DI Boost High performance gasoline direct injection

Performance without compromise

A collaborative development programme in partnership with the Robert BOSCH Corporation
“Ricardo is a leading provider of technology, product innovation, engineering solutions and strategic consulting to the world’s automotive industries.”
Contents

4 - The Ricardo group
5 - A climate for change
   Direct gasoline injection & turbocharging
   The DI Boost project
6 - Platform & powertrain selection
7 - Base engine design and mods
8 - Centre spread
10 - Turbocharger & air handling systems
11 - FIE & Engine Management System
12 - Development approach
    Simulation activities
    Calibration development
14 - Results & project achievements
The need to minimise the environmental impact of future vehicles is a major driver for our own technology research programme, one of the principal means by which Ricardo maintains its technological edge. Recent benefits of this approach are apparent, for example, in the leading position Ricardo now occupies in the development of hybrid vehicle systems and of clean diesel and gasoline engine technologies offering improved fuel economy, reduced \( \text{CO}_2 \) and low regulated exhaust emissions.

"The need to minimise the environmental impact of future vehicles is a major driver for our own technology research programme”

With our commitment to excellence and industry leadership in technology and knowledge, our greatest asset is our people, approximately 70% of whom are highly qualified multi-discipline professional engineers, consultants and technicians. Together, our vision is to make Ricardo the natural partner of choice for all our customers in all sectors.
A climate for change

The development of engines with high specific output and low specific fuel consumption is now, more than ever, becoming a principal focus for powertrain product development. A combination of two primary factors is driving this demand: global increases in fuel cost, due to energy security concerns and stricter government regulations to address the ever present issue of climate change.

As worldwide fuel prices continue to increase, consumers are shifting their purchasing interests toward more fuel-efficient vehicles. In the US market the new federal corporate average fuel economy (CAFE) regulations that are in place for the timeframe from 2008 to 2011 are further fuelling the demand for more fuel efficient powertrain solutions.

Direct gasoline injection & turbocharging

One concept to provide both high specific output and low specific fuel consumption is the combination of turbocharging and gasoline direct fuel injection. This is an attractive concept for the North American market where sport utility vehicles, light trucks and sports cars of all sizes are in demand from consumers.

In contrast to this are consumers’ vehicle performance and capability demands. Sport utility vehicles, cross-over vehicles, light duty trucks and both mid and full size passenger cars continue to be a significant portion of vehicles sold in North America. Consumers expect these vehicles to have good driveability characteristics regardless of their size and mass. These vehicles require relatively large engines with moderate to high output to achieve the desired driveability characteristics.

One method of improving fuel economy is to shift the operation of the engine to areas of higher thermal efficiency and to reduce pumping losses. This can be accomplished by decreasing the engine’s displacement, either by using cylinder deactivation or downsizing. However, downsizing alone leads to lower output and a driving experience that no longer meets the consumers’ expectations. The combination of downsizing and forced induction regains the lost performance but with some limitations associated with each method. Turbo charging counteracts the power lost from downsizing without the parasitic losses associated with supercharging.

The combination of gasoline direct injection and turbo charging is an ideal combination for both reducing fuel consumption and emissions. The direct injection allows for high compression ratios, which improve engine efficiencies while also allowing fuelling strategies that assist in reducing engine out emissions and decreasing catalyst light-off times. The addition of turbo charging can be used to create engines with high specific output. Turbocharging allows the down-sizing of these engines while still meeting the power objectives. The downsized engine will operate in its most efficient range for a greater proportion of its running time thereby decreasing consumption.

The DI Boost project

The objective of the DI Boost project was to demonstrate the benefits of a downsized, turbocharged direct injection concept on a full scale application. The benefits of direct injection in combination with turbo charging have been demonstrated several times on smaller displacement 4-cylinder engines, as a viable alternative to medium displacement 6-cylinder engines.

The DI Boost project was undertaken to demonstrate the same downsizing benefits apply to a medium displacement 6-cylinder engine as a viable alternative to a large displacement V8 engine.

The key deliverables from the project were to demonstrate:

- Negligible change in performance compared with the larger displacement, Naturally Aspirated V8 baseline power train
- Improved fuel economy compared with the baseline (target 15% improvement)
- SULEV emissions potential

Efficient-C

Full-hybrid diesel demonstrator vehicle emitting 99 g/km CO₂ (equivalent to 3.75 liters per 100km or over 75 mpg) based on a fully featured Citroen Berlingo Multispace family car.

X-Axle Torque Vectoring™

Advanced X-Axle Torque Vectoring™ demonstrator that allows redistribution of drive torque to dramatically influence the handling response and safety of the vehicle.

2/4 sight

2/4 stroke switching concept based on an innovative combustion system design, combined with advanced valve train and control technologies. Targeting up to 30% fuel economy improvement.

Delivering Value Through Innovation & Technology
The GM global V6 gasoline engine was selected as the base engine platform for the DI Boost project. Ricardo acted as the principal design and development partner for the GM global V6 gasoline engine family programme, initially released in 2004, following the previous highly successful collaboration on the development of the 4-cylinder Ecotec (L850) engine. Details of Ricardo’s role in this programme are outlined in detail in Ricardo Quarterly, Q4 2005 (please contact us for a full copy of the article).

The US Market – Demand for fuel efficient powertrain solutions

Historically low gasoline prices and a lack of comprehensive and coordinated market based incentives has not, until recently, stimulated the US end-consumer to consider more fuel-efficient vehicles. However a number of factors are driving a wave of change in the US market: record high’s recorded for domestic fuel pricing; changes to current and proposed legislation restricting CO₂ emissions; increasing CAFE requirements; all of these factors are driving demand for engine technologies that provide no degradation in performance but deliver improvements in fuel efficiency.

In combination with the required improvements in fuel economy are reductions in tailpipe and evaporative emissions. Legislation in place in the state of California requires large volume manufacturers to meet a 10% zero emission vehicle (ZEV) requirement. Of this 10%, Partial zero emission vehicles (PZEV) can be used to fulfil up to 6% of the requirement. PZEV vehicles are required to meet SULEV tailpipe emissions and have zero evaporative emissions.

The GM global V6 engine platform

The GM global V6 gasoline engine was selected as the base engine platform for the DI Boost project. Ricardo acted as the principal design and development partner for the GM global V6 gasoline engine family programme, initially released in 2004, following the previous highly successful collaboration on the development of the 4-cylinder Ecotec (L850) engine. Details of Ricardo’s role in this programme are outlined in detail in Ricardo Quarterly, Q4 2005 (please contact us for a full copy of the article).
Base engine design & modifications

Cylinder head mods
The cylinder head was re-designed to provide improved flow efficiency and motion, optimal high pressure injector placement and the provision for a cylinder head mounted high pressure fuel pump. The fuel injector is located under the intake port and inclined as much as possible relative to the flame deck. The intake port flange position was raised to be level with the head frame rail. This layout helped the overall packaging of the injector as well as allowing more freedom in terms of the port shape. The intake port was re-designed to provide the optimum trade-off between flow efficiency and mixture motion. Improvements were realized using a combination of in-cylinder CFD modelling and test cell development (discussed in more detail later).

The combustion chamber shape is shown in figure 2. The injector pocket, located on the intake side is blended to the chamber. The chamber volume is minimized to allow the desired compression ratio to be achieved.

Piston & connecting rod
The piston and connecting rod were designed to cope with the increased cylinder pressures and meet the durability requirements of the project.

The powder metal connecting rod, an ‘H-beam’ design with a fractured split cap, is capable of sustaining maximum cylinder pressures of 100 bar. The design has a non-tapered small end to reduce bearing loads.

The piston is a forged hypereutectic alloy design. The piston crown incorporates a small bowl, which is shaped and positioned in such a way that it greatly enhances the combustion process during the catalyst heating phase of engine operation. Direct injection fuel systems can run in various modes that can allow multiple injections during each engine cycle. One mode is called ‘HSP mode’ where an initial injection is made during the intake stroke and then a second injection is made close to top dead centre. The piston bowl feature is designed to transport the fuel injected late in the compression stroke towards the spark plug. In the case of catalyst heating, it is desirable to have a rich zone around the spark plug at approximately 20 degrees after top dead centre. This then allows the engine to be run with very late combustion while still achieving acceptable combustion quality. High exhaust gas temperatures can therefore be realized with stable combustion. The piston crown design is shown above in figure 3.

Valve train / VVT system
The basic configuration of the valvetrain remained essentially unchanged from the production engine. The layout is a Dual Over-Head Camshaft (DOHC) type 2-roller finger follower layout with Static Hydraulic Lash Adjusters (SHLA). The main design change from the engine launched in May 2003 is the provision of an additional lobe on the exhaust camshaft to drive the cylinder head mounted fuel pump. The fuel pump arrangement on the rear of the trailing bank cylinder head is shown in figure 4.

The lift profile and number of lobes for the fuel pump is dictated by the overall fuel demand of the engine. In the case of the DI Boost project, the number of lobes was 4 and the profile was revised to match the increased power output. This can be seen in figure 5.

Each camshaft is equipped with an oil pressure controlled vane type cam phaser, capable of 50 crank degrees of authority. As part of this study, the camshaft profiles were changed from the production units in the original naturally aspirated engine. The camshaft profiles were changed to enhance the transient response of the Turbocharging system. Valve sizes remained unchanged from the current production engine; however the exhaust valve material was upgraded to cope with higher operating temperatures associated with a turbocharged engine. The exhaust valve spring rate was increased to counteract the effect of higher backpressure associated with a turbocharged engine.
Second Generation BOSCH Gasoline Direct Injection

10% improvement in combined cycle fuel economy

Outstanding performance characteristics

SULEV emissions potential
Advanced air handling & control
Turbocharger & air handling systems

Intake System

The intake manifold design was changed from the naturally aspirated engine. The manifold volume was reduced by approximately 25% to ensure good transient response. An electronic throttle was sized for the turbocharged application.

The crankcase ventilation system was modified for operation under boosted conditions and to cope with the increased levels of blow-by. Both high and low load circuits were implemented. When under low loads, crankcase air is reintroduced upstream of the compressors.

The induction system for the DI Boost vehicle consisted of a single airbox and air meter, twin induction paths merging into a single throttle body. The existing air box was retained; however, a Bosch digital mass airflow (MAF) sensor was installed. Pressure pulsations between banks can cause compressor surge under certain conditions. Twin intercoolers were used to keep the induction paths separated. By keeping the induction paths separated until near the throttle body, compressor surge was prevented.

Exhaust system

The exhaust manifold design was challenged by extremely tight packaging constraints resulting in a design that was not optimum for performance and assembly. Considerations as to the impact of bank-to-bank differences were important and every effort was made to minimize bank-to-bank backpressure differences.

The prototype exhaust system and rapid-prototyped D5S cast steel manifold was developed in-house by Ricardo, using the expertise of the Ricardo Prototechnik product group.

The first ‘post-turbine’ upstream catalyst utilized a perforated metal matrix substrate, with a cell density of 900 CPSI (cells per square inch) at 100 g/ft$^3$ loading, pre-aged to 70hrs (GMAC 875) - equivalent to 120k miles of service. The second downstream three-way catalyst utilized a ceramic substrate with a CPSI density of 600 at 51 g/ft$^3$ loading, again pre-aged to 70hrs (GMAC 875)

A schematic of the exhaust system layout is outlined in Fig. 6.

Turbocharger system

Two Borg Warner single scroll K04 turbochargers, with water-cooled bearing housings were chosen for the application. In this scenario a twin scroll design offered no advantage over a single scroll design, as the even firing order already provided the optimum pressure pulse separation.

The compressors and turbines were sized using the Ricardo WAVE simulation software. The turbochargers selected represent the state of the art for low-cost, high volume production technology and offered a good match for the application’s performance requirement.

Conventional materials were selected for turbine wheel and housing offering a maximum turbine inlet temperatures 980°C.
FIE & Engine Management System

BOSCH second-generation gasoline FIE

The fuel system employs Bosch’s second generation DI components, which includes 6-hole high-pressure fuel injectors with a static fuel flow rate of 22.5 cc/s @ 10 MPa. The high-pressure fuel pump delivers a nominal fuel flow of 1.2 cc/cam revolution and was sized to cope with the increased flow demand from the turbocharged engine. The stainless steel fuel rails with high-pressure fuel lines are part of the fuel rail assembly as is the pressure sensor. A maximum operating pressure of 15 MPa is applied for best spray atomization and smallest droplet size. It also helps achieve maximum dynamic flow range. Figure 7 above shows the layout of the fuel system including the high pressure pump, fuel rails, fuel injectors and fuel pressure sensor.

Engine Management System

The engine management system (EMS) used for the project was the Bosch DI Motronic MED9 engine control unit. It contains a 32 bit microprocessor that communicates via LAN. The vehicle communications are via GM class 2 communications, so an interface box was used to translate messages for the instrument cluster, climate control and other vehicle systems. The ECU incorporates 32 kilobytes of internal RAM, 32 kilobytes of external RAM, and 2 megabytes of external flash memory. The processor speed is 56 MHz.

The EMS is a torque-based system that controls the positions of the intake and exhaust cams, throttle, and waste gate positions based on inputs from the various sensors and the pedal demand of the driver. Air fuel ratio is closed-loop controlled utilizing signals from a mass-air-flow meter and a wideband lambda sensor positioned in front of the close-mounted catalyst. The EMS controls injection duration, injection timing, fuel pump delivery, fuel-rail pressure and ignition timing. Two knock sensors, positioned one on each bank of cylinders, are used to control knock. Figure 8 below shows a schematic of the EMS.

Engine Management System Schematic

Engine speed is generated by a 58X digital crankshaft position sensor. Camshaft positions are sensed with 4X digital sensors on the front of each camshaft. Ignition is provided by one high-energy 54kJ coil-on-plug unit per cylinder. The unit contains integrated pulse-width-modulated coil-driver electronics, in addition to the coil.

The EMS system also controls other functions such as canister purge control, lambda control, feed-back boost pressure control, diagnostics, fuel enrichment for component protection, and cruise control.
The initial development stages of the project focused on simulating the engine concept using Ricardo’s 1-D ‘WAVE’ simulation software. The primary tasks in this phase of the project were to develop:

- Intake and exhaust system specification
- Turbocharger selection
- Camshaft profile selection
- Intake and exhaust manifold design

Initial performance estimates for intake restriction were set at a depression of 7kPa @ rated power, this restriction being measured at the entrance to the compressor.

The exhaust system back-pressure of the V8 vehicle was measured at 35 kPa. Backpressures up to 70kPa were studied during the simulation phase of the project in-line with the expected restriction imposed by the target SULEV aftertreatment solution.

Turbocharger selection was made using the results of the WAVE simulation. The WAVE simulation provides a mass flow rate to reach desired power at each rpm set point. The mass flow combined with the estimate of pressure ratio was used to select a suitable compressor match.

Transient response is critical with any turbo application, particularly with DI Boost where any perceivable turbo lag would be unacceptable. WAVE has the ability to run under transient conditions as well its more conventional steady state conditions. With rotating inertia values for the turbocharger provided by the supplier, time to reach 95% of maximum torque or maximum boost was predicted following a snap throttle manoeuvre. Modelling was performed to further improve the transient response through optimization of cam profiles and timing.

Camshaft profiles were selected to provide optimum transient response. In this particular application it was decided to leave the naturally aspirated intake cam profile unchanged while the exhaust cam duration was reduced by 10 degrees crank angle (CA) from the naturally aspirated variant.

Intake and exhaust manifold designs were studied in a similar manner to cam profiles. The geometry of the exhaust and intake manifold was optimized to give the best balance between transient response and wide-open throttle pumping losses.

Calibration development

The base engine parameterization was developed using Design of Experiment (DoE) methods. DoE methods are an effective and established solution for isolating the influence of each variable under consideration. Traditional mapping methods are not feasible given the large number of variables in a gasoline direct injection with dual independent cam phasing. Of the available advanced modelling methods available the Stochastic Process Models (SPM) methodology was chosen as the most suitable for this application. Stochastic process models are a development of the statistical method known as Kriging; an SPM response interpolates between data points after adjustments for any noise on the data.

The DoE used was at eight discrete speeds in the stoichiometric region of operation. At each speed the design was an optimal Latin Hypercube design with 60 test points. This approach results in testing a total of approximately 480 individual test points. The variables included in the DoE were:

- Mass air flow, Intake cam timing (IVT), Exhaust cam timing (EVT), Fuel Pressure and Injection Timing

Spark timing was not included as a variable because a response of optimum spark timing would be created.
Calibration development (continued)

For each experiment, response models were created for:
BSFC, CoV of IMEP, HC, NOx, Smoke and Optimum spark
The models were used to determine the optimum settings of IVT, EVT, injection timing and rail pressure for stoichiometric ECU airflow based break point.

For each ECU map site at each speed, the optimisation objective was minimise fuel consumption with the following constraints:
CoV of IMEP (< 3%), Smoke (< 0.1 FSN)
Figure 9 shows an example response at 2000 rpm.

Figure 10 shows a comparison of the DI Boost engine and the LS6 engine at the same torque at 2000 rpm. It can be clearly seen the advantage of DI Boost in terms of fuel consumption at typical road load conditions.

Transverse response was developed on the dynamometer using “snap throttle” transient tests. Changes to the calibration were evaluated in the most critical speed range of engine operation @1000 to 2000 rpm. The throttle was “snapped” open from 20% to 100%. Figure 11 shows the final compressor map operating line after development to optimize transverse response. With the use of proprietary EMS strategies and induction system design, the engine can operate very close to the surge line at low-end speeds without encountering surge.

Smoke levels at WOT were initially higher on the DI Boost project than would be recorded from a naturally aspirated gasoline direct injection engine. Through a combination of spray pattern development, mixture motion optimization, and calibration the smoke number was reduced. Figure 12 shows the improvements made in the smoke levels at 2000 rpm. For a range of injection timing between 295 and 305, the filter smoke number (FSN) can be kept to 1.0.

After establishing the base engine maps, the remaining calibration tasks were completed. These included charge determination, manifold pressure model, torque model, component protection fueling, boost pressure control, minimum spark, etc.
Results & project achievements

Performance results

Results from the Engine performance development show the DI Boost engine surpassed the target on torque and was just short of the target on power. Enhanced low-end torque is one of the synergies that the combination of direct injection and turbo charging provides. When combined with dual independent cam phasing an exceptional torque curve shape can be realized.

Throughout the development of DI Boost a challenge to the project was developing a fuel system capable of delivering sufficient fuel at rated power conditions. The engine, whilst achieving the low to mid speed torque targets, was not able to achieve the peak power target. Packaging limitations also resulted in a higher than desired intake restriction, being close to 9 KPa at rated power.

During test bed development, brake mean effective pressure (BMEP) levels well in excess of 2000 kPa were recorded; however the peak value was limited to 1990 kPa in order to achieve acceptable durability of both the prototype engine and vehicle driveline components. There was also a conscious decision to maintain a high geometric compression ratio (10.5:1) to preserve part load fuel economy.

Figure 13 shows the final developed torque curve compared to the benchmark LS6 engine that was original equipment in the CTS-V. The final vehicle performance figures demonstrate the excellent results achieved by the DI Boost demonstrator vehicle. The baseline V8 production vehicle was tested to establish the objectives both in terms of acceleration and fuel economy performance.

The acceleration testing was performed at the Bosch test facility in New Carlisle, Indiana. The surface of the test track is aged bituminous asphalt not typically used for acceleration testing. This may explain why the baseline numbers for the V8 are slightly higher than other published sources have reported.

The acceleration testing from a standstill showed nearly equivalent results for both powertrains. The production vehicle with the V8 ran a best 0-60 mph time of 5.65 seconds. The DI Boost vehicle ran nearly equal with a best 0-60 time of 5.68 seconds. The quarter mile performance was also quite similar, but the power deficit of the DI Boost was evident in the top speed at the end of the quarter mile. The production CTS-V ran a best quarter mile of 13.97 seconds at 107.6 mph. The DI Boost vehicle ran a best quarter mile of 14.20 seconds at 102.6 mph. The results of the testing are shown in figure 14 / Table 1.

Figure 14: Quarter mile performance run

The torque characteristics of the two engines are quite different. In an effort to illustrate the torque differential, top gear acceleration from 50-70 mph was tested. The V8 powered vehicle took 10.0 seconds to accelerate from 50 to 70 mph in 6th gear. It only took the DI Boost powered vehicle 8.7 seconds to perform the same manoeuvre. The results are shown in figure 15.

Figure 15: 50-70 mph Acceleration

Transmission gear ratio optimization for the DI Boost vehicle was not possible before the acceleration and fuel economy testing was conducted. The DI Boost engine has a lower maximum engine speed than the V8 engine. During the 0-60 acceleration testing, the lower engine speed necessitated an additional gear shift to reach 60 mph.
Fuel economy results

The emissions and fuel economy testing was performed at the Bosch Farmington Hills test facility. As with acceleration testing, the production CTS-V vehicle used for the project was tested to establish fuel economy and emissions baselines. The tests used to establish fuel economy were the US FTP75 and the US highway fuel economy test (HWFET). The FTP75 is commonly called the city cycle and the HWFET is commonly called the highway cycle. These two tests are combined, with a weighting of 55% for the city and 45% for the highway, to create a fuel economy number used to determine a manufacturer’s CAFÉ.

The fuel economy testing shows a clear advantage for the DI Boost vehicle. A three test average on the production CTS-V vehicle yielded a fuel economy of 16.0 mpg for the city cycle and 30.8 mpg for the highway cycle, using the transmission ratios from the baseline V8 application.

The initial three test average on the DI Boost vehicle yielded a more than 10% improvement of 17.7 mpg for the city cycle and a 1.3% improvement on the highway cycle of 31.5 mpg.

Further development testing was undertaken using revised transmission ratios and an optimised calibration. With these revised settings the DI Boost vehicle achieved a fuel economy of 18.3 mpg for the city cycle and 31.0 mpg for the highway cycle. The combined fuel economy improvement achieved was close to 10%.

Exhaust emissions results

The emissions performance achieved by the DI Boost vehicle demonstrator show the potential for SULEV emissions compliance for the concept, given the correct specification and control strategies employed for the exhaust aftertreatment system.

With the exception of HC emissions, all of the regulated emissions targets for SULEV compliance were achieved by the DI Boost demonstrator vehicle, which is a significant achievement given the performance specification and fuel economy achieved.

A key challenge for achievement of SULEV compliance in highly-boosted applications is often related to the requirement for secondary air systems, which add both feature cost and complexity to such systems.

Two key strategies were employed to enhance catalyst light-off performance and to minimise engine-out HC emissions. These were multiple/homogenous split injection (HSP) and ‘high pressure start’ respectively.

Test results indicated that the HSP strategy resulted in a significant reduction raw HC emissions, allowing the engine to run very retarded spark timings under stable operation, resulting in comparable heat generation when compared with a secondary air system (and hence excellent catalyst light-off performance).

High-pressure start mode allowed for an efficient means of minimizing engine-out HC emissions upon initial start-up.

A further stage of development activity is planned to develop the concept toward full SULEV emission compliance.

<table>
<thead>
<tr>
<th></th>
<th>CO grams/mile</th>
<th>NOx grams/mile</th>
<th>NMHC grams/mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>SULEV</td>
<td>1.000</td>
<td>0.020</td>
<td>0.010</td>
</tr>
<tr>
<td>Test Results 06/15/07</td>
<td>0.864</td>
<td>0.018</td>
<td>0.022</td>
</tr>
</tbody>
</table>

Table 2: SULEV targets vs. achieved results

Figure 16: Fuel economy test results

Figure 17: HPSS strategy
The information provided in this brochure contains merely general descriptions or characteristics of performance which in case of actual use do not always apply as described or which may change as a result of further development of the products. An obligation to provide the respective characteristics shall only exist if expressly agreed in the terms of contract. Availability and technical specifications are subject to change without notice.

Contacts

Ricardo UK Ltd
Shoreham Technical Centre

Steve Sapsford
Global Product Director, Gasoline
Shoreham-by-Sea
West Sussex
BN43 5FG
T: +44 (0)1273 794301
F: +44 (0)1273 794111
E: Steve.Sapsford@ricardo.com

Ricardo UK Ltd
Midlands Technical Centre

Tim Lake
Technical Specialist
Southam Road
Radford Semele
Leamington Spa
Warwickshire CV31 1FQ
T: +44 (0)1273 794178
F: +44 (0)1273 794584
E: tim.lake@ricardo.com

Ricardo Inc.
Detroit Technical Centre (DTC)

Mark Christie
Chief Program Engineer
Detroit Technical Centre (DTC)
40000 Ricardo Drive
Van Buren Township
MI 48111
T: +1 734 394-3874
F: +1 734 397 6677
E: Mark.Christie@ricardo.com

Ricardo GmbH
Germany

Uwe Moser
Leiter der Produktgruppe Ottomotoren
Schwabisch Gmünd
Technical Centre
Guglingstraße 66-70
73529 Schwabisch Gmünd
T: +49 (0)7171 9821-315
E: uwe.moser@ricardo.com