Porsche Engineering
MAGAZINE

CUSTOMERS & MARKETS Sports car development for the future and innovative engineering services
TRENDS & TECHNOLOGIES Real driving feeling on a virtual driver's seat
ENGINEERING INSIGHTS Numeric models for simpler calibration

ISSUE 2/2016

Dirk Lappe and Malte Radmann,
Managing Directors of Porsche Engineering

About Porsche Engineering

Creating forward-looking solutions was the standard set by Ferdinand Porsche when he started his design office in 1931. In doing so, he laid the foundation for today's engineering services by Porsche. We renew our commitment to that example with each new project that we carry out for our customers. The scope of services provided by Porsche Engineering ranges from the design of individual components to the planning and execution of complete vehicle developments, and is also transferred to other sectors beyond the automotive industry.

Dear Readers,

_____ Thinking back to your childhood, can you picture the advances in technology that have taken place over the past few decades? We saw cassette tapes give way to CDs, which were then replaced by digital downloads. Recall the moment you sent your first fax, and later your first e-mail. When did you take your first digital photo and set aside those good old rolls of film? None of that was very long ago, but today most of us carry smartphones—the latest communication tool that also includes a music player and a camera.

We are children of a digital age, and many of us have followed its rise from the early days. Despite that, and precisely in a world changing ever more rapidly due to the successes of digitization, physical experiences mean more to us than ever before. Whether it's driving a sports car on the Nordschleife of the Nürburgring or sharing a meal with friends, we also value the analogue experiences amidst all the digital opportunities. The constantly recurring combination of what is new with what has proven itself in the past is the essence of what attracts us to the future.

And so this issue of the magazine is dedicated to one of Porsche's classic core areas of expertise—driving dynamics—and combines it with current highlights of the digital transformation. Sports cars from Porsche feature unparalleled chassis design that enables the greatest possible driving dynamics. We are expanding this proven quality and unique performance with new possibilities offered by digitization, while also taking changing framework conditions into account.

This issue invites you to find out more about how Porsche and its engineering services are combining tradition and innovation.

We wish you much reading pleasure.

Malte Radmann and Dirk Lappe

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TRENDS & TECHNOLOGIES
VIRTUAL DRIVER'S SEAT

Real driving feelings thanks to optimized simulation: With the virtual driver's seat Porsche provides a highly modern development tool to enhance the connection between the driver and the vehicle.


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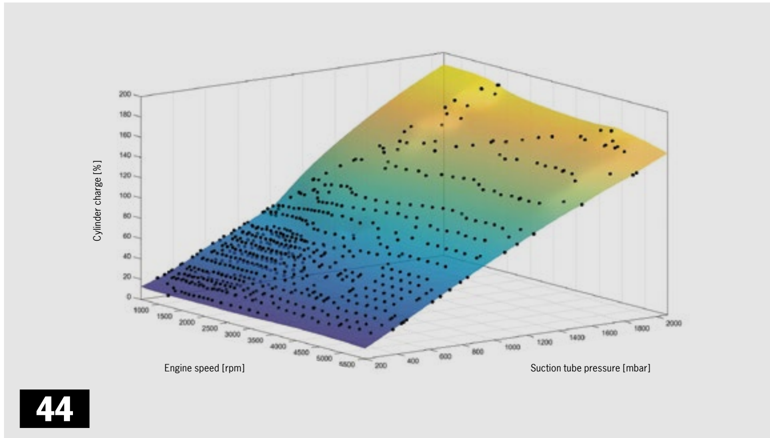
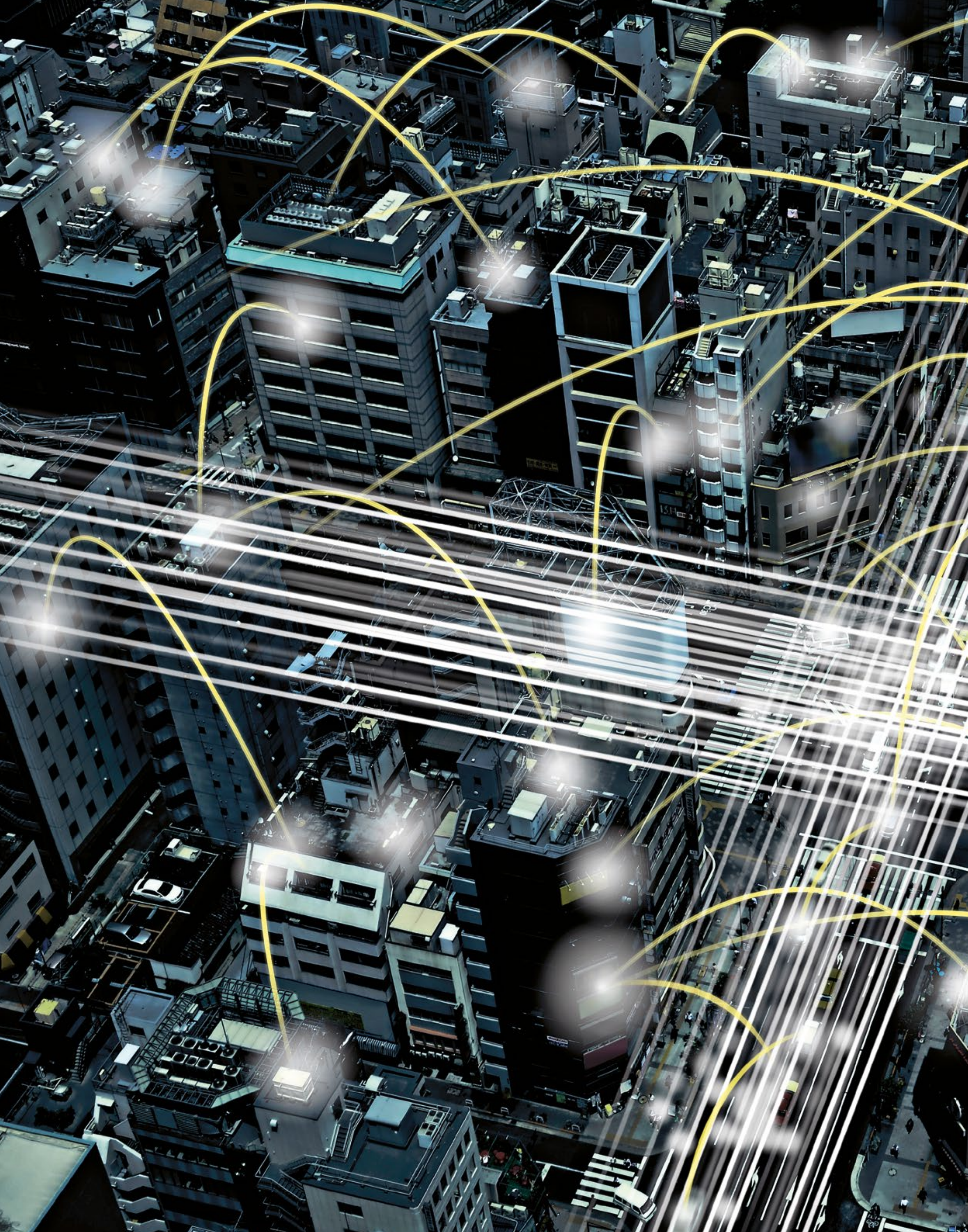

Cylinder charge [%]
Engine speed [rpm]
Suction tube pressure [mbar]
44



PORSCHE ACCELERATES DIGITIZATION

_____ Porsche is taking further steps as part of its digital transformation. The company is instituting numerous changes to meet the challenges of a digital future. In addition to starting Porsche Digital GmbH, headquartered in Ludwigsburg, and launching Porsche Digital Lab in Berlin, it has recently founded Porsche Engineering Romania in the city of Cluj-Napoca. This subsidiary will play a key role in developing innovative solutions for mobility—and fully embrace the newly developed Porsche Engineering Strategy 2025.

Porsche Digital GmbH serves as a center of expertise that defines and further develops digital customer experiences, products, commercial fields and business processes. Its responsibilities also include scouting on a worldwide basis. It identifies and analyzes new trends and secures access to relevant technologies in the process. In addition to its own potential for innovation, Digital GmbH also seeks partnerships around the world. This applies especially to the fields of connectivity, smart mobility and autonomous driving. According to Thilo Koslowski, Managing Director of Porsche Digital GmbH, this networking approach is creating “the typical fascinating and intelligent experiences that customers expect from Porsche—both inside and outside the car.”

The Porsche Digital Lab, which recently opened in the Berlin district of Friedrichshain, is also transferring the profound changes underway in the digital transformation to automotive engineering. Its developers are examining how Porsche can apply innovations in big data, machine learning, micro services, cloud technologies, Industry 4.0 and the Internet of Things to practice. This subsidiary’s activities extend from scouting for trends and ideas to building IT prototypes and components.

In the Romanian university city of Cluj-Napoca, one of the most innovative places for software development in Europe, Porsche Engineering is applying ideas and strategies for a digital future directly to concrete projects for the automotive industry. The range of activities at the subsidiary in Cluj-Napoca covers everything from vehicle-related software and function development to other fields of automotive development such as simulation and design. “Cluj will help us make cars more digital,” says Marius Mihailovici, Site Director for Porsche Engineering Romania.

Porsche Engineering’s youngest site is therefore an excellent example of its newly developed Strategy 2025. “Porsche Engineering stands for first-class expertise in three major fields of automotive development that are both rooted in the present and oriented toward the future,” says Malte Radmann, Managing Director of Porsche Engineering. “In addition to classical derivatives and systems development, which we have been pursuing ever since Ferdinand Porsche founded his design office, the other two main pillars of our range of services are testing and digitization.” With its combination of traditional and innovative engineering expertise, the international company will continue to meet the needs of its customers around the world. ■

NEW GENERATION OF CABS

DEVELOPMENT FOR SCANIA PRESENTED

___ In August 2016 Scania presented, for the first time, a series of trucks with new driver's cabs that were developed together with Porsche Engineering. The cabs are based on a modular system of different models, which will start with the R series along with the completely new S series. With its S series, Scania is presenting the top model of cabs with flat floors. The new cab range does not share any components with its predecessor. However, all the positive cab features that Scania is known for are being transferred to the new series. The developers took equal account of customer needs and regulatory requirements, in both current and future-oriented forms. ■

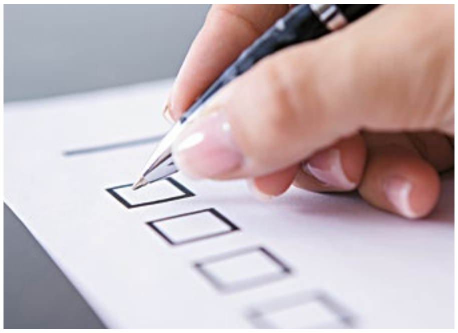
OPENING CEREMONY

SITE IN CLUJ-NAPOCA

___ Porsche Engineering's new development site in Cluj-Napoca in Romania was officially opened in mid-July of this year. The company held a press conference to announce its plans for growth and introduced Marius Mihailovici as the director of the new site. Those attending the ceremony included not only Porsche Engineering employees and partners but also Judith Urban, the German consul in Sibiu, Emil Boc, the mayor of Cluj-Napoca, and other representatives of research, business and government. The same day as the opening ceremony, Porsche Engineering signed an agreement with the Cluj-Napoca Technical University on an Automotive Engineering master's program. The company is also holding talks on joint projects with Babeş-Bolyai University, which is located in Cluj-Napoca. ■

READER SURVEY

ENHANCING THE CUSTOMER MAGAZINE



___ A reader survey was carried out in conjunction with the previous issue of *Porsche Engineering Magazine* (1/2016) on how the magazine might address the wishes and needs of its readers even better—with respect to both its selection of topics and its design and layout. Porsche Engineering would like to thank all those who participated for their helpful feedback. For each completed questionnaire, the company is donating five euros to LWV Eingliederungshilfe Markgröningen, with which it has worked in the past. LWV is an organization that facilitates the integration of disabled people in all aspects of society. ■

News

CONNECTED DRIVING

RESEARCH INITIATIVE IN SHANGHAI

___ Porsche Engineering Shanghai is expanding its work in connected driving. In July 2016, this Chinese subsidiary became a member of the United Innovation Centre for Intelligent and Connected Vehicle Industry Technology (UIC), a pilot zone for vehicle connectivity and autonomous driving. The UIC was created in July 2015 by the Shanghai International Automobile City and ratified by the Ministry of Industry and Information Technology (MIIT). The UIC works together with international companies, research institutes and universities. Porsche Engineering is supporting the development of this testing zone and participating in the lively exchange on the latest developments in the Chinese automotive industry, legislation and general research. In the future, the Automobile City will cover more than 100 square kilometers. ■

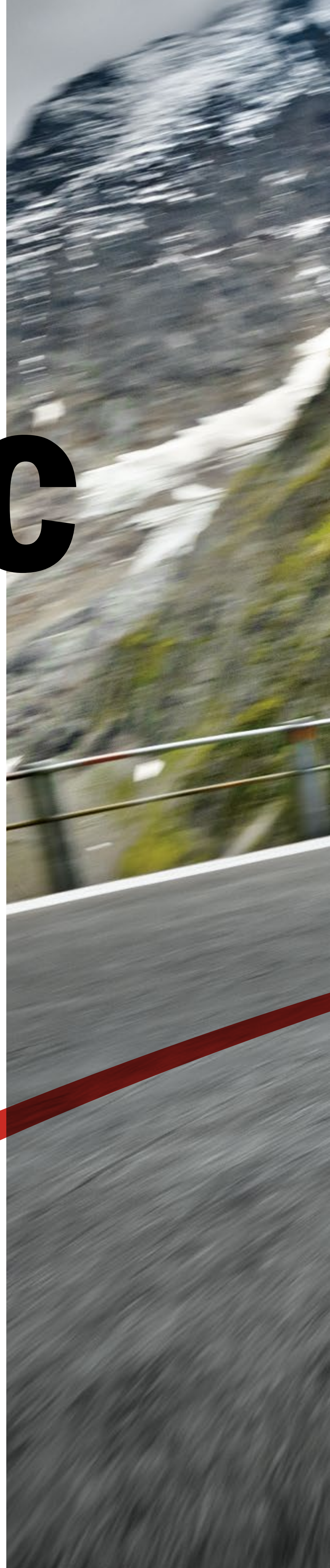
OPTIMIZED DIAGNOSTIC TOOL

MEASURING COMPONENT TEMPERATURES

___ This non-contact system for measuring component temperatures (see *Porsche Engineering Magazine* 1/2015) has been optimized and further developed. Its diameter was reduced to 26% of the original size, which also enables a reduction of the measurement distance to 30% and the measurement position to 60% of the original values by means of freely designable optics. Greater proximity to the measurement object enables greater signal intensity and accuracy. Combined with a smaller measurement position, this enhances the detection of dynamic effects and increases measurement quality. ■

Dynamic

Performance-oriented chassis design is at the heart of Porsche's brand. The combination of optimum dynamics and comfort is a classic trait of Porsche sports cars. Find out how Porsche today develops chassis that fulfill the highest standards, which new developments the digital evolution is making way for, how the day-to-day usability of the Porsche 911 is continually improved and how automated tests and simulated testing can increase development efficiency.



