigma_{cy}} F(T,t)$ $Z_D = 1{,}45 \frac{\Delta\sigma^2_{I,\,eff}}{E} + \frac{2{,}4}{\sqrt{1+3N}} \frac{\Delta\sigma^2_I}{\Delta\sigma_e} \Delta\varepsilon^{vp}_e$

The parameter Z_D is an estimation for the cyclic J-Integral [10]. σ_{cy} is the cyclic yield stress. $\Delta\sigma$ and $\Delta\varepsilon^{vp}$ are the range of the stress and the viscoplastic strain of saturated stress-strain hysteresis loops. The indices I and e indicate the principal stress and the von Mises equivalent stress, respectively strain. *E* is Young's modulus and *N* the hardening exponent of the Ramberg-Osgood law. Crack closure is taken into account via the effective stress range $\Delta\sigma_{I,eff}$, which depends on the ratio of the minimal and maximal stress (*R*) of the hysteresis loop.

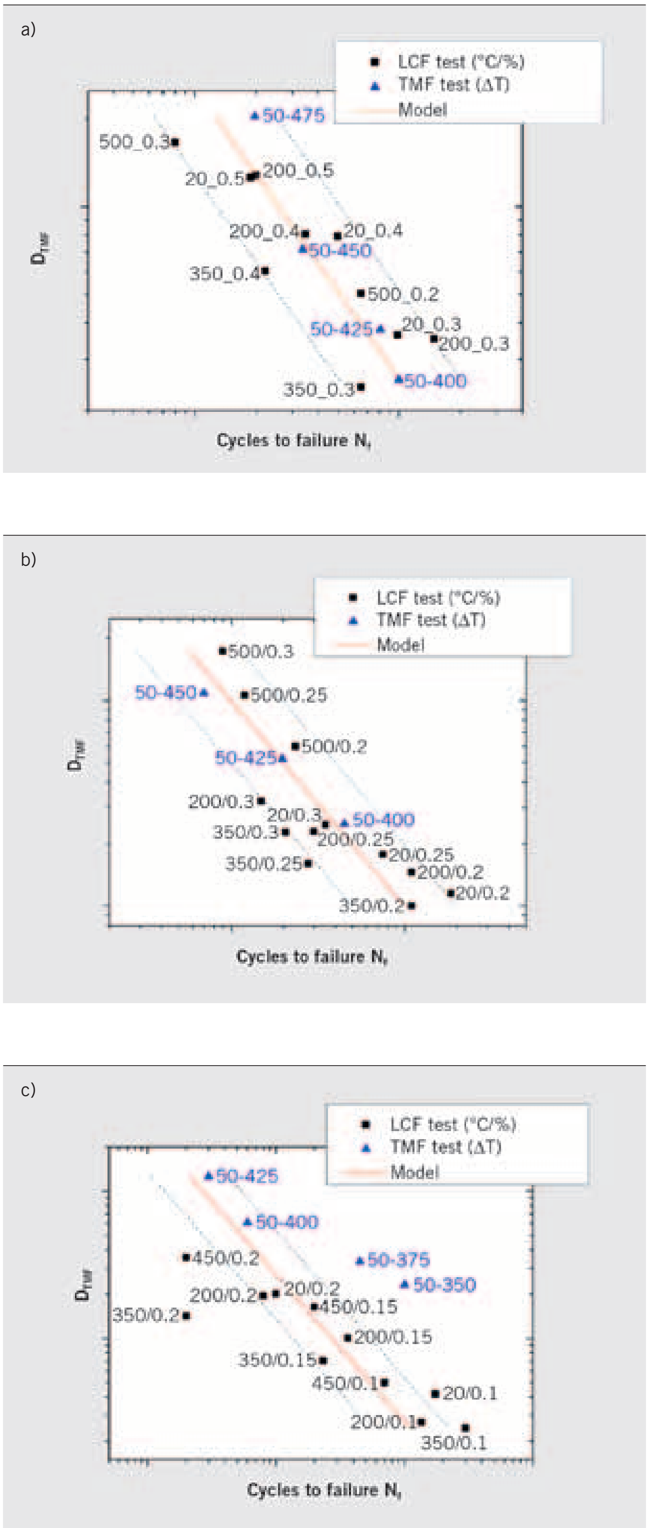
EQ. 18	$\Delta\sigma_{I,eff} = 3{,}72 \frac{\Delta\sigma_I}{(3-R)^{1{,}74}}$

Integration of equation (16) from an initial to a final crack length yields the cycles to failure.

EQ. 19	$N_f = A(D_{TMF})^{-B}$

A and *B* are adjustable parameters. The damage parameter D_{TMF} is plotted against the experimentally determined cycles to failure [1] for the three materials, ❹ (a) to (c). The red line corresponds to the damage parameter predicted by the model. The dashed lines define a scatter band of factor 2 around the model prediction. The mechanism-based model allows a good description of the lifetimes.

To represent the thermomechanical loads that occur at cylinder heads, a notched specimen (EN GJS700) with a rectangular cross section of 4x6 mm and a notch radius of 4 mm was loaded thermomechanically. In total, three experiments were accomplished with fully constrained total strains. The recalculation of the experiments with the before mentioned material model was done with the finite element software Abaqus/Standard. The ratio of the cycles to failure between the experiment and the simulation is 0.68, 1.17 and 0.742.

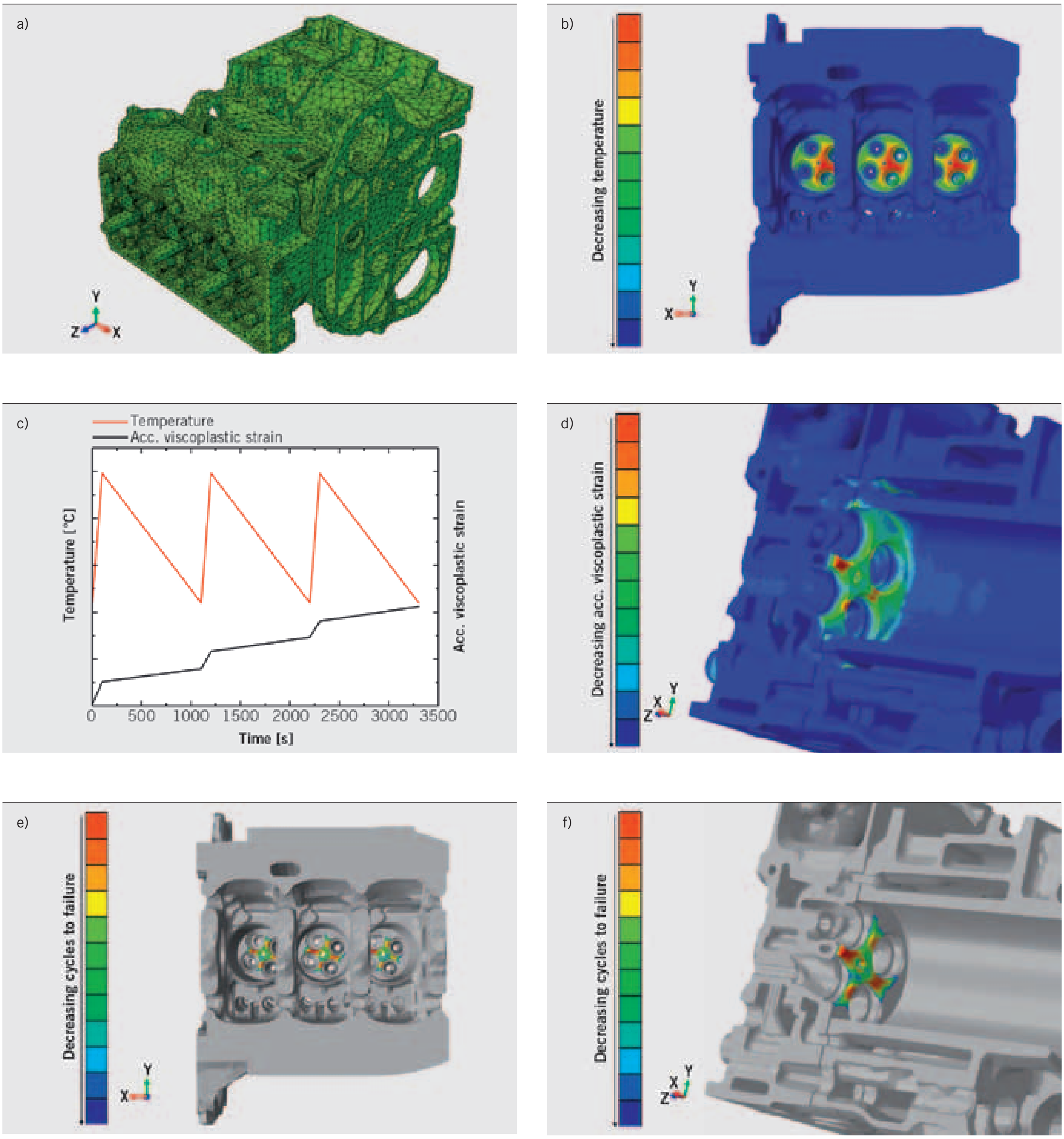


❹ Lifetime prediction, (a) EN GJS700, (b) EN GJV450, (c) EN GJL250

5 APPLICATION OF THE MODELS FOR LIFETIME ESTIMATION

The finite element submodel of a six-cylinder in-line engine of Ford Otosan [11] was computed with the before described material model for EN GJV450. To this end, the material routine was applied, which was developed for finite element programs. The finite element mesh of the model is shown in ❺ (a). In total, 340070 tetrahedron finite elements with hourglass control and 4 integration points each were used. The temperature distribution in the hot stage is shown in ⑤ (b). In total, three thermo cycles were computed. The heating up period takes 100 s, cooling down to room temperature takes 1000 s.

The temperature history and the evolution of the accumulated viscoplastic strain on the surface between the bore holes of the valves are shown in ⑤ (c). ⑤ (d) shows the area where the maxi-



❺ (a) Finite element mesh of the submodel, (b) temperature distribution, (c) temperature and accumulated viscoplastic strain at surface between bore holes, (d) accumulated viscoplastic strain after third cycle, (e) N_f overview, (f) N_f detail in middle cylinder mal accumulated viscoplastic strain occurs (red) and where the thermal expansion of the material is severely constrained. This area is also determined by the model as the critical region with the lowest number of cycles to failure, ⑤ (e) and (f).

6 CONCLUSION

The models that were particularly developed for cast iron, can describe the time and temperature dependent plasticity and micro crack growth of the investigated materials well. The models are implemented into finite element programs, so that they can be applied to component simulations. The application of the models to the lifetime estimation of a cylinder head shows plausible results with respect to the critical location in the component and the local lifetime. Thus, an efficient optimization of components in computer simulations is possible.

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SIMULTANEOUS COMBUSTION – METHANE-FUEL AND METHANE-DIESEL MIXTURE PREPARATIONS

Fuels such as natural gas offer a possibility to effectively reduce CO_2 emissions. There are however certain negative aspects to the use of natural gas that should be mentioned: Firstly, the high air requirement for stoichiometric combustion; secondly, the effects on attainable engine torque; thirdly, the stability of CH_4 gas which makes catalytic aftertreatment more difficult. At the Technical University of Kaiserslautern, certain procedures allowing the utilization of natural gas in gasoline- as well as diesel-run engines have been developed which enable the simultaneous use of two different fuels. In these procedures, the separate fuels are injected as required according to the engine load.

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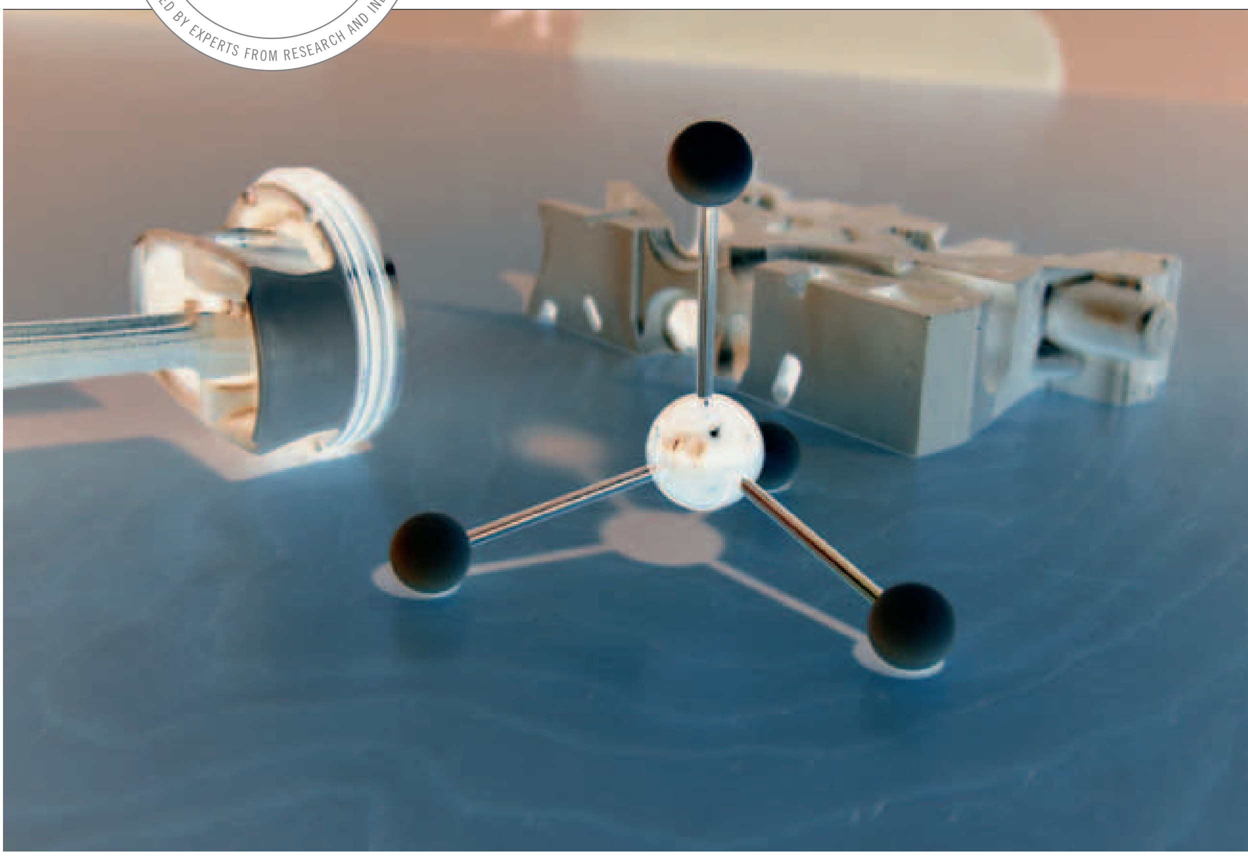


1 INTRODUCTION

Rising energy demands worldwide and the resulting emission of climate changing carbon dioxide, require that the search is made for alternative and environmentally friendly energy sources and fuels. The increasing scarcity of oil supplies and the growing political unrest in North Africa has only put further pressure on the cost of fuel. Likewise, the controversy over nuclear power plants' running times as well as the necessary substitution of nuclear energy with conventional coal-fired power stations has further aggravated debates on CO_2. Since road traffic is responsible for approximately 14 % of anthropogenic CO_2 emissions worldwide [1], the usage of methane (CH_4) or natural gas offers the possibility to effectively decrease CO_2 emissions in this regard.

2 THE USAGE OF METHANE IN COMBUSTION ENGINES

Under standard conditions, methane exists as a gaseous energy resource, which is either available as a fossil gas (in gas- and oilfields or as a methane hydrate in the deep sea) or can be derived from manure. Natural gas' specific properties make it particularly suitable for its utilization in combustion engines, ❶.

Concerning its characteristics, the high RON of 140 should be noted. This comparatively high octane count is in fact attained without the need for any complex treatments such as thermal cracking, reformation or any other further additivation.

The amount of CO_2 emissions at a stoichiometric combustion is essentially determined by the ratio of carbon to hydrogen atoms in the utilized fuel. Furthermore, the CO_2 emissions emitted at the fuel's point of production have to be taken into account. Out of all carbonic fuels, methane exhibits the most advantageous C/H ratio, as shown in ❷.

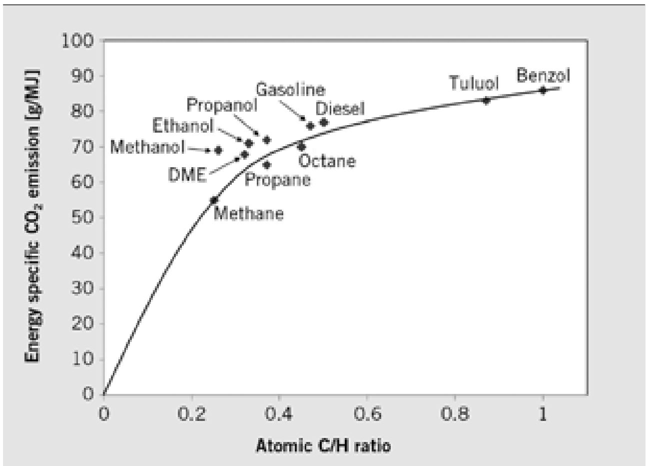
Similarly, the amount of energy stored in a kilogram of fuel is, in the case of methane, higher than in fuel or diesel. However, to equip a vehicle with a suitable range at an acceptable tank size, the gaseous fuel has to be compressed down to a specific volume of 29 dm^3/kg by increasing the pressure to approximately 220 bars. Despite this compression, the volumetric energy content of liquid fuels such as petrol or diesel is clearly higher than that of natural gas. Therefore, one liter of petrol contains approximately as much as 3.4 times more energy than one liter of natural gas at 200 bar. This, of course, fundamentally shapes the scope and tank size of a gas-powered vehicle. Methane's air requirements during combustion sit at 17.1 kg air/kg fuel and are thus clearly higher than those of petrol or diesel fuels ranging between 14.5 to 14.7 kg air/kg fuel. Filling an engine's cylinder with the same amount of air, a methane powered gasoline engine shows approximately 10 % less torque than a fuel powered engine with the same fuel/air ratio λ [2].

Depending on its origin, natural gas occasionally only consists of 85 % methane which reduces the attainable torque of a natural gas powered gasoline engine even further. As a result of its high resistance to knocking behavior, engines which are run with natural gas can however be equipped with a higher geometric compression ratio without being influenced negatively through knocking combustion. In the case of natural gas powered gasoline engines, it is also possible to increase the engine's torque through turbocharging. In so doing, the gas' high resistance to knocking behavior can be exploited.

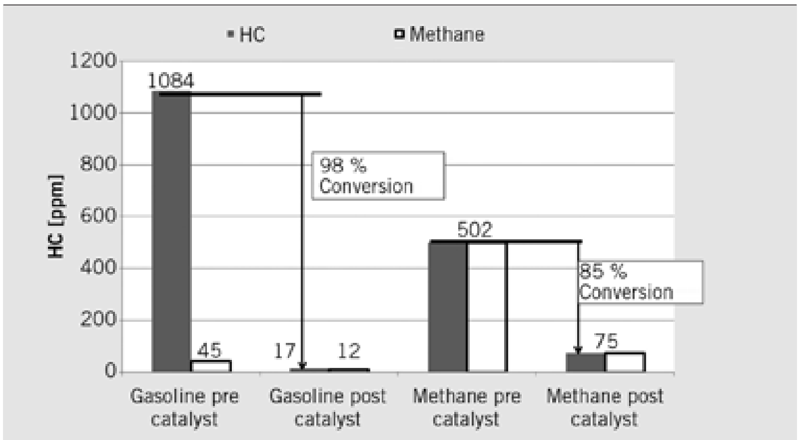
When using methane as a fuel in gasoline engines, the molecule's stability puts decisive constraints on the implementation. In the case of catalysts that are not optimized for natural gas,

PROPERTIES	FUEL	METHANE
RON	95 … 100	120 … 140
AIR DEMAND FOR STOICHIOMETRIC COMBUSTION [KG AIR/KG FUEL]	14.7	17.1
LOWER HEATING VALUE [MJ/KG]	44.5	50
LIMIT OF FLAMMABILITY	$0.6<\lambda<1.6$	$0.7<\lambda<2.1$

❶ Physical and thermo-dynamic indexes of fuel and methane



❷ Energy specific CO_2 amount depending on the C/H-ratio of different fuels

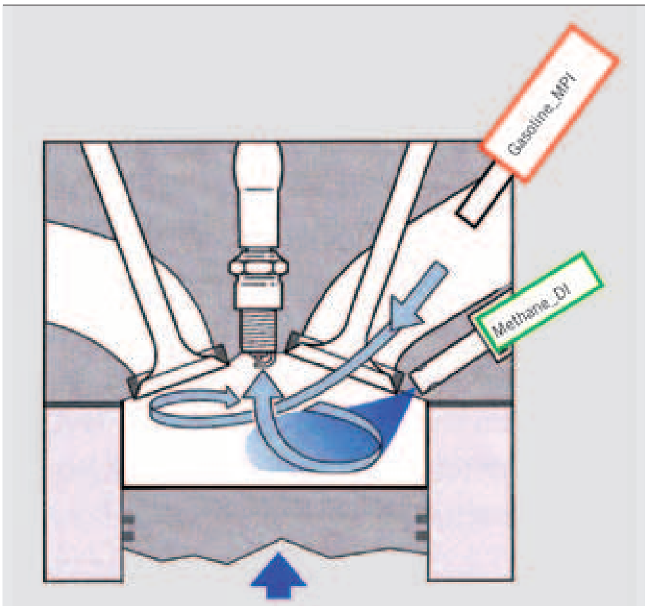


❸ Measured total HC- and Methane emissions in gasoline-and natural gas-run engines before and after the catalyst (BMW 518 g E34)

methane's conversion rate is lower than that of unburnt hydrocarbon resultant from partially combusted fuel. Additionally, methane's greenhouse activity has its own effects, which are about 25 times higher than those of carbon dioxide. Measuring methane's crude emissions in an older natural gas car reveals a rate 10 times higher than that of gasoline served cars- the conversion of methane is likewise lower, ❸.

To minimize the emissions of unburnt hydrocarbons in a natural gas run engine as much as possible (where CH_4 is injected in the inlet manifold), an overlapping of the inlet and outlet valvelift has to be avoided. Yet, this either leads to poor charge-cycle work at full load or does not allow to wash out residual gases through scavenging by turbocharged engines (when avoiding HC emissions at full load).

This disadvantage can however be avoided by directly leading the gaseous fuel straight into the combustion chamber, as for example after the closing of the outlet valves. The gaseous fuel's smaller volumetric energy content, as well as its approximately 8 bar fuel pressure, demands that the diameter of the fuel injector be relatively large. The manifold pressure of turbo-charged engines makes at full load further great demands on the injection of gaseous fuels and hence results in comparably large fuel injectors. Yet, these large fuel injectors cannot be integrated into existing gasoline engines without fundamentally changing the engine's design. In fact, such injectors require space that is not existent in today's highly sophisticated and downsized turbo engines.



❹ Combustion chamber with direct injection of CNG and MPI-fuel injection for liquid fuels

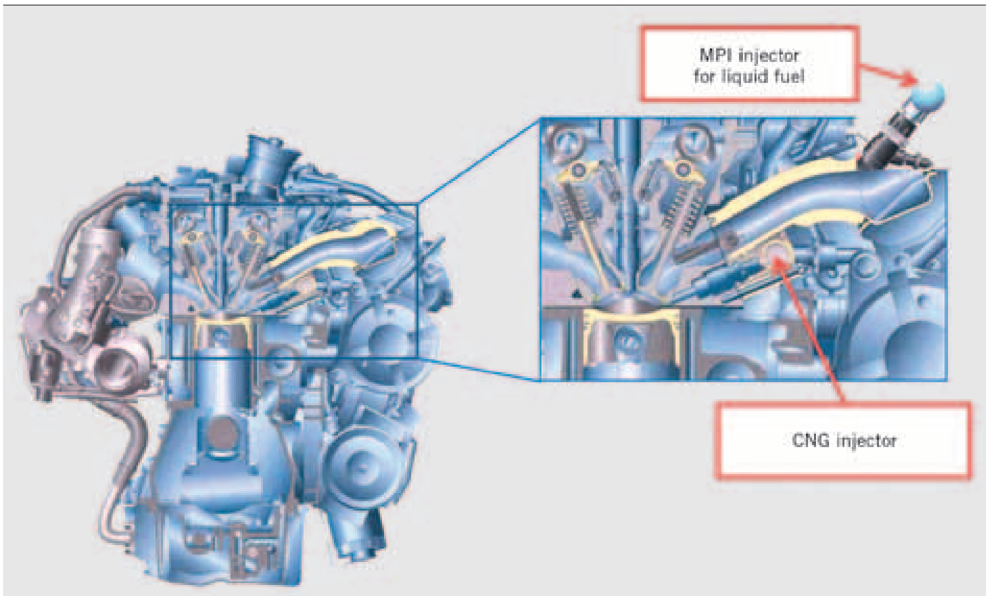
3 METHANE AND GASOLINE MIXTURE PREPARATIONS

By utilizing a fuel injector for the natural gas which has the same dimensions as a typical gasoline injector, no package-problems arise. Yet, at full load the fuel consumption can nevertheless only be partially supplied due to the limited gasflow. Through the employment of an additional gasoline injection nozzle, which is conventionally positioned inside the inlet manifold, the liquid fuel can be additionally mixed with the natural gas at full load. ❹ lays out this scheme in action.

By using two distinct fuels according to requirements and dependant on load and torque, the advantages of both these energy sources can be used purposefully to optimize emissions, fuel consumption and CO_2 emissions as well as torque and power. At part load, methane is primarily directly injected into the combustion chamber. Beyond the increased air requirements which positively affect the charge-cycle work, methane's advantageous C/H-ratio also leads to decreased CO_2 emissions. The gas is thereby injected in the intake stroke, after the outlet valves have been closed.

During acceleration and at full load, natural gas' high air requirements coupled with the impossibility of scavenging has negative effects on the attainable torque. The utilization of liquid fuels leads here to maximum torque and acceleration results.

That is why liquid fuel is preferred at full load and during moments of acceleration, whilst at part load gaseous fuel is favored. In both these processes, the injection of natural gas always takes place after the outlet valves have been closed. It is during charge-cycle-work that the lowest pressures were measured in the combustion chamber, which allows the optimum usage of the gas tank volume. By utilizing the two fuels, the range of gas-powered vehicles is at least on the same level as today's gasoline cars.



❺ Package situation

In an engine package of a typical gasoline engine in series production, ❺, the utilized natural gas-DI-nozzle can be replaced modularly with a gasoline injection nozzle. The fuel rail for the gaseous fuel is directly connected with the tank by a pressure reducer (input 220 bar, output 8 bar). The MPI-injector nozzle for the liquid fuels can be accommodated as a standard feature inside the intake manifold. The high-pressure pump of the gasoline direct injection is not necessary anymore.

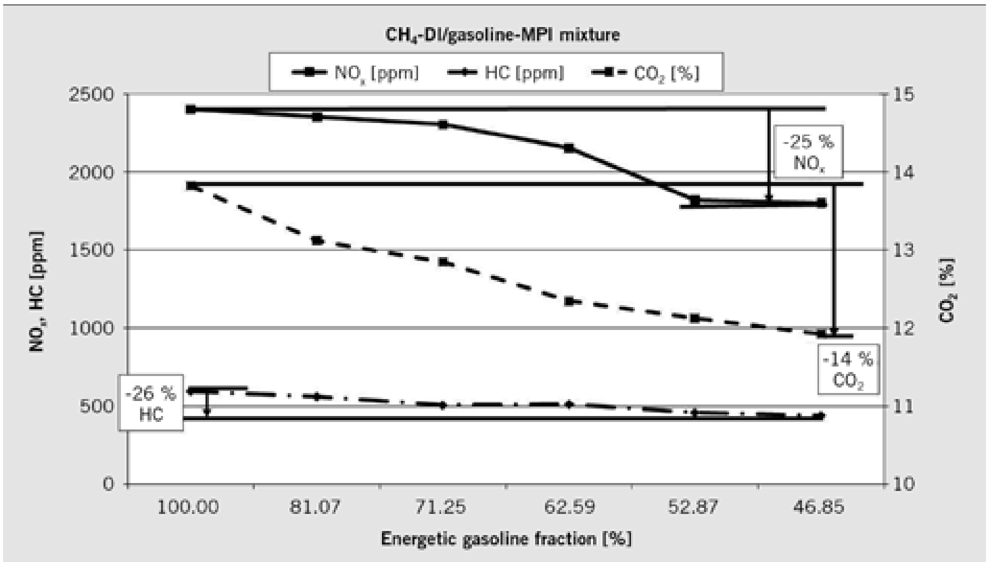
4 EXPERIMENTAL ENGINE

For this research, a 2-l four-cylinder-gasoline engine was equipped at the Technical University Kaiserslautern with the mechanically fully variable valve train Univalve as well as methane-direct injection and a MPI for liquid fuels. To avoid the corrosion of the natural gas injector's nozzle due to friction, a carbonic coat has been applied for protection. The liquid fuels utilized in this experiment are gasoline and ethanol (E85). This research project was supported by the Rheinland-Pfalz's Foundation for Innovation.

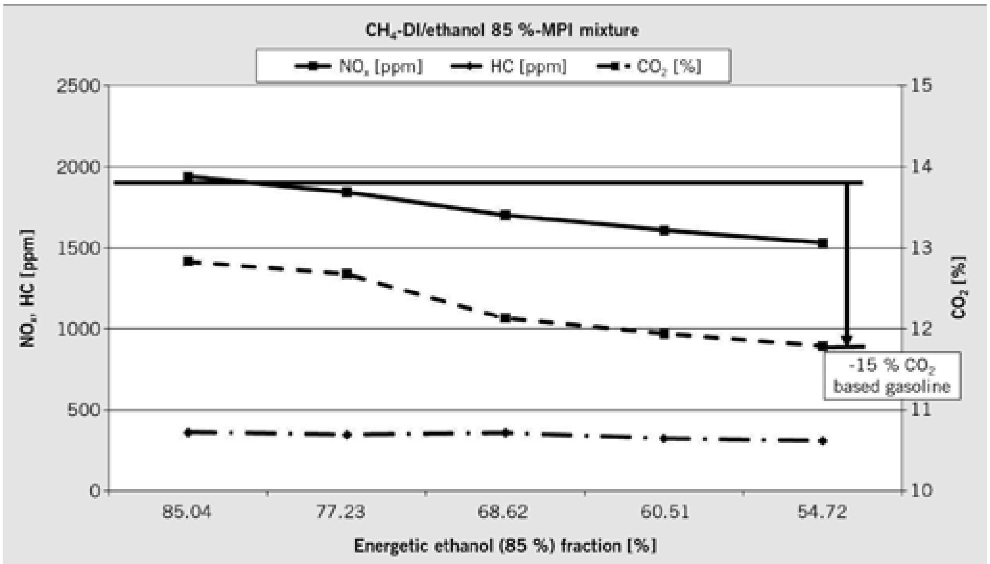
5 FIRST TEST RESULTS

A first test series at part load was conducted with an engine speed of n = 2000/min and a brake mean effective pressure of b_{mep} = 2 bar. Based on engines purely run on gasoline, the amount of gas was gradually increased in these procedures. In all performances a stoichiometric fuel-to-air ratio and a peak pressure point of 14° CA after TDC were fixed.

❻ shows the emissions of unburnt hydrocarbons (THC – Total Hydro Carbons), the NO_x and the emitted carbon dioxide. During these



❻ Measured emission with the combined use of gasoline and compressed natural gas in different mixtures



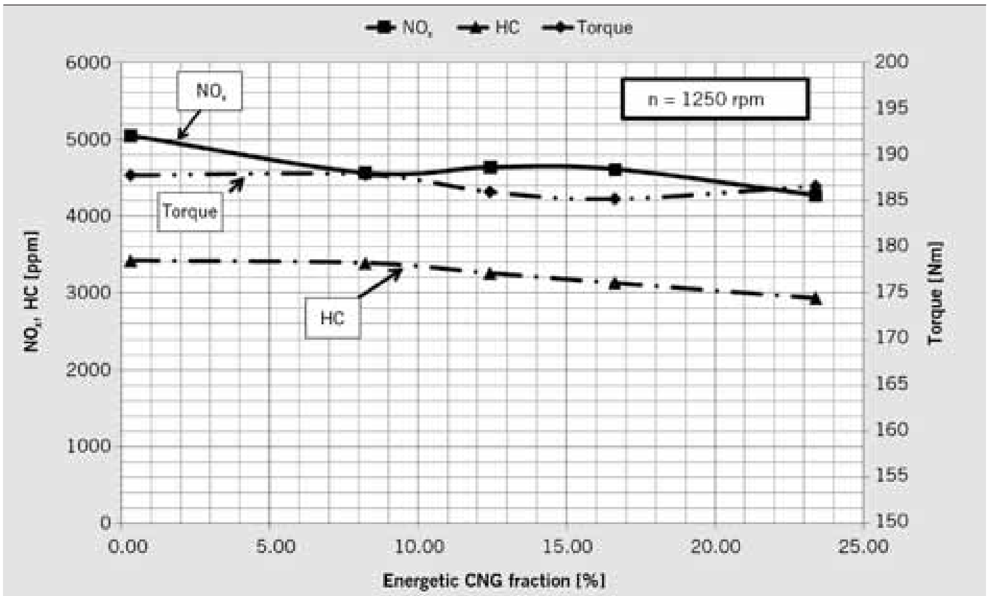
❼ Measured emission with the combined use of E85 and compressed natural gas in different mixtures

tests, the amount of energetic natural gas was gradually increased up to approximately 55 %. In so doing, it was possible to reduce the raw emissions of CO_2 by approximately 14 %, whilst the NO_x emissions went down by 25 % and the HC emissions decreased by approximately 26 %. The improvement in CO_2 emissions is caused by the better C/H-ratio of the methane. The higher air mass in the cylinder (higher air demand of the methane) results in reduced peak temperatures and lower NO_x emissions. The gaseous fuel improves the mixture preparation so that the HC emissions decrease.

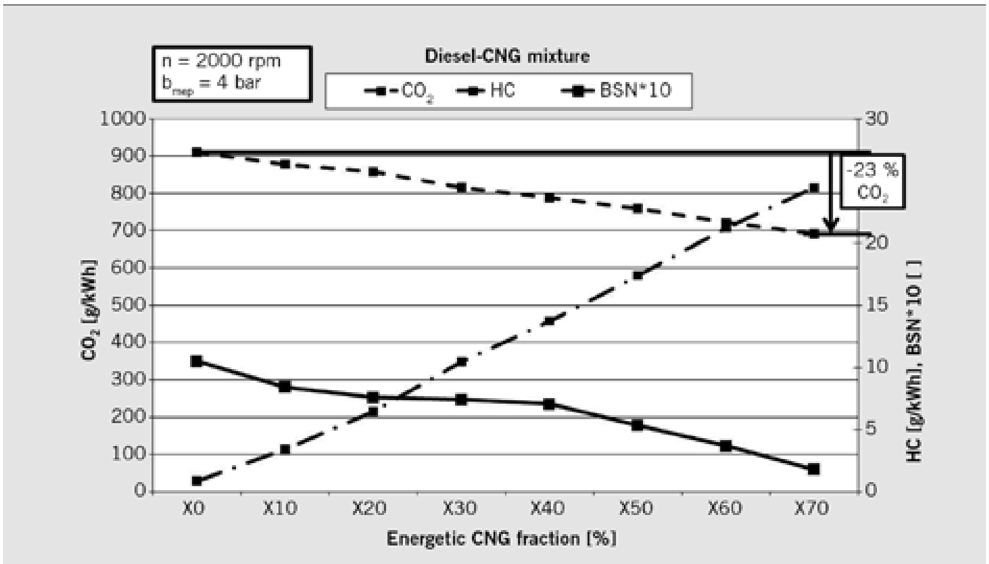
In the next step, experiments analogous to this first series of tests were conducted, but instead using E85 (85 % ethanol, 15 % unleaded fuel). The test results are displayed in ❼.

In comparison to an engine run purely with gasoline (MPI), the raw CO_2 emissions decreased in these tests by approximately 15 % when substituting gasoline with an amount of up to 45 % of natural gas. The NO_x emissions were reduced by approximately 36 % here. The HC emissions went down by approximately 48 % in contrast to the results seen with engines run entirely on gasoline. Likewise, the behavior at full load ($\lambda = 1$) with the further addition of natural gas was investigated. Whilst run in a gasoline engine the ignition timing was limited due to knocking combustion at 3° CA after TDC, the additional injection of natural gas had positive effects on the fuel mixture's knocking resistance. The ignition timing was therefore able to be adjusted until it reached the knocking limit of 7° CA up to 4° CA before TDC, which offered advantages in the high pressure process.

When evaluating the test results of pressure indication, it became clear that the addition of natural gas actually led to a distinctly faster combustion (compare laminar flame speed of methane and gasoline).



❽ Torque at full load with an increasing amount of natural gas



❾ Variations of the amount of natural gas in a diesel engine

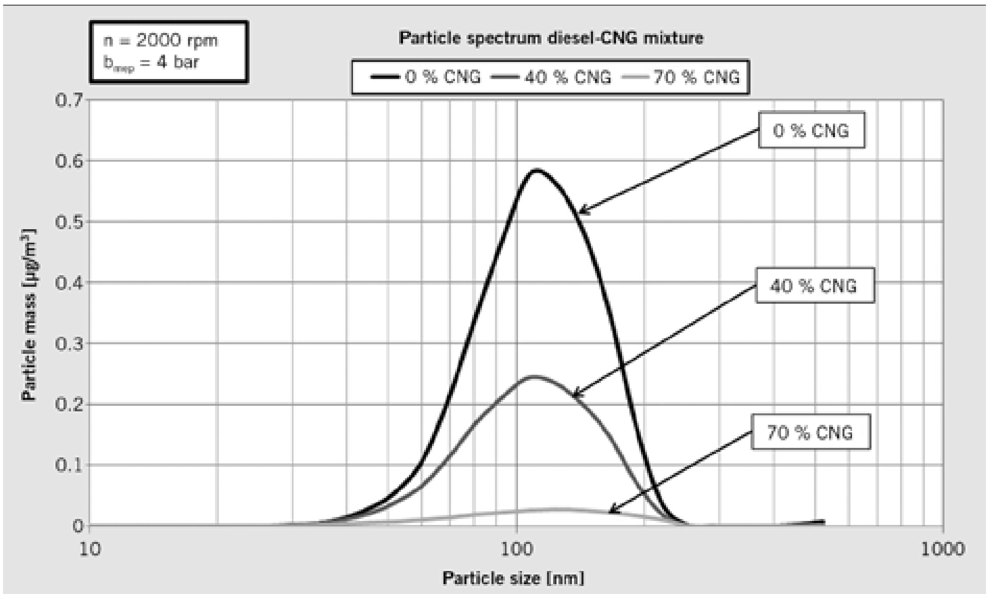
❽ shows the attainable torque at full load based on a gasoline-run engine with an amount of natural gas up to 25 %. As a result of the growing advantages in combustion, which are due to the improved knocking behavior, the torque remained close to steady despite the addition of 25 % of natural gas.

6 UTILIZATION OF NATURAL GAS IN DIESEL ENGINES

As well as gasoline engine, a diesel engine's CO_2 emissions can also be optimized by partially substituting diesel fuels with natural gas. Natural gas also proves to be a particularly suitable substitute for diesel. At part load, natural gas' high knocking resistance offers advantages in the diesel engines with their high compression ratio. This is in contrast to the gasoline engine, which can either be run with fuel or natural gas homogenously, whereas a diesel engine can only be run inhomogenously. This research was supported by the European Funds for Regional Development (EFRE).

To be able to run the engine on a mixture of diesel and natural gas, a homogenous and lean natural gas premixture was combined with the inhomogeneous diesel process. Apart from the CO_2 emissions, ❾ also gives insight into the unburned HC as well as the Bosch smoke number (BSN) over the amount of natural gas. The amount of energetic natural gas was increased up to 70 %.

When the amount of energetic natural gas reached 70 %, the CO_2 emissions could be successfully reduced by 23 %, due to the influence of the beneficial C/H-ratio. However, the more natural gas that was injected, the greater was the production of unburned hydro carbons at these adjusted injection parameters. In fact, the amount of hydro carbons increased by a factor 10, which can be attributed to the homogenous – inhomogeneous combustion.



❿ Spectrum of emitted particles with different amounts of natural gas in a diesel engine

Since these high HC emissions demand a more complex catalytic aftertreatment, they preclude running an engine on a mixture of natural gas and diesel on certain predefined operation points and at times when the engine is warming up. Another positive effect of the increased amount of natural gas can also be discerned in the BSN. Indeed, the soot emissions decrease when more natural gas is used.

A detailed measurement of the soot particles in terms of their size and number in relation to different amounts of natural gas is portrayed in ❿. What becomes clear here is that not only are the particle emissions reduced by using an increasing amount of natural gas across the whole range measured, but also the spectrum of the particle size remains unchanged.

7 SUMMARY AND OUTLOOK

Using two distinct fuels in combustion engines is shown to open up new possibilities to further optimize emissions, CO_2 outputs and fuel consumption. In fact, to date, there are no known technical measures that are able to reduce CO_2 emissions by 10 % to 20 % without inhibiting the vehicle's driving performance and which dramatically increase costs. Utilizing natural gas with its advantageous C/H-ratio therefore offers the potential to further improve the gasoline as well as the diesel engine's fuel consumption and emissions.

The gasoline engine should be powered at part load homogenously with a preferably high amount of natural gas, whilst at full load it should be supported with liquid fuel. Conversely, the diesel engine is run with a combination of a homogenous premixture with inhomogeneous diesel fuels.

Furthermore, since the low tax rates for natural gas are guaranteed until 2018, gas-powered vehicles' higher operating costs become equivalent to those of vehicles run with conventional fuels. If the combined usage of raw oil supplies with natural gas and methane resources succeeds, the dream of free mobility can be fulfilled by combustion engines for a clearly longer time span.

Future research into mixture preparations for gasoline engines aims to realize a stratified operation mode whereby methane molecules can be purposefully directed to the cylinder's border zone. The cylinder's border zone has the highest need for such knock resistant fuels as natural gas because of the increased risk of knocking in this area. Additionally, future research will focus a keener look on the compression ratio at part load. Further tests of liquid and gaseous fuel mixtures shall reveal the engines' performance with hydrogen/fuel mixture preparations.

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