911 R
Fuel consumption (in l/100 km):
urban 20.1 · extra-urban 9.3 · combined 13.3
CO_2 emissions: 308 g/km
Efficiency class: G

Optimum Performance

How Porsche designs performance-oriented chassis

____ In every market segment, a Porsche represents class-leading driving dynamics combined with an ideal interplay between driving dynamics and comfort. Every model line and every individual model is designed and optimized to that end. Only a precisely balanced interaction between the (overall) concept, drive technology and chassis can generate driving dynamics. This performance-oriented approach is part of the brand core of Porsche and will, as the digital evolution continues its forward march, continue to give rise to new functions and innovations that generate an unparalleled driving experience.

By Peter Mevißen and Norbert Schote; photos by Victor Jon Goico

Overall vehicle concept	Chassis mechanics	Mechatronic systems
> Consistent consideration of driving dynamic requirements within the overall vehicle concept	> High-performance tires > Performance fixed-caliper brakes > Precision axles	> Further increase in performance potential > Achievement of both driving dynamics and comfort

The three pillars of the performance-oriented overall concept

The performance-oriented overall concept is founded on three pillars: The first consists of *basic concept characteristics* such as the wheelbase, track width and weight. The *chassis mechanics,* with the axle concept, brakes and tires, form the second pillar. The third pillar is comprised of the *mechatronic chassis systems,* such as the electromechanical steering system (EPS, electric power steering), the active anti-roll stabilization system (Porsche Dynamic Chassis Control) and semi-active engine suspension. The goal of chassis development is class-leading driving dynamics with exceptional comfort characteristics. In more precise terms, the three pillars of the overall concept feature the following characteristics:

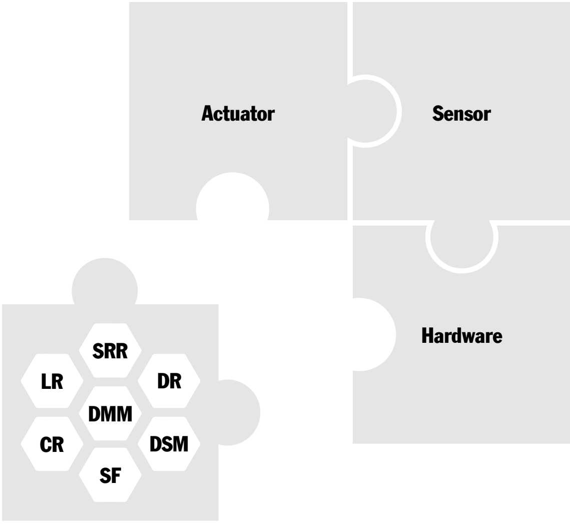
The basis for the performance-oriented design of the driving characteristics begins with the *overall vehicle concept.* A long wheelbase ensures strong directional stability and long track widths, and a low center of gravity for low wheel load fluctuations in corners. For the driver, it means high lateral acceleration, low load change reactions and minimal roll tendency. A balanced axle-load distribution in conjunction with a rear-heavy drive torque distribution results in optimal traction and neutral self-steering properties.

With the *chassis mechanics,* defining the dimensions of the wheels and tires is the first step. Porsche utilizes mixed tires

(wider tires in the rear) on all model lines, and in the super sports car segment also uses mixed wheel diameters (wheels on the rear axle have larger diameters as well). For optimal braking performance, robustness and a good braking feel, all Porsche models employ fixed-caliper brakes. The axle concepts, with continuously updated kinematic characteristics, ensure the correct positioning of the wheels in relation to the driving surface in all driving conditions and thus optimal power transmission of the tires to the road.

Mechatronic systems are gaining increasing significance in chassis concepts in terms of driving characteristics and comfort aspects. Porsche developed the core elements in-house. The control unit for the electromechanical steering system, for example, was designed with in-house expertise for the highest feedback quality with outstanding steering comfort. To further enhance the driving dynamics (agility and stability), an additional rear-axle steering system was developed for the 911 and the new Porsche Panamera.

Further interconnected control systems with an impact on driving dynamics have been in use in Porsche cars for years, in many cases as standard equipment: The on-demand Porsche Stability Management (PSM) system is often combined › with Porsche Torque Vectoring (PTV) to optimize stability and agility. Porsche Active Suspension Management (PASM) regulates the damping force on the wheels and the active engine suspension actively influences the oscillation of the drivetrain. In conjunction with the controlled air suspensions, the tricky combination of comfort and sportiness can be significantly enhanced. And with the all-wheel models, Porsche Traction Management (PTM) contributes to enhanced performance with regard to the situational torque distribution between the front and rear axles.



SRR: spring rate regulator
DR: damper regulator
DSM: driving status monitor
SF: safety functions
CR: component regulator
LR: level regulator
DMM: driving mode manager

Architecture of the ECP control unit

Chassis systems with custom functionalities

The specific development of function algorithms enables optimal utilization of system potential and the implementation of defined scopes. The result is custom functions. One integral part of vehicle development for mechatronic chassis systems at Porsche is their modeling in terms of physical driving characteristics. This makes it possible to coordinate functions easily with a limited number of physical parameters. They are also easy to apply to different variants and other model lines.

Model-based function development and its easy transferability enable continuous refinement and optimization of the algorithms. Application concepts can be standardized across model lines and yet it remains possible to create customized solutions for the different systems. This in turn makes it possible to generate additional customer benefits with the same system hardware.

Debut in the Porsche Panamera: the electronic chassis platform

One example of in-house development of chassis functions is the chassis control systems of the electronic chassis platform (ECP) in the new Panamera. The ECP control unit integrates numerous previous control units (see figure above).

The primary focus of the engineers in the development of the concepts and functions was on achieving the optimal combination of performance and driving comfort. The goal, as always, is to secure Porsche its customary best-in-class designation. The foundation for resolving conflicting objectives is a sensor and actuator technology concept that goes well beyond the market standard. The concept, in conjunction with the controlled chassis systems, makes it possible to address every set of driving and environmental situations in optimal fashion.

For the vast number of required functions, in the past there were a number of control units. With the introduction of the electronic chassis platform in the new Panamera, the multiple control units have now been combined and centralized in a single control unit. The combination of all shock and damper controls in a platform avoids redundancies and reduces the number of interfaces. This not only yields benefits in terms of bus load and signal propagation times, but also enables a highly agile development process.

Porsche quickly recognized the unprecedented degree of complexity in the development and integration of this new mechatronic unit. Based on a targeted in-house process analysis, the development department defined and implemented a new model for interdisciplinary control of the project.

For the most part, the ECP project model is based on a conventional matrix organization. Each software component is assigned to a specific project area responsible for the development of the function. The overarching integration department provides the project manager, who in turn is supported by sub-project managers. For various subjects, such as monitoring the maturity level or the testing and qualification planning, special committees were set up. The concept has proven useful: Smooth and schedule-oriented management of the project is assured as the employees involved from various departments come into contact with different operational supervisors along the way.

PDCC Sport: electromechanical anti-roll stabilization in the Porsche Panamera

For the second generation of the Porsche Panamera, the active anti-roll stabilization system was redeveloped as well. The PDCC Sport electromechanical system replaces the hydraulic variant familiar from the first generation. For the driver, the new system has a variety of advantages, such as enhanced subjective solidity and better control of the self-steering properties through a very strong power build-up.

Due to the continuously rising degree of electrification in the drive technology area, electromechanical systems make sense. Thanks to the availability and functional advantages of 48-volt technology, the system power supply at precisely this voltage level is assured. This enables a higher number of electromechanical components. One positive aspect of these systems is the considerably reduced package costs. The required components are easier to standardize and integrate into multiple vehicle platforms thanks to their small number. The system will later be used in the same form in other vehicles of the VW Group using the modular principle.

The active anti-roll stabilization system is comprised of two sub-systems connected by a cable harness: the actual *actuator* for introducing power into the vehicle structure and the *control unit* with a power supply of 48 volts (see figure below).

For each axle, the *actuator concept* consists of a basic actuator with two anti-roll bar halves. In the basic actuator, a brushless DC motor (BLDC motor) powers a three-stage planetary gearbox. The actuator twists the two anti-roll bar arms in opposing directions with a maximum torque of 1,200 Nm. The planetary gearbox is optimized for high efficiency and low noise emissions during dynamic operation.

The two essential components of the active anti-roll stabilization—actuator and control unit

The second essential subsystem is the *control unit* with its 48-volt power supply. The integration of all components in a very compact construction space and the achievement of target values for electromagnetic compatibility (EMC) present a challenge. The length of the connection between the control unit and actuator can be up to three meters. The fordability (watertightness during water crossings) of the control unit enables great flexibility in positioning within the vehicle package. Communication of the control unit with the vehicle is handled by a CAN connection. The software on the control unit—based on AUTOSAR—is supplied with all requisite driving state signals by the vehicle's network.

One challenge in the development of the system was optimizing the driving comfort functions. Achieving the defined objectives requires highly complex control capabilities, which were developed through simulations, test bench testing and extensive testing in driving operations.

Innovative steering controller for sports cars

For the driver, the controller for the electromechanical steering system is the most important source of information about the driving state: The more direct and clear the feedback, the more dynamic and precise the sports car. Porsche therefore developed its own steering system software.

The goal of the innovative control concept, on the one hand, is to raise the conceptually reduced road feedback from electromechanical steering systems regardless of the steering component supplier to the high level of hydraulic steering systems. At the same time, the system should retain the many advantages of electromechanical steering gears to the fullest extent. In addition to the entire control structure, the core of the software also includes numerous function modules developed on the basis of Porsche-specific requirements in terms of driving dynamics and integrated into the overall architecture of the control unit. The result, ultimately, is an in-house steering function library that can be used regardless of the model line and steering system supplier.

The concept of assist power control (APC) is based on the online calculation of the force components impacting the steering system. These components consist of the driver's steering force, friction and inertial forces, the actual assistance force from the servo motor and the force applied by ›

The basis of all Porsche chassis: functionally optimized and continuously developed hardware for the axle system, tires and brakes.

the tire-road contact. The total forces are calculated using an observer approach with minimal deviation in the control unit of the steering system and provided to the software function modules. The calculation is therefore performed exclusively through existing measurement signals without additional sensors.

The target assist force on the rack is then defined by a controller that was tested in simulation and on the test bench. It works in a dependent relationship to the frequency of external excitation. This makes it possible to make frequency bands with useful information transparent to the driver and dampen bands with disturbing excitations in the transmission. The effect: The steering comfort can, in typical EPS fashion, be enhanced without compromising driving-dynamic feedback or naturalness.

Even the resetting of the steering system is no longer based on synthetically applied steering functions, but derives from the actually applied restoring forces acting on the tires (see figure on page 17). Particularly for threshold maneuvers such as under- or oversteering, the assist force control functionality manifests itself quite noticeably. In addition to the feedback-amplifying control, there is also a whole series of additionally integrated functions such as a low frictional indication, hands-off detection or situational stabilization that contribute to the situationally appropriate and safe functioning of the steering system.

With these new steering functions, the driver experiences the typical Porsche steering feeling of solidity and immediate feedback. The most important aspects are the improved vehicle guidance and precision at the limits of driving dynamics capabilities.

Chassis of the future: digital evolution

Advancements in digitization, sensor technology and actuator technology will have a defining impact on future chassis development. The increasing utilization of these capabilities is helping mitigate compromises and resolve conflicting objectives to an ever greater degree. The combination of sportiness and comfort is becoming ever more refined and is continually augmented by new functions.

Chassis development at Porsche—trends and new technologies

Intelligent vehicle

> Operational and load data
> Predictive/individual maintenance
> Field monitoring/early warning
> Software updates

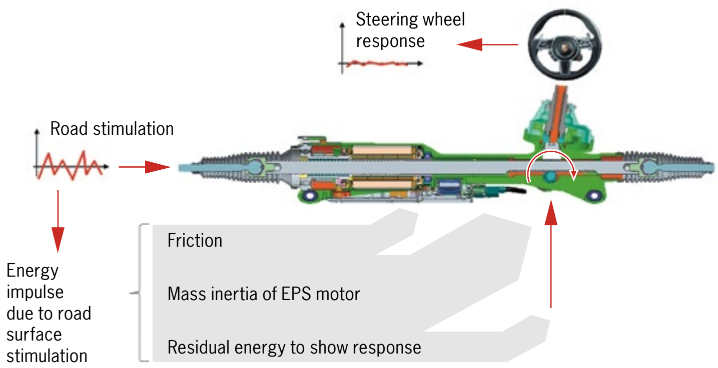
Innovative products

> New chassis systems/sensors
> Intelligent tires
> System linking
> Adaptive chassis—int./ext. data

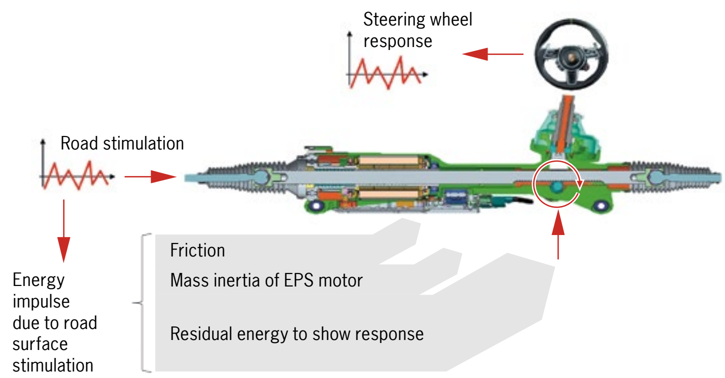
Product development

> Digitization of development
> OTA support for prototype vehicles
> Documented fleet protection
> Off-board analyses

Feedback path of an EPS with a conventional regulation philosophy



Feedback path of an EPS with assist power control (APC)



Feedback optimization through inertia compensation

Digitization and connectivity, e-mobility and autonomous driving are the defining trends of today and tomorrow in the carmaking industry. The associated rapidly rising connectivity, well beyond vehicles alone, will have a substantial impact on individual chassis systems, but also on their interaction in the vehicle and the interaction of the systems with the outside world. Within the vehicle, an intensification of mutual information exchange between the systems is all but certain. This growing connectivity expands our capacity to further enhance both the driving dynamics potential and driving comfort.

In the foreseeable future, communication between vehicles will be added to the mix. One possibility, for example, would be a central knowledge base and database fed by both vehicles and the environment that supplies drivers and vehicles with information. This, in turn, would enable engineers to make vehicles and chassis even safer as well as more reliable and customer-oriented. One crucial component of the digital capabilities for vehicle control is undoubtedly an over-the-air update (OTA update) function.

This expansion of functionality is associated with a vastly increased complexity of the systems. At the same time, this means that the development processes will need to be adapted substantially in the near future. The focus of the reorientation will be on shortening development times in order to keep pace with the rapid developments in the digital market. Another emphasis will be on the functional validation of the systems as errors in the hardware and software of a chassis must be ruled out with certainty.

The basis for Porsche chassis will, nevertheless, always be comprised by the functionally optimal, continuously enhanced hardware of axle systems, tires and brakes. It is the foundation of Porsche DNA, which is composed of class-leading driving dynamics and braking performance, track-worthy speed and handling, comfort and impeccable efficiency. This ensures, irrespective of the drive topology, that driving behavior will remain the central element of the Porsche brand core. ■

Intelligent Solution

Development of a front axle lift system for the Porsche 911

____For the first time, Porsche is offering a lift system on the front axle for the new street sports car generation of the 911. This option contributes to additional enhancement of the day-to-day usability of the legendary sports car.

By Olaf Ahrens and Benjamin Reddingius

The optional front axle lift system substantially increases the everyday usefulness of the vehicle for the customer. The option pays off in particular with steep garage access ramps as the approach angle of the vehicle can be increased from 9.7° to 12.7° within four seconds. This all but eliminates the risk of damage due to scraping the bottom of the vehicle. This enhancement results from lifting the front end by about 40 mm at the nose, or roughly 34 mm at the suspension strut.

The system also aids in driving over speed bumps as it is available at speeds of up to 35 km/h.

The key impetus for the development of the front axle lift system came from the customer side. Porsche customers demonstrated significant interest in a lift system that could be directly added to new vehicle orders without having to accept limitations in terms of their other equipment desires as a result. The system should also increase the day-to-day usability of the vehicle without at the same time compromising other characteristics such as the luggage compartment volume. Another important criterion was system integration with the vehicle's operating and display concept.

One of the challenges was to integrate the system to be developed in every variant of the 911 series, excepting the GT variants. Because the suspension struts vary between the Coupé, Cabrio, Targa and Turbo models as well as between the two- and four-wheel-drive models, the front axle lift system increased the number of variants twofold.

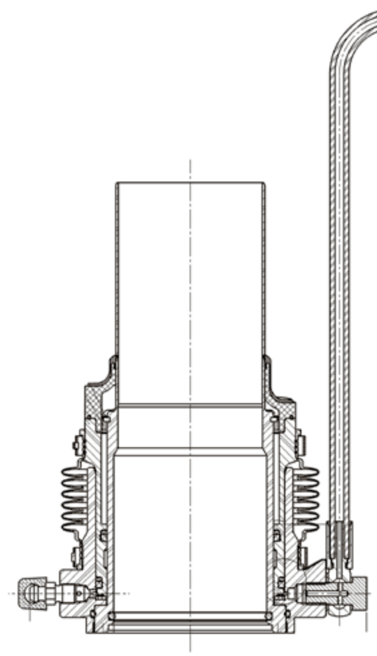
The concept: one hydraulic actuator on each front suspension strut

The engineers designed a front axle lift system comprised of two actuators on the front suspension struts. The actuators are hydraulically powered cylinders with an annular clearance as the effective area. A hydraulic solution was selected due to the very compact package parameters in the area of the front axle.

The connection between the actuator and the coil spring, the spring rubber and the corresponding spacer consist of one plastic component with an integrated rubber spring seat. The rubber seat also has a molded-on sealing lip that prevents moisture from penetrating the system. This sealing lip sits on a cylinder that slides over the reservoir tube of the front axle vibration damper. The cylinder is subject to special surface requirements in terms of the sealing effect between the lip and the cylinder as well as sound.

911 TARGA
Fuel consumption (combined): 9.0-7.9 l/100km
CO_2 emissions (combined): 208-182 g/km
Efficiency class: F-D

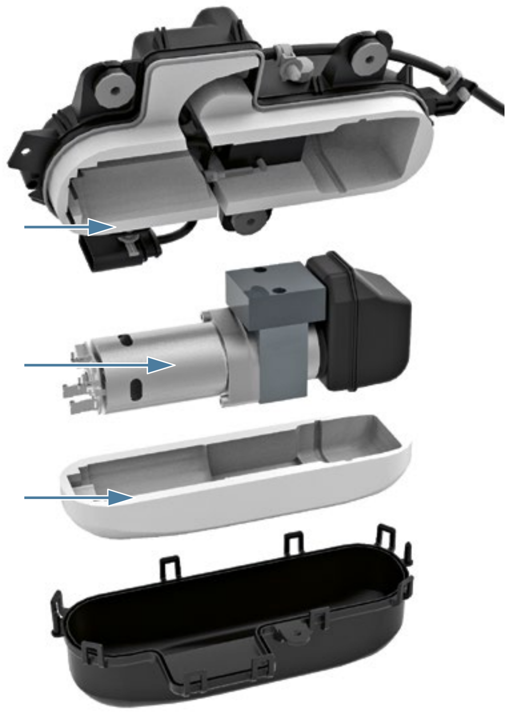
911 TURBO
Fuel consumption (combined): 9.3-9.1 l/100km
CO_2 emissions (combined): 216-212 g/km
Efficiency class: F



Hydraulic actuator

The connection between the hydraulic actuators (see figure above) and the fixed lines in the front end of the vehicle is done using flexible hoses with quick-disconnect couplings (see figure on top left-hand side of page 20). These special couplings are attached to the body with specially developed mounts: Both ends of the lines can be inserted under full system pressure without the possibility of air penetrating into the hydraulics. The quick-disconnect couplings come from the motor racing milieu, where they are used in the brake area. ›

Quick-disconnect couplings with mount



Pump housing

Prefilled system for the lowest-possible assembly time

The advantage that emerges from the solution described previously is that the actuator can be delivered to the assembly site in a completely prefilled state. After connecting the coupling the spring pre-tensioning ensures that the hydraulic fluid is pressed from the actuators into the lines to the pump and the supply tank through the coupling. For its part, the tank is dimensioned such that the additional hydraulic oil from the actuators ensures that the system's correct operating amount is achieved. This obviates the need to fill the system from the outside and no additional step is required in the vehicle assembly process.

From the quick-disconnect coupling, two fixed lines run to the center tunnel, where they merge into a single line. This runs to the pump and is comprised of flexible hose material to enable the best possible insulation of the pulsation of the hydraulic pump. The course of the lines is designed in such a way that it is suitable both for rear-wheel and all-wheel drive models.

The pump unit, which is responsible for supplying the required hydraulic pressure, is located under the floor of the right rear seat and consists of a drive motor, pump, valve block and supply tank with hydraulic oil. The unit is mounted in rubber bushes and protected against dirt and water by an IP67 housing. For acoustic insulation (air and body noise), molded foam encases the entire pump/valve unit (see figure at top right).

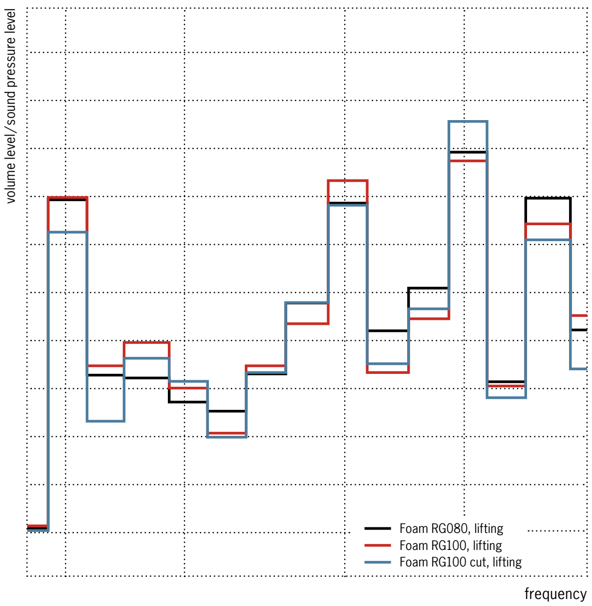
The latter consists of adapted components originally used in the roof drive of the 911 Cabriolet. To achieve the desired sound insulation, during the development process the density of the molded foam was adjusted from 80 kg/m³ to 100 kg/m³. The objective of the change was to optimize the sound in the frequency range—roughly 1,000 Hz—most audible to humans. In a direct comparison, the higher density yields lower frequency bands in the high-frequency range and higher frequency bands in the low-frequency range. Subjectively, the result is a more voluminous and rich pump sound (see figure on page 21).

The system design makes work on the system by customer service or repair work extremely easy. Filling and venting requires only the removal of one of the two front wheels. The hose itself, as it is now already installed in the series and from which the eyelet is removed, now functions as a tool. It can be ordered as an individual part. To bleed the system, the thus-created tool is connected via the quick-disconnect coupling in the wheel well and the system then completely emptied via the diagnostic function of the control unit.

In order to refill the system back to the required operating amount, the hose with the open end is dipped into a container filled with hydraulic oil. The oil can then be sucked up with the diagnostic function. Upon completing the refilling of the system, the tool is removed from the quick disconnect coupling and the actuator reconnected with the regular connector hose.

Controlled self-heating for full functionality down to –25 °C

The hydraulic oil used (Vitamol ZH-M) becomes increasingly viscous at low temperatures, which has a major impact on system performance. In the optimization process of low-temperature performance, the first step was to identify the contact points in the system that react in a critically sensitive way to high fluid viscosity. This applied in particular to areas within the valve block of the supply unit. To ensure the desired lowering and lifting times even at temperatures around –25 °C, a solution concept was developed based on these insights. The system is automatically activated below a temperature level of –5 °C and the oil heated up in an internal circuit. The result is that the lift system is available to the driver without limitations even at very low temperatures. ■



Pump sounds

Control unit with extensive monitoring functions

Completing the system is a control unit in the vehicle interior. The programming takes account of numerous functions, including:

> The lowering of the front end is prevented if one of the two vehicle doors is open (anti-pinch protection).

> If a door is opened during the lowering procedure, the control unit automatically switches back to the rise function.

> During and at the end of the lifting or lowering process for the front axle, the system checks the clearance using a plausibility check function.

> Depending on applicable pedestrian protection regulations, country-specific control variants for the automatic lowering speed can be implemented.

> The rebound damping of the active Porsche PASM damper control system will be brought up to a higher power level in order to enhance comfort with “lift active.”

> For improved comfort, particularly in terms of sound, a controlled power shutdown takes place at the end stop of the lift process.

> To ensure the longest-possible lifetime for the hydraulic unit, a temperature model has been implemented.

> Diagnostic functions enable emptying and filling by customer service.

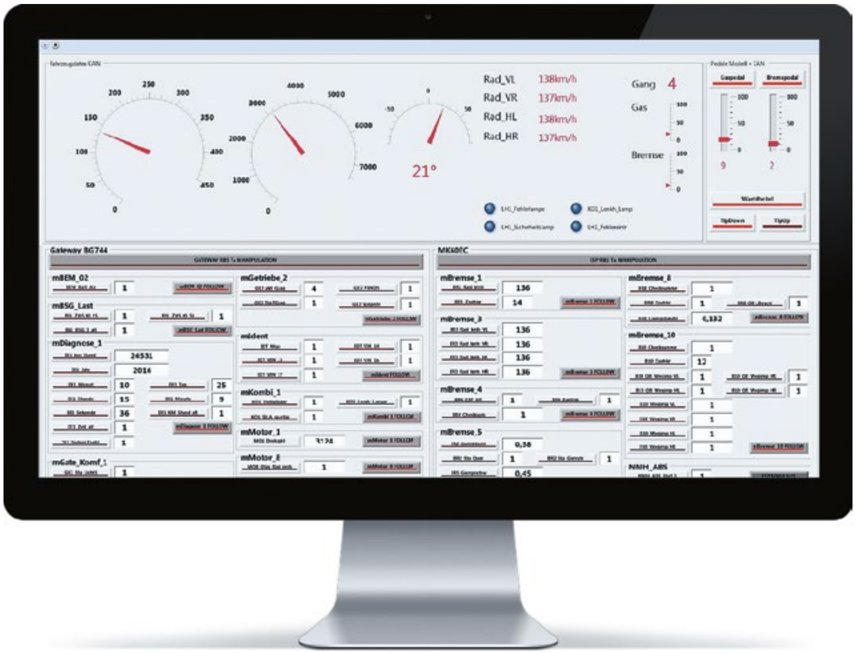
Efficient Testing

Control device development and testing with custom-tailored test benches

____The network of control systems for driving dynamics is becoming ever more expansive and powerful. Particularly in the development of small-scale series production vehicles, and all the more in the high-performance area, engineers face enormous challenges. With automated tests and simulated trials, Porsche Engineering saves both time and costs.

By Holger Dinkelaker and Philipp Eiber

Steering HiL with real-time computer, driver's seat, EPS and E-motor



Simulation environment/control panel

In view of the ever growing performance potential of premium vehicles, the development and testing of the control of driving dynamics-relevant systems is a particular challenge. For starters, they must enable the driver to ensure safe control of the vehicle even at very high speeds. Then comes the extreme divergence between the different driving requirements: from easy-going or dynamic driving on rural roads to high-speed Autobahn driving and even stints on the race track, the customer's expectations must be satisfied.

These functional capabilities place massive demands on control units. Current vehicle concepts, for example, demand active chassis control from redesigned standard components combined with in-house developments tailored to meet the individual requirements of the respective vehicle. This includes active dampers and suspension, stabilization and brake systems, variable aerodynamics and adaptive steering.

Automated tests complement simulated trials

In the development of exclusive small-scale series production vehicles, the factors of time and economy take on particular importance. The earlier in the creation process that control units and their interactions are tested and optimized, the leaner and more efficient the entire development process. Among other tools, Porsche Engineering uses in-house-developed hardware-in-the-loop test benches (HiL test benches) for this purpose. Here the test bench simulates an as-real-as-possible vehicle environment for the vehicle control units and checks the specified control functions as well as the desired system behavior. The HiL tests also allow risk-free fail-safe tests in which component failure, error compensation reactions and misuse are tested. This enables comprehensive assurance of system functionality even under extreme conditions. ›

Customized chassis HiL for systems without driver feedback

In addition, all control devices are verified in terms of their interaction with the rest of the vehicle both in conjunction with the other control devices and in individual tests. Among other things, this testing procedure checks the network interfaces, communication and start-up behavior and signaling of warnings and detected errors. The HiL and lab tests therefore represent an important basis for the development and qualification of the vehicle. In automated tests, thousands of previously defined test steps are conducted in various constellations.

Simulated driving tests below and beyond the limit

In these synthetic tests, system behavior can be simulated, but not in a way that can be experienced by the tester. To enable truly meaningful interpretation of the measured values, an alternative approach is called for. Electric power steering (EPS) is one of the systems through which the driver can directly experience the vehicle's steering behavior and the feedback on the steering wheel.

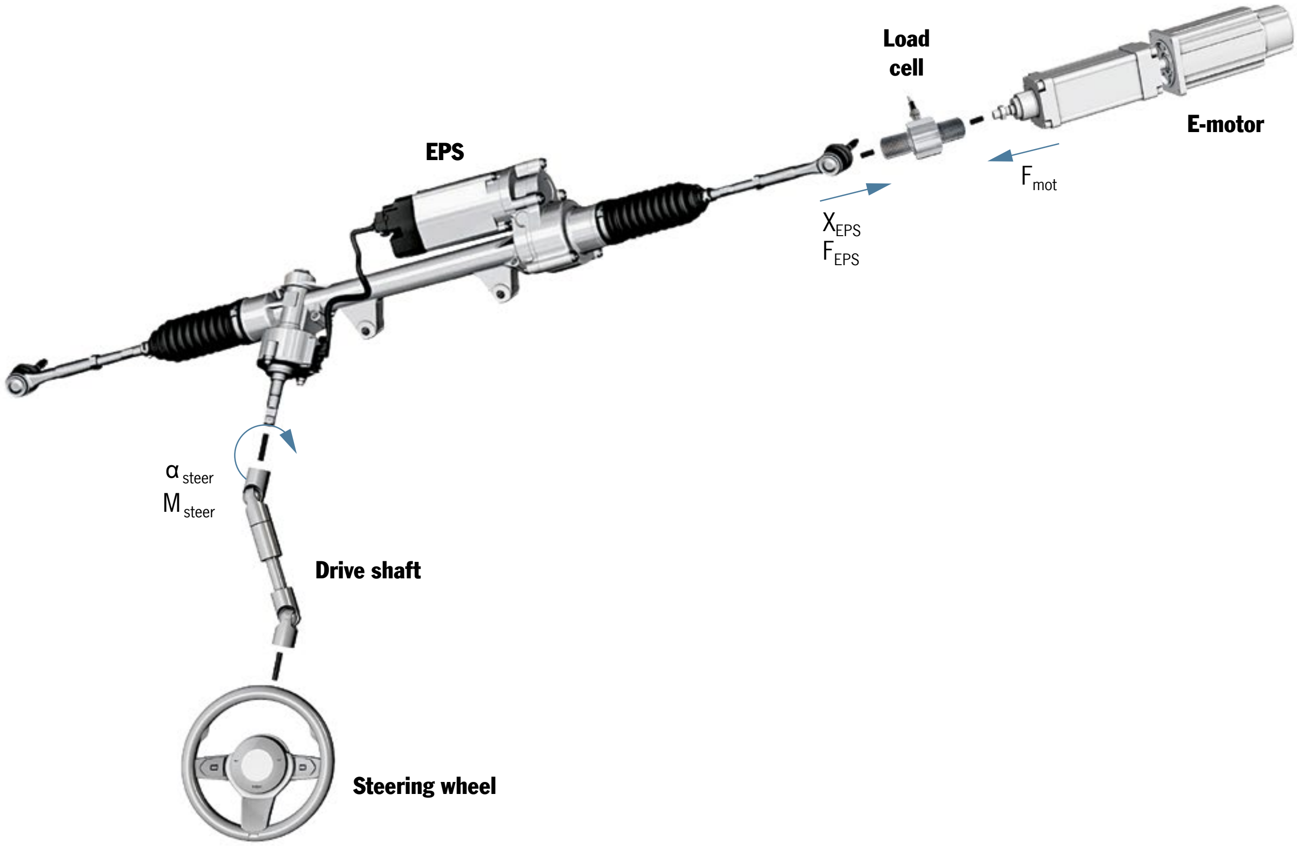
To make it possible to experience the behavior of the EPS and the steering torque feedback, Porsche engineers combined a HiL test bench with a seating buck (see figure on page 22). In a closed-loop simulation, the control unit is subjected to electrically simulated environmental conditions while a servo motor directly applies forces to the mechanical steering and the power pack of the EPS. On a real-time computer, a sophisticated vehicle model simulates the driving situation while a high-performance motor simultaneously applies tie rod forces directly to the steering system.

This concept enables an evaluation of the electric power steering, steering torque, error compensation reactions of the control unit when components fail and the manageability of the situation even at a (simulated) top speed—all under safe conditions. The simulation environment enables the recording and evaluation of all relevant measurement data, which the engineers can then aggregate with their subjective impressions of the steering wheel feedback to form an assessment of the system. The visual simulation of the driving situation supports the tester in the assessment by translating numbers and measured values into an assimilable form.

Advantages of the test bench: safety, economy, availability

With this simulator, any given driving maneuver can be tested, even at top speed, on a virtual, infinitely large dynamic surface, in an absolutely safe environment. If the feedback forces on

Visualization of steering behavior on the HiL (based on TORCS, The Open Racing Car Simulator licensed under the GPL)



Mechanical structure

the steering wheel in extreme cases become too great, a safety switch shuts the HiL off. The procedure enables detailed and improved system tests even in extreme speed and acceleration ranges.

An in-house-developed test bench also yields benefits in terms of availability and economy. In contrast to conventional, standardized HiL test rigs available on the market, the individual design aspect is limited to the required test environment for the steering system and is therefore less expensive. Due to the combination with the seating buck, the test bench also reduces the gap between the purely theoretical software test on the computer and the practical testing in the vehicle. This makes it possible to compensate for the generally low availability of prototypes in the development of extremely small-scale series production vehicles. Moreover, the HiL test bench itself is available at any time irrespective of the time of day or climatic conditions.

With this special testing facility, Porsche engineers offer a solution custom tailored to precise requirements. It enables the development of an electromechanical steering system in a significantly shorter time than is usually required. This makes it possible to evaluate system behavior and correct implementation of specified functions at an early stage and have that information conveyed to the vehicle development team and the suppliers of the steering system. If necessary, errors of all types can be reproduced on the test bench without excessive effort and remedied quickly. The vehicle manufacturer therefore has more development time at its disposal to dedicate to optimizing the system parameters and achieving the desired driving behavior. ■

Technology, Future, Tradition.

____ Dr. Michael Steiner, Member of the Executive Board—research and development—at Porsche AG, and Malte Radmann, General Manager of Porsche Engineering, talking about the future of sports car development, innovative engineering services and the Porsche tradition of working for external customers.

Interview by Frederic Damköhler; photos by Victor Jon Goico

Dr. Steiner, how is Porsche approaching current trends such as autonomous driving and connectivity?

Dr. Michael Steiner Innovations have played a fundamental role at Porsche since the very beginning, and that will remain the case in the future as well. That is the only way for us to keep customers fascinated. Electrification, digitization and connectivity are creating new challenges for the automotive industry. That is why we work continuously on the future: to master these and other challenges.

What do the Porsche solutions for the aforementioned future subjects look like in detail at this point?

Dr. Steiner The new Panamera makes clear how we can mesh groundbreaking technologies with the traditional Porsche genes to engender a new sense of mobility. Through the multiplicity of communication, comfort and assistance systems that are integrated in the Panamera, this vehicle is changing mobility even today. With Porsche InnoDrive, for example, an electronic co-pilot was developed that can be activated if needed to increase driving efficiency. Overall, we're employing a wide spectrum of driver assistance systems to create a new mobility experience while always keeping the human driver in mind at the same time.

Where is the Porsche journey headed?

Dr. Steiner Connectivity and driver assistance systems with a trend towards piloted driving are very exciting for us as well. Not because we dream of a driverless car but because we know that our customers will be stuck in traffic jams in their Porsches as well. We want to ease the experience in such situations. Another convenience function we offer is automated parking. But as soon as the traffic clears or there's a rural road on which the customer wants to take back the reins, we will always enable our customers to get back to enjoying the pleasure of driving a Porsche. Connectivity offers a wealth of possibilities as well: online updates for enhanced functionality, for example, or the linking of the intelligence of the vehicle sensor technology with swarm information. What we can do with that, what could make

Dr. Michael Steiner: "We have a few surprises up our sleeves when it comes to linking the intelligence of the vehicle sensor technology with swarm information."

our vehicles even sportier—we have some good ideas there and will deliver some surprises.

Mr. Radmann, what effects do these trends have on engineering services by Porsche?

Malte Radmann As an engineering services provider, we have to identify trends at an early stage and do our best to stay a step ahead of them so that we can always provide the ideal solutions. Having an eye for industry and market changes is essential. An engineering services provider must be able to act in an exceptionally flexible and agile manner in order to stay competitive. So we've continued to develop our strategy while incorporating the dominant trends and market developments. As we do so, we focus on three strategic business segments that will shape our business in the future: derivative and system development, testing and digitization.

What are you working on in particular?

Radmann In terms of "derivative and system development," we're forging ahead with the traditional themes of vehicle development while augmenting them with current trends in the field of virtual methods. The "testing" area encompasses new methods of virtual testing as well as, naturally, conventional testing of all vehicles, components and concepts developed by the customer. The "digitization" field encompasses topics relating to digital transformation in the vehicle and the vehicle-related environment. With the founding of our subsidiary for digitization in Cluj-Napoca last year, we're making › sure that we keep our finger on the pulse of the times in what's been called Europe's Silicon Valley and can be a driver in the latest developments in this field of activity.

Dr. Steiner Together with Porsche Digital GmbH, which we founded in early 2016, the subsidiary in Cluj will play an important role in the digital transformation in automotive development.

What role will the proving ground in Nardò play in the testing of future vehicle concepts?

Radmann Nardò has a strategic function. The proving ground has become an integral component of the Porsche group while maintaining its role as an important resource for the entire automotive industry. In the future, the focus will be on the further development of Nardò as an excellent test center for digitization and partially and / or fully autonomous driving without losing sight of conventional vehicle testing. But testing means much more to us than just the proving ground in Nardò: Testing and trials start with individual small components and have to be conducted at early stages of development, in particular on the virtual level. In addition to the relevant technical resources—at the Porsche Development Center in Weissach, among other locations—we have experienced employees with the requisite skills and can therefore offer comprehensive hardware- and software-in-the-loop solutions.

The future of vehicle technology often begins on the race track. What is the influence of motor racing on series development at Porsche?

Dr. Steiner In the motor racing milieu, state-of-the-art technologies are developed and tested under extreme conditions. In the process, we gain important insights that flow into series development. The 24 Hours of Le Mans, for example, are an extraordinary endurance test for high-performance lithium-ion batteries and other components. The experience that we gain here is enormously important for the ongoing development of electromobility, to name one example.

Radmann We're particularly proud that we were able to play such an important role in the LMP1 project as part of the overall battery development process for the Porsche 919 Hybrid, from the mechanical structure to complete system control and testing. We very much appreciate the trust that our parent company invested in us in that context.

The external business of engineering services is and will remain firmly anchored in the Porsche brand core.

What role will engineering services for external customers play for Porsche in the future?

Dr. Steiner Porsche and the engineering services have been inextricably linked since the very beginning. The origins of Porsche lie in engineering services. With the founding of his design office in 1931, Ferdinand Porsche strode into professional independence offering development services for vehicle technology. For Porsche, the developers of Porsche Engineering are today and will continue to represent an important internal wellspring of expertise which, drawing on its experience with projects for different industries, frequently brings a differentiated perspective to particular issues and thereby offers valuable "outside-the-box" thinking in development and problem-solving processes.

Radmann At the same time, we continue to pursue the projects for our customers in the global automotive industry with great passion. The external business of engineering services is and will remain firmly anchored in the Porsche brand core.

Dr. Steiner, between 2002 and 2005 you were the chief representative of Porsche Engineering. What experience did you draw from that period?

Dr. Steiner Then, as now, I was particularly impressed by the variety of technical requirements that are brought to Porsche

Malte Radmann: "As an engineering services provider, we have to identify trends at an early stage and do our best to stay a step ahead."

through the customer development projects—be they from the automotive world or other technical fields. These projects are handled by a highly motivated team that quickly adjusts to technical changes and a vast range of different customer requirements. A company must always be sufficiently broad-based and flexible in order to demonstrate expertise precisely where the customer needs support and experience. This flexibility and targeted definition of expertise ensures that we're well-positioned to handle market fluctuations and always have the right solution for customers.

Is there a project from that time that you recall with particular fondness?

Dr. Steiner During my time with Porsche Engineering, I was able to gain my first significant exposure to China. Projects for the Chinese market with very particular requirements and their international and intercultural challenges were especially exciting for me. I think back on that time very fondly. ■

Michael Steiner

Dr. Michael Steiner (52) studied mechanical engineering at the Technical University of Munich. After several years in management positions at Daimler AG, Michael Steiner came to Porsche in 2002. Here, he took over the management of innovation and concepts, bore responsibility for the Panamera series and was Vice President Complete Vehicle Engineering/Quality Management. Between 2002 and 2005, he was also Chief Representative of engineering services by Porsche. In 2016, Michael Steiner was appointed member of the Executive Board—Research and Development—of Dr. Ing. h.c. F. Porsche AG and chair of the shareholders' committee of Porsche Engineering.

Malte Radmann

After his vocational training, Malte Radmann (63) was in senior sales positions for Daimler-Benz Aerospace Dornier and for Zung Fu, a Mercedes-Benz retailer in Hong Kong and China. In 1996, Malte Radmann came to Porsche as Head of Sales for the Porsche customer development for the markets Asia/Europe/USA. In 2005 he became Deputy Chief Representative of Porsche Engineering Group GmbH/Porsche Engineering Services GmbH and in 2009 he was appointed chairman of the management.

____ In no other type of vehicle is the connection between the driver and vehicle so intense as in a sports car. With the second-generation virtual driver's seat, Porsche has a highly modern development tool to enhance this connection even further and transfer the insights it yields to the entire Porsche product lineup. The simulator enables highly precise tests of the interaction between the driver and the technology in practically every stage of the creation of new vehicles, systems and functions. The application spectrum ranges from the display of virtual reality within and outside of the vehicle to tests with complete vehicles.

Virtual Driver's Seat

Simulation optimizes the ongoing enhancement of ergonomics and user-friendliness

By Rainer Bernhard and Ingo Krems; photos by Victor Jon Goico

Driving simulations in the vehicle development process are the early interface between the human and the machine. They enable "test drives" with virtual vehicles in any digitized environment. Critical situations can be simulated in a risk-free and reproducible manner. And they significantly shorten development times: real components can be swapped in a flash, and virtual elements can be changed at the push of a button.

Porsche put the first virtual driver's seat for the examination of the interaction between the human and the machine into operation in 2007. The second generation of this development tool was designed based on experiences gathered with the first generation model. Some of the concepts from the first system were adopted in the second generation, while others were further developed or completely redesigned from the ground up. The new virtual driver's seat is distinguished in particular by its variability and broad spectrum of application. On the platform of a hexapod, any given payload weighing up to 1,500 kg can be mounted—from simple seats to complex seating bucks and even entire vehicles in which the smaller motion pulses are directed through the front axle. The development engineers distinguish between three basic functions:

> *Throne* is the name of the mode for pure visualization in which the only hardware is the driver's seat.

> *Seating buck* is the name of the configuration for interactive driving simulations with complete motion capability for the driver's seat.

> The *entire vehicle* option enables the incorporation of a real vehicle.

(see figure at top of page 32.) ›


cruden
cruden

Throne

This is the mode for pure visualization in which the only hardware is the driver's seat. In this case the motion capabilities of the hexapod are not used; instead, the six-sided projection capability including floor and ceiling can be used for a 360° visualization.

Seating buck

This basic function is the configuration for interactive driving simulations with complete motion capability for the driver's seat. Among other things, this makes it possible to test ergonomically distinct vehicle conditions. In the process, additional force-feedback components such as steering wheels and pedals are used.

Entire vehicle

Particularly extensive tests are enabled by the "entire vehicle" basic function, which incorporates real vehicles into the simulation. The movement of the front wheels on the motion platform in a vertical direction, for example, makes it possible to simulate a jolt of the brakes.

Hexapod with six degrees of freedom simulates accelerations

A core component of the virtual driver's seat is the motion system. It consists of six independently controllable electric actuators and a platform for payloads. This hexapod with six degrees of freedom represents the accelerations that take place in the vehicle. It is installed in a pit in the simulator room and has a motion range of ±40 centimeters in longitudinal, lateral and vertical directions and ±30 degrees of rotation (pitch, roll and yaw) respectively.

A specially developed access system to the platform ensures that payloads can be mounted easily without the aid of a crane and that getting into the seating buck does not require stairs or a ladder. In addition to easy accessibility, safety plays a central role in the simulator concept. A fence, surveillance camera and numerous sensors—on the belt buckle and doors—ensure safe operation.

The simulator design makes it possible to replicate longitudinal and lateral acceleration, body roll (for example while driving on inclines or at a transverse angle to the road) and oscillations of the types that can occur on uneven surfaces. The longitudinal and lateral dynamics of a vehicle are represented in the virtual driver's seat in two different ways.

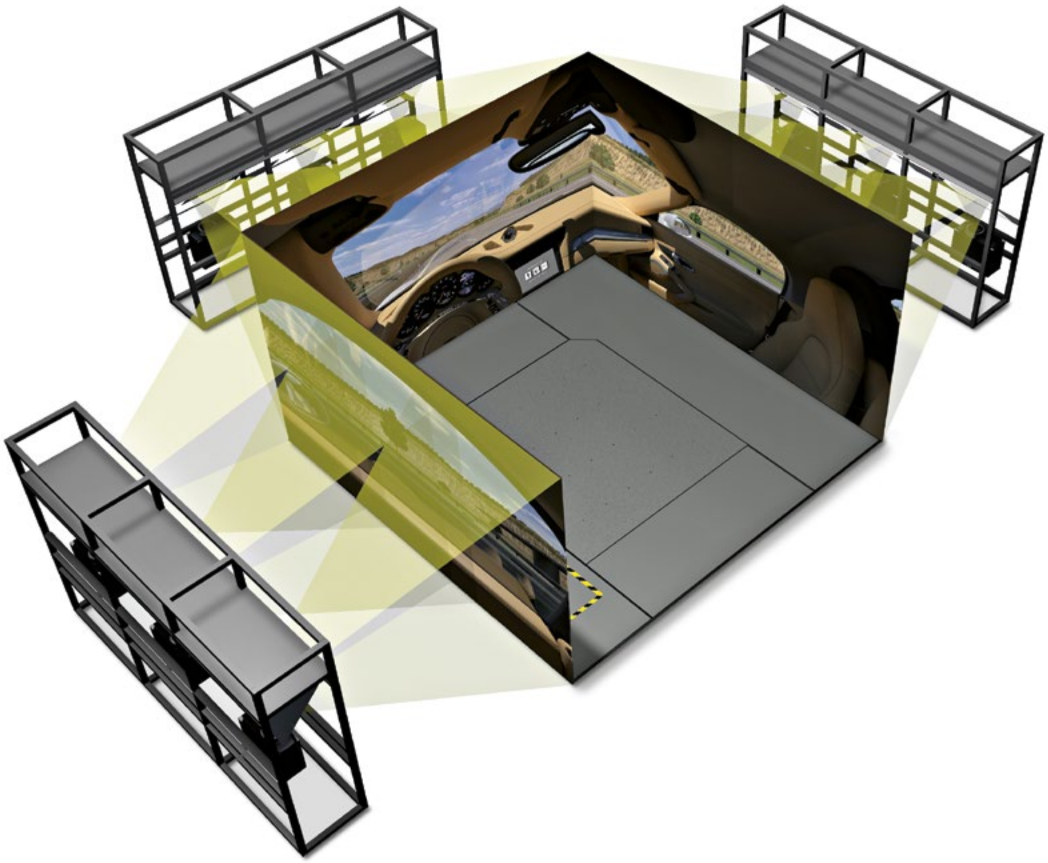
> *Translation* of the platform generates a realistic driving experience. Due to the limited travel paths, however, the accelerations can only be simulated for relatively short periods of time.

> *Rotation* of the platform gives the driver the impression of a long-lasting acceleration through a slow tilt of the platform. The function makes use of human physiology: The human body perceives rapid rotations as, indeed, rapid rotations, but slow ones as a change in the acceleration acting on the body.

The simultaneous use of both types of motion creates as realistic a driving situation as possible. The represented environment adapts to the motions.

The motion of the virtual vehicle is determined on the basis of the real-time-capable calculation models devised and provided by the respective development departments. In addition

For a detailed display of the computer-generated images on the projection surface, three high-resolution stereo projectors are used per side. In addition, there are another six projectors for the ceiling, floor and rear projection.



to the calculation of the position of the vehicle in the virtual environment, the simulator also determines accelerations, roll movements and steering forces. The input from the driver, such as the steering angle and pedal positions, serves as an electronic input signal into the driving dynamics calculations. In a process known as "motion cueing," the calculated accelerations in the vehicle are transmitted to the motion of the hexapod.

The images are projected from behind onto the screens via high-precision optical mirrors. This avoids objects or people in the interior casting shadows.

Three-dimensional visualization via rear-projection screens

The representation of the environment and the vehicle components that are not physically present is done through projection onto up to six sides of a cuboid. Up to 15 projectors generate the graphics on specially coated rear-projection screens. The cuboid has edge lengths of 4.2 × 4.2 × 2.6 meters. This arrangement is known as a cave automatic virtual environment (CAVE).

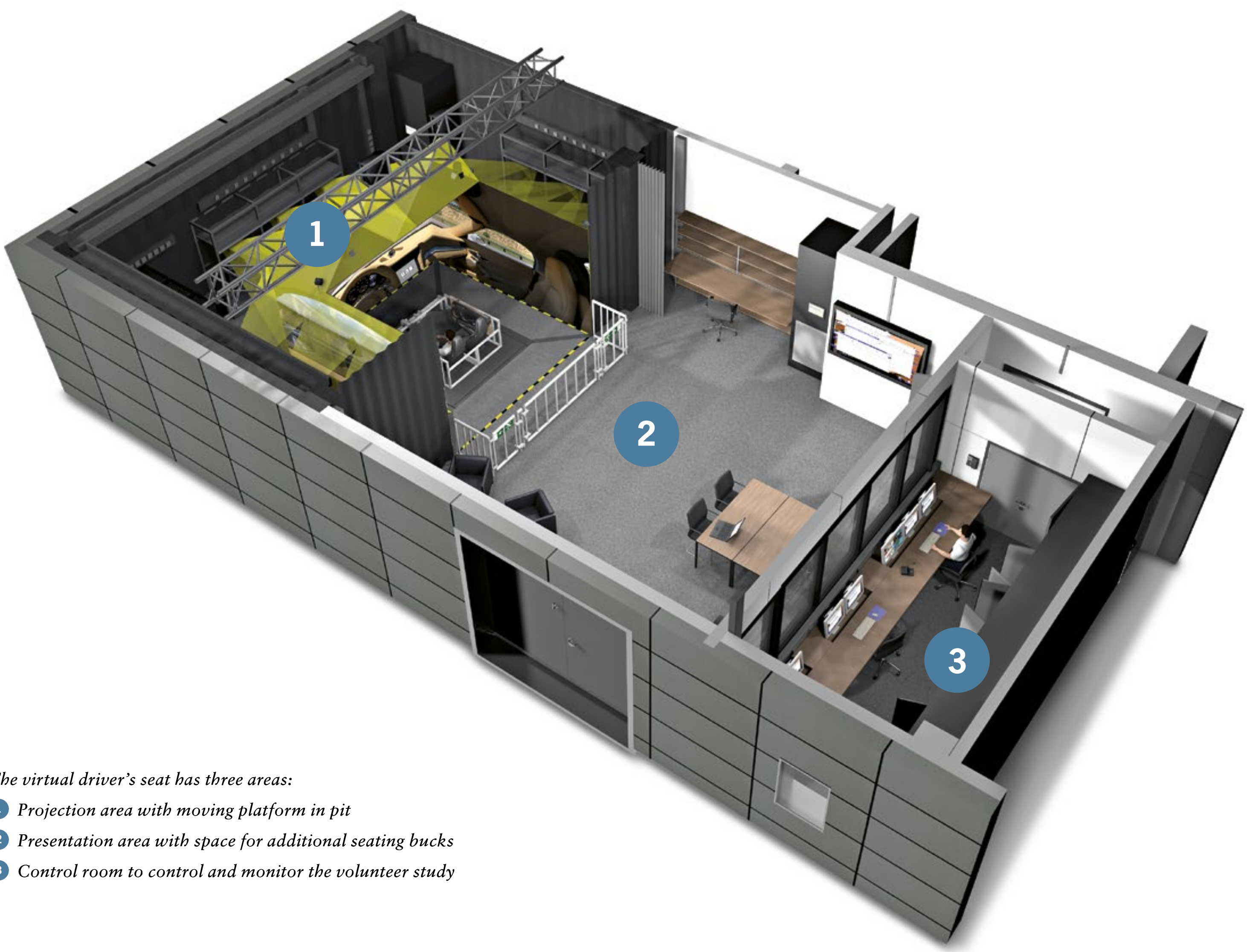
The projectors generate approximately 3,840 × 2,160 pixels per side, which corresponds roughly to the 4K resolution used in digital cinemas today. Through an active stereo projection method, three-dimensional graphics can be generated that the observer perceives as spatial images through special glasses. ›

An optical tracking system makes it possible to measure the precise position of the driver's head within the CAVE. This information is required by the graphics PCs to represent the physically correct driver perspective. The effect of this is that the driver, depending on their head position, can either see a pedestrian or not because the pedestrian is blocked by the A-pillar, for example. For realistic immersion into this virtual reality, the simulation of sound is also essential. The simulator simulates not only the sounds of the driver's vehicle, but also those of the environment, such as cars driving past.

All systems of the driving simulator are real-time-capable and communicate with each other at very high data rates. The input of a new steering angle, for example, is transmitted via a data bus to the driving dynamics simulation, which calculates the new position of the vehicle in the virtual environment and then sends the coordinates through the network to the graphics PCs, where the 3D visualization is created. This all happens at clock rates from 60 Hz (visualization) to 1,000 Hz (driving dynamics calculation).

Test candidates: rear-view mirrors, luggage compartments, assistance systems

Porsche uses the virtual driver's seat for new vehicle concepts such as the fully electric Mission E as well as for the ongoing development of existing model lines. Among other things, the simulations focus on the two primary points of emphasis: ergonomics and the human-machine interaction (HMI). Ergonomics testing involves elements such as visual examinations of rear-view mirrors, shape and position of the vehicle



The virtual driver's seat has three areas:

1. *Projection area with moving platform in pit*
2. *Presentation area with space for additional seating bucks*
3. *Control room to control and monitor the volunteer study*

Behind the wheel of a virtual vehicle: The tracked 3D glasses ensure that the driver can perceive the physically correct spatial perspective. Just as when driving "for real", the driver is wearing his seat belt for safety reasons.

windows, and camera systems. It also includes testing of active safety functions and vehicle components such as luggage compartment variants. In the HMI area, testing focuses on driver assistance systems and the design of information transmissions—with the aim of arranging the components in such a way that the driver can rapidly receive information and react with commensurate quickness. In order to use real vehicle components as part of the simulation, it is necessary to address the control units—for instance an instrument cluster or button—via CAN bus and ensure functionality through remaining bus simulation.

One elementary component of the simulator is the recording and storage of the relevant data from a virtual drive. The key information pertains not only to the behavior of the simulated vehicle, but indeed the physiological data for the driver in relation to their environment as well. This makes it possible to examine and evaluate influences and reciprocal effects, for example through the position of the simulated vehicles in the vicinity and driver reactions such as eye position or head-turn angle.

Simulator: an effective cross-specialization development tool

The test results from the simulator make it possible to assess the function and effects of the vehicle and components implemented within it at a very early stage in the vehicle development process. The simulation environment is particularly ideal for analyzing systems in which the human interacts with the vehicle. Moreover, Porsche also uses the virtual driver's seat as a platform on which engineers from the various disciplines can test, discuss and present issues in an interdisciplinary context and make decisions on that basis.

The advantages manifest themselves directly in the development process: the results determined in the upstream virtual development cycles with the virtual driver's seat improve the quality of the prototype vehicles produced later in the process and make it possible to make high-impact decisions at an early stage. The virtual driver's seat therefore leads to an overall reduction in development times and more effective use of real testing components. ■

____Formula Student Electric is regarded as a proving ground for the engineers of future electromobility and is, at the same time, a pool of highly talented engineers. Porsche Engineering has been supporting the GreenTeam from the University of Stuttgart in the development of its electric race cars since the team's founding in 2009. A collaboration with two winners: The students benefit in terms of practical knowledge, and the company benefits from having skilled new talent coming up through the ranks.

GREEN TEAM with Porsche Genes

By Peter Weidenhammer; photos by Felix Bezler and Jörg Eberl

The record speaks for itself: third place this year on the Hockenheimring; continuously in the top six of the world rankings since 2009, including the top ranking in the first year; and an impressive acceleration record in 2015. Every year the GreenTeam from the University of Stuttgart works with unflagging determination to build a race car to put to the test in a series of competitions. Once again this year, the up-and-coming engineers of the GreenTeam are waging a successful campaign against the international competition in the Formula Student Electric championship with their self-developed, designed and built electric vehicle.

Formula Student

Formula Student is an international design competition for students with racing events held in locations such as Barcelona, Melbourne and Detroit. For the teams, the objective is to design and build a race car and compete against other teams from around the world. The winner, in the end, is not necessarily the fastest car, but the team with the best overall package consisting of the design, racing performance, financial planning and sales arguments.

There are two classes in which the students can compete: The Formula Student Combustion (FSC) is the class for ›

The test design event: Students on the GreenTeam exchange ideas with engineers from Porsche Engineering.

combustion engines, and the Formula Student Electric (FSE) is for vehicles with electric motors, which are tested for example on the Hockenheimring. Due to the increasing popularity of the competition, prospective entrants must in many cases go through an application phase before they can enter the main competition with teams from other top universities such as Zurich, Delft and Karlsruhe. Only after a strict inspection to ensure that the car complies with the international Formula Student rules are the cars approved for race action.

In two discipline types, a total of 1,000 points are on the line. In the static disciplines, the cars' costs, mock marketing and engineering performance are evaluated by a jury of experts. In the dynamic disciplines, the cars are submitted to practical tests on various tracks—here the times and energy efficiency are decisive. As the individual categories are weighted differently, the right tactics can be key to victory.

The collaboration

Porsche Engineering is among the main sponsors of the GreenTeam and provides not only financial support, but also material support and the provision of test benches, know-how and advisory services in the vehicle development process. "The collaboration with Porsche Engineering helps us with the ongoing of our high-voltage components. Without the valuable test bench time, we wouldn't be able to push the envelope the way we do," says Alexander Stemmler (25), student of aerospace technology and responsible for aerodynamics and thermodynamics on the GreenTeam, with evident satisfaction.

The long-standing collaboration between students and experts in the engineering services areas is advantageous for both sides. Young prospects come into contact with the company at an early stage and can establish valuable contacts for their later career development. They gain practical experience and learn how to deal with business partners. The companies, too, benefit from direct contact with the young engineering prospects and the associated link to the university and instructors.

The E0711-7 race car

In the current E0711-7 race car, the GreenTeam opted for controlled all-wheel drive with four AC motors installed near the wheels. Each of the electric motors generates up to 35 kilowatts of power and a maximum torque of 36 newton-meters. The energy is provided by a 6.8 kWh high-voltage battery. To handle the heat generation during high dynamic loads, the accumulator and inverter have an oil-based cooling system. The open-wheel car reaches a top speed of 123 km/h. Most impressive of all is its acceleration: It takes just about 2 seconds for the speedster to accelerate from 0 to 100 km/h. The system electronics required to achieve the feat were also developed by the students.

Sophisticated race car technology is also present in the chassis and aerodynamics. For example, the engineering prospects developed a space-saving and lightweight monospring system with one transverse spring per axle. The generation of downforce and thus high lateral acceleration in competition is achieved by means of a comprehensive aerodynamics package, which enables the race car to achieve a lift coefficient of $c_A = -2.8$.

From the concept to the race track

The creation process of a GreenTeam race car stretches over a roughly eight-month period and encompasses the four phases of concept, design, production and assembly. In September of the respective year, the overall concept is hashed on the basis of insights from the last competition and knowledge transfer from the previous year's team. The focal points at this stage are the especially important vehicle development topics such as battery cooling, high-voltage system and aerodynamics. Collaboration with Porsche Engineering begins already at this early stage. The team benefits from early professional feedback and tips for the implementation of the electric race car.

In the *concept phase*, both the targeted time objectives for the vehicle and the sales strategy to be presented to the Formula Student jury are discussed and defined in detail. At a later stage, the team must explain its vehicle concept, costs and other development details to the Formula Student jury panel. In the following work step, *design*, which extends from October to mid-December, the future race car is designed on the computer using CAD technology. After that comes the *production* phase in which the electric vehicle is constructed in collaboration with manufacturing partners. Over a lengthy period within this phase, components of the car are subjected to loads and coordinated with each in successive testing operations. The final step in the process is the *assembly* of all components to complete the car.

With the rollout at the end of April—the first official presentation of the vehicle to sponsors, supporters, friends and family—the students reach one of their most important intermediate goals. "We learn a lot from the experienced Porsche engineers and are then really excited to show them our own developments," says Alexander Stemmler. As one of the main sponsors, Porsche Engineering holds a "test design event" in preparation for the presentation of the vehicle to the Formula Student jurors. The race car is presented in a similar manner as in the later contest and discussed and evaluated together with the Porsche engineers. This enables students to acclimate themselves to critical questioning, and they receive an independent estimation of their race car as well as final tips for the competition. Finally, in July and August the electric race cars must ultimately demonstrate how successfully they measure up against the competition from the international university teams in terms of concept and tactics. ■

The GreenTeam

The GreenTeam of the University of Stuttgart was formed in 2009 as a non-profit organization and emerged from the Uni Stuttgart e.V. racing team, which develops race cars with combustion engines. The GreenTeam, by contrast, is aiming to occupy one of the top places in the world rankings with a purely electrically powered vehicle in the Formula Student Electric category of the yearly Formula Student competition.

This year, a team of 45 University of Stuttgart bachelor's and master's students from the fields of vehicle and engine technology, mechanical engineering, electromobility and environmental protection technology developed an overall concept for an electrically powered race car. Participation in the project, for which some students actually postpone their studies for two semesters, is available to students in their fourth semester or later. For nearly a year, the prospective engineers spend some 60 hours a week tinkering with their electric vehicle—an undertaking that involves comprehensive engagement with topics such as control technology, power electronics and driving dynamics. In addition to responsible handling of the technology, the project also depends on aspects such as time management, teamwork and economic viability.

In recent years, the GreenTeam has scored some successes at the international Formula Student events: In 2015, for example, Stuttgart students set an acceleration record with the E0711-5. With a 0 to 100 km/h time of 1.779 seconds, the electric vehicle was entered in the Guinness Book of World Records.

Sustainability Meets Performance

The Porsche Panamera 4 E-Hybrid

PANAMERA 4 E-HYBRID
Fuel consumption (combined): 2.5 l/100 km
Electricity consumption (combined): 15.9 kWh/100 km
CO_2 emissions (combined): 56 g/km
Efficiency class: A+

____At Porsche, the term "hybrid" has always been synonymous with not only sustainable mobility, but performance too—a fact proven not least by the victory of the 919 Hybrid in the 24 Hours of Le Mans race in 2015 and 2016. This philosophy is now also defining the Panamera 4 E-Hybrid.

The new Porsche Panamera 4 E-Hybrid offers impressive system power of 340 kW (462 hp) and consumption of only 2.5 liters per 100 km in the New European Driving Cycle for plug-in hybrid models. It always starts in purely electric mode. The Panamera 4 E-Hybrid can reach a range of 50 kilometers and a speed of max. 140 km/h as a zero-emission vehicle.

And yet this Panamera too is a sportscar among the luxury saloons: The all-wheel Porsche achieves a top speed of 278 km/h and delivers a system torque of 700 Nm from stationary without hesitation. The four-door hybrid sports car breaks the 100 km/h barrier in just 4.6 seconds. The torque is transferred to all four wheels and the standard three-chamber air suspension ensures an optimum balance between comfort and dynamism at all times.

New hybrid strategy based on the Porsche 918 Spyder

The superlative performance is no accident: The new Panamera 4 E-Hybrid features a hybrid strategy never before seen in this segment—a strategy based on the 918 Spyder. The 652 kW (887 hp) 918 Spyder is the fastest series-produced vehicle ever to circumnavigate the Nürburgring Nordschleife. Its record lap time of 6:57 minutes can in part be attributed to the additional power provided by two electric motors.

As with the 918 Spyder, the power of the Panamera electric motor—100 kW (136 hp) and 400 Nm torque—is made available as soon as the driver touches the accelerator pedal. On the predecessor model, the pedal needed to be pressed at least 80 per cent of the way down to unleash the additional power of the electric drive. Now, the electric motor and petrol engine interact in perfect harmony from the very outset.

Like with the 918 Spyder, the electric motor is available to deliver additional power at all times. This, together with the performance characteristics of the new 2.9-liter V6 biturbo engine (243 kW/330 hp/450 Nm), generates an impressive boost scenario based on electric motor and turbochargers. ›

In the Panamera 4 E-Hybrid, the electrical energy is also used to increase the car's top speed. At Porsche, this new type of "E-Performance"—more power, more driving fun, lower fuel consumption—is seen as the performance kit of the future.

New hybrid module and fast-shifting eight-speed PDK

Together with the V6 petrol engine decoupler, the electric motor heralds the new generation of the Porsche hybrid module. In contrast to the electro-hydraulic system of the predecessor model, the decoupler on the new Panamera is actuated electromechanically by an electric clutch actuator (ECA), resulting in even shorter response times. As on the other second-generation Panamera models, a new, extremely fast and efficient-shifting Porsche eight-speed Doppelkupplung (PDK) transmission is used to transmit the power to the all-wheel drive. This transmission replaces the eight-speed automatic torque converter transmission on the predecessor model.

The electric motor is supplied with power via a liquid-cooled lithium-ion battery. And despite the fact that the energy content of the battery (which is integrated under the luggage compartment floor) has been increased from 9.4 to 14.1 kWh, its weight has remained the same.

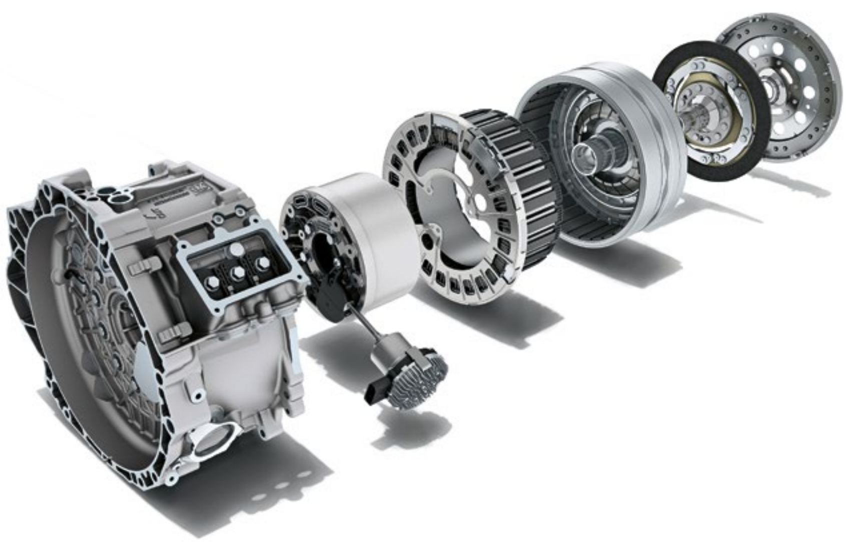
The high-voltage battery takes just 5.8 hours to fully charge via a 230 V, 10 A connection. If the driver chooses to use the optional 7.2 kW on-board charger and a 230 V, 32 A connection instead of the standard 3.6 kW charger on the Panamera, the battery fully charges in just 3.6 hours. The charging process can also be started using a timer via Porsche

Instrument cluster with power meter and hybrid-specific screens

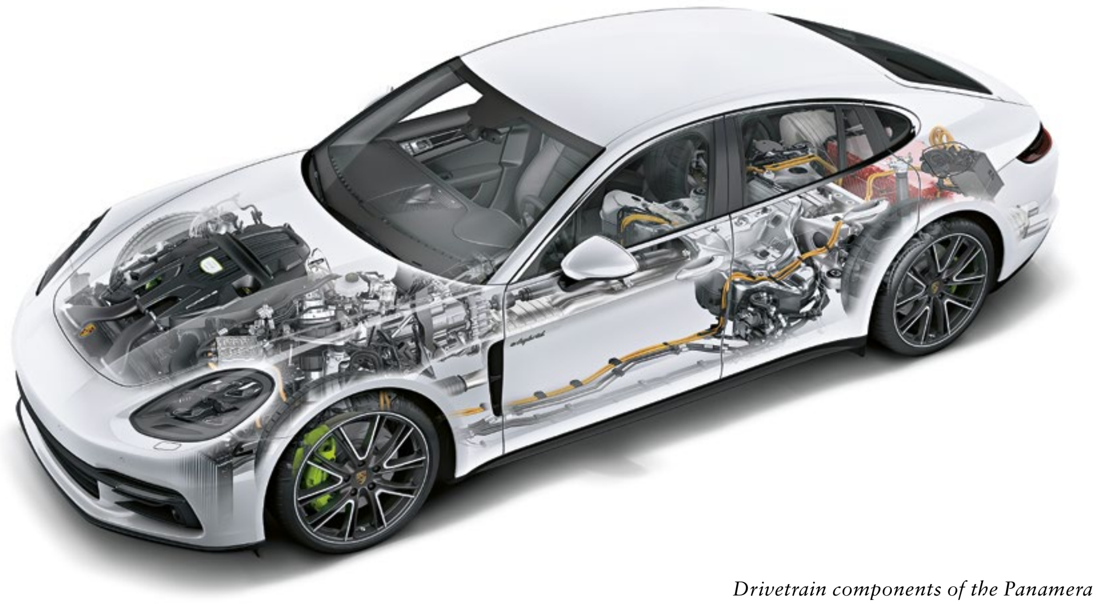
Communication Management (PCM) or the Porsche Car Connect app (for smartphones and Apple Watch). Moreover, the Panamera 4 E-Hybrid is fitted as standard with auxiliary air conditioning to cool or heat the passenger compartment during charging.

Porsche Advanced Cockpit with hybrid-specific displays

One highlight of the second-generation Panamera is the newly designed display and control concept in the form of the standard Porsche Advanced Cockpit with touch-sensitive panels and individually configurable displays. Two seven-inch screens either side of the analog rev counter form the interactive cockpit, and, in contrast to the other versions in the



The hybrid module of the Panamera 4 E-Hybrid



Drivetrain components of the Panamera 4 E-Hybrid

model line, the Panamera 4 E-Hybrid features a power meter tailored to hybrid operation.

The intuitive operating principle of the hybrid-specific displays is similar to that used in the Porsche 918 Spyder super sportscar. The power meter provides data such as the amount of electrical energy currently being used as well as that recovered through recuperation.

A 12.3-inch touchscreen functions as a central PCM control and display unit. The driver can access various items of hybrid-specific information both here on the dash and in the instrument cluster. The boost assistant and hybrid assistant are both practical and informative. The boost assistant display shows the energy available for boosting, while the hybrid assistant provides various visual signals for regulating the electrical drive power.

Ultimate efficiency in "Hybrid Auto" mode

The Sport Chrono Package including the mode switch integrated into the steering wheel forms part of the standard equipment on the Panamera 4 E-Hybrid. The mode switch and Porsche Communication Management are used to activate the various driving modes. These modes include the familiar "Sport" and "Sport Plus" modes from the other Panamera models equipped with the Sport Chrono Package. The hybrid-specific modes are "E-Power," "Hybrid Auto," "E-Hold" and "E-Charge."

The Panamera 4 E-Hybrid always starts in the purely electric "E-Power" mode. The "Hybrid Auto" mode is a completely new development. When this mode is selected, the Panamera changes and combines the drive sources automatically for ultimate efficiency.

The "E-Hold" mode allows drivers to consciously conserve the current state of charge to enable them to switch to electric and therefore zero-emissions mode in an environmental zone at their destination, for example. In "E-Charge" mode, the battery is charged by the V6 engine; to achieve this, the petrol engine generates a higher level of power than is actually needed for driving.

The highest level of drive performance is made available in the "Sport" and "Sport Plus" modes. The V6 biturbo engine is active continuously in these modes. In "Sport" mode, the battery charge is always maintained at a minimum level to ensure there are sufficient e-boost reserve capacities when needed. "Sport Plus" mode is all about maximum performance and allows the Panamera to reach its top speed of 278 km/h. This mode also recharges the battery as quickly as possible with the help of the V6 biturbo engine. ■

Numeric Models for Simpler Application

Faster and more precise calibration of engine control functions

____The requirements in terms of harmonizing disparate engine characteristics are ever more demanding. Power and efficiency, dynamic response and exhaust emission quality are just four factors that need to be coordinated. To meet those requirements, engine functions and the associated calibration of the engine control system are increasingly complex. This applies in particular to the two fundamental functionalities of engine control: the air charge model and the torque model. Without the use of powerful application tools, their exact calibration is no longer feasible. Porsche Engineering has developed an alternative method employing a model-based application.

By Matteo Skull

The charge and torque models give the engine control unit (ECU) the ability to calculate with great precision the current cylinder air charge and the resulting torque on the crankshaft in view of the operating conditions. As both model output values are further processed by virtually all other functions of the ECU, their impact on engine behavior, such as drivability and emissions, is very significant. The quality demands in terms of the precision of their calibration are accordingly high. In the ECU, these functions are derived from physical and thermodynamic models and implemented as complex algorithms.

One of the great challenges here is that the characteristic curves and control maps have to be calibrated very precisely although their outputs do not correspond to any directly measurable physical and thermodynamic values. Due to the complex interactions between the calculated values of the engine control unit and the complexity of calculation models, it has now become impossible to parameterize the charge and torque model—i.e. directly adjust the maps—during ongoing operations on the engine test bench. The basic calibration must therefore be conducted using special tools that enable correct calibration of maps using measurement data. The significance and use of such tools has risen enormously and their development is a core competence in the field of engine calibration.

Implementation of physical models in the ECU using the charge model as an example

Implementation of the charge and torque model in the ECU is done through the implementation of equations derived from the laws of thermodynamics and physics. The charge model that calculates the quantity of fresh air in the cylinder is based on the ideal gas equation and solves it according to the gaseous mass, i.e. the air. To solve the equation, however, it is necessary to know various temperatures and pressures. As these cannot be measured in a series vehicle, they must be modeled by the ECU. To create the model, during development the engine is equipped with elaborate measurement technology and tested under specific operating conditions on the engine test bench until a sufficient number of measurements is available for the calibration of the models.

Implementation of the ideal gas equation in the engine control unit is done in the form of control loops that logically link the tables and characteristic maps. The maps are addressed with input variables, such as the engine speed and the position of the intake and exhaust valves, that unambiguously describe and impact the engine operating point.

Conventional method: numerous iteration loops

The conventional approach to calibrating the maps is based on regarding their output variables as unknowns and thus setting up an equation system that corresponds to the physical model. Using calculation programs and solvers such as the method of least squares, solutions can then be determined for the unknown variables and thus the map outputs.

Though this conventional approach does enable high calibration precision, it does come with a number of drawbacks: For the equation system to be mathematically solvable, there have to be as many equations as unknowns, which requires an accordingly high number of measurements. Another drawback is that the values are calculated per operating point and no useful context of the solution values across all operating points is established. This can result in solution values that strongly deviate from each other from operating point to operating point, which leads to discontinuous map progressions that do not correctly depict the physical relationships between the variables.

Physical basis of the charge model

Ideal gas equation:

$$m = PV/RT$$

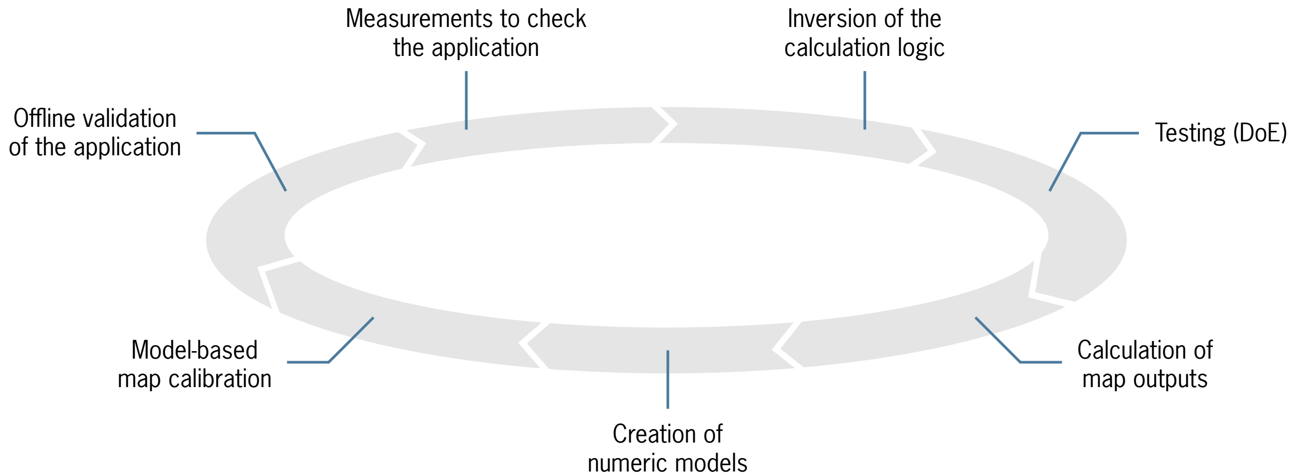
Ideal gas equation applied to the gas cycle:

$$\Delta m = m_{in} - m_{out} = P_{in} V_{in} / R T_{in} - P_{out} V_{out} / R T_{out}$$

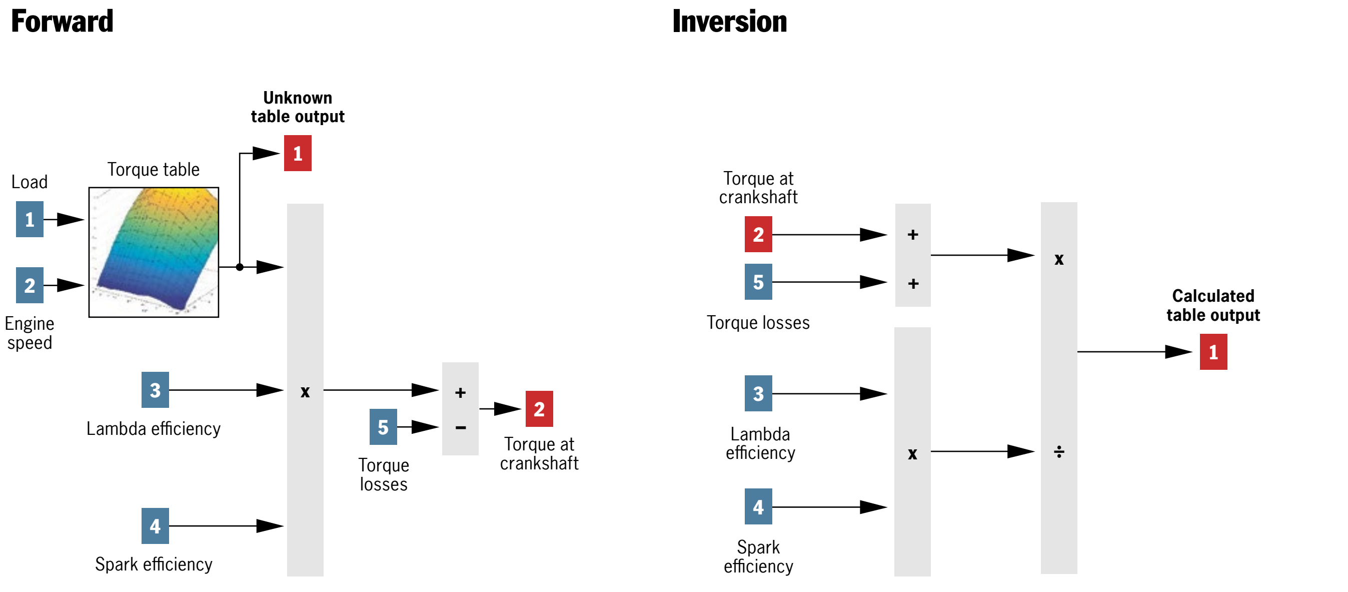
For the calibration of the gas cycle model, calibration of the following model is necessary:

T_{in} : Combustion chamber temperature model
T_{out}: Exhaust gas temperature model
P_{out}: Exhaust backpressure model

Under dynamic and transient conditions, such discontinuous map progressions can substantially compromise engine behavior. It is therefore frequently necessary to smooth the maps later. What that means, however, is that the relationship to the physics and the original measured data becomes less precise. To avoid these issues while simultaneously improving the quality of the calibration and significantly reducing the number of measurements, Porsche Engineering developed an alternative method based on model-based calibration (see figure below). ›



Inversion of the calculation logic and creation of numeric models



Alternative method based on inversion of the calculation logic and numeric models

Alternative: inversion of the calculation logic and creation of numeric models

The alternative model is based on two essential steps: inversion of the calculation logic of the functions to be parameterized and the creation of numeric models (see figure above).

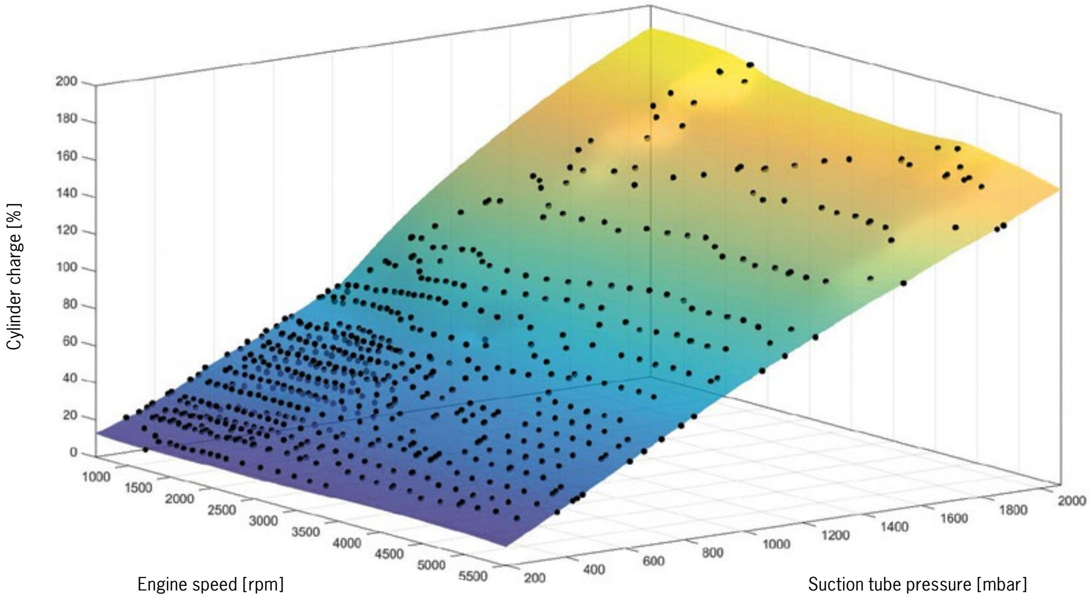
As described earlier, the maps are the building blocks of a function whose output values are, in practice, generally not directly measurable and whose output does not correspond to a concrete, measurable, physical variable. The outcome and inputs of a complete function, such as exhaust-gas temperature or exhaust backpressure in the respective model, however, do correspond to concrete physical variables that can be measured precisely on the engine test bench.

By inverting the logical path of a complete function whose outcome corresponds to a measurable physical variable, it is possible to derive the precise value of the map output for each executed operating point. As soon as the map outputs for all operating points are known, numerical models are created that calculate the relationships between the input and output values of the maps. Using these models, the respective maps are then calibrated. Before approving the calibration data, the entire calculation chain of the charge and torque model is tested in a simulation and optimized as necessary. Finally, measurements on the engine test bench verify the calibration.

Model-based calibration with major advantages

One advantage of creating a numeric model prior to the actual calibration of the map is that the calibration engineer can depict the relationships between the inputs and outputs of a map in a graphic illustration. This step makes it possible to assess the progression trend of the map from a thermodynamic standpoint. This in turn makes it possible to critically examine any peculiarities in the model progression and, if necessary, adjust the grid points of the map or run additional measuring points. Another significant advantage is the ability to precisely calculate values for any map grid point using the numeric model. The represented numeric model (see figure at the top of page 47) shows whether the modeled torque behaves as expected across loads and engine speeds and whether measurements were taken for a sufficient number of points to precisely and usefully parameterize the map.

The calibration of the maps and characteristics strongly depends on the precision of the models, for which, in turn, the quality and distribution of the measurement data is decisive. For this reason, model-based calibration is incorporated as early as the testing planning phase as the training data for model creation is determined in the context of grid measurements and parameter variations. The primary objective is to define the measurement range and the minimum number of measurements required for a good model. If there are ranges



Calculation of map values using numeric values

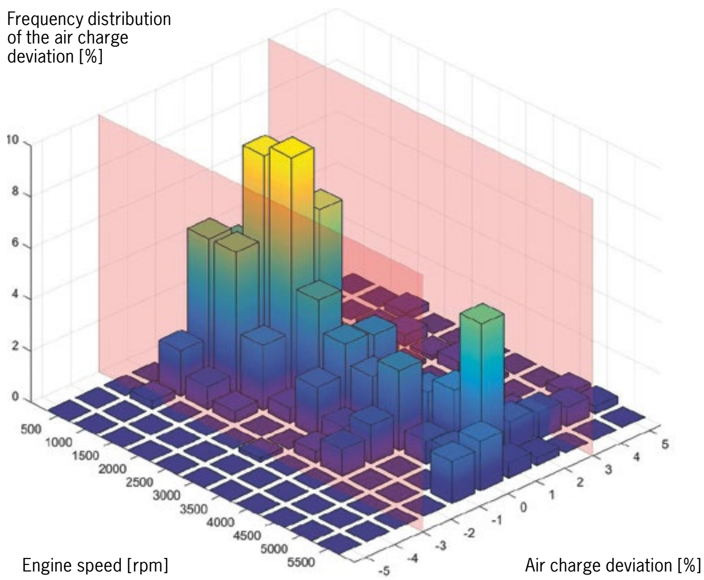
that have a disproportionately large amount of data compared to other ranges, those ranges are given greater weight and the models become more precise in those places. In order to determine a suitable test plan, DoE (Design of Experiment) plans are created based on experience and statistical test planning.

Model selection and evaluation

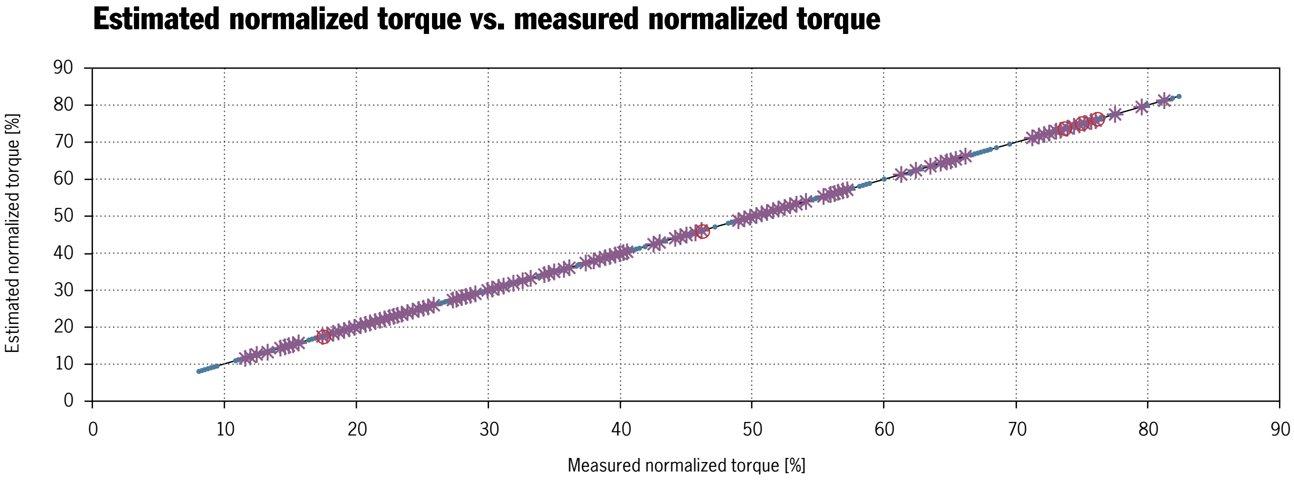
For the determination of the relationship between the input and output values of a map, the selection of a suitable mathematical model is crucial. So in order to select the optimal model for the respective use case, a series of further evaluations based on quality criteria are needed. These evaluations are based on statistical and graphic analysis methods systematically tested in the context of a defined assessment method.

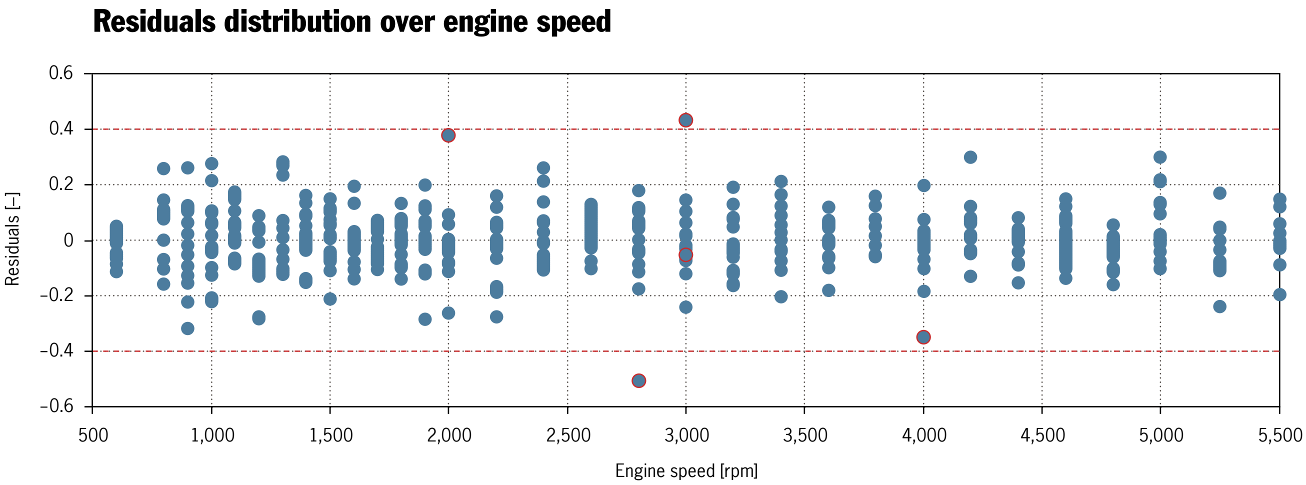
The objective of the modeling is that the measured values and the values predicted by the model at the respective operating points precisely match. The engineer first checks whether all modeled and measured points lie on a line through origin with an incline of one (see graphic at top of page 48). For a further model evaluation, another option is the method of least squares, which minimizes the sum of squared model errors (residuals) through regression. Through the graphic representation of the distribution of residuals (see figure in center of page 48), the model quality can be evaluated. Evenly distributed residuals suggest a suitable model. Further mathematical relations enable an even more detailed model selection.

The tables and characteristics maps calibrated using numeric models comprise the fundamental components of the ›



Frequency distribution of charge deviation across the engine speed





Checking the model quality

application of the charge and torque model. Their initial verification takes place through simulation and only then on the engine test bench. Charge and torque models are integrated in a Simulink environment and the results of the model-based calibration are loaded as maps. In this virtual environment, it can then be checked whether the torque and cylinder charge still fulfill the highest standards of precision even when input parameters such as the valve timing or ignition angle are changed. A part of the systematic evaluation consists of representing the frequency distribution of the difference between the just-calibrated cylinder charge and the measured cylinder charge over engine speed (see figure at the bottom of page 47). This makes it possible to recognize inconsistencies in the calibration at an early stage and remedy them as necessary through the use of an optimizer. A systematic and defined evaluation method enables a precise prediction of the quality of the calibration.

Datasets exceed requirements in terms of precision

The alternative approach for charge and torque parameterization through inversion of the calculation logic and numeric models has proven successful at Porsche Engineering. Model-based calibration is also successfully used for numerous ECU-internal determinations of engine-relevant parameters such as exhaust-gas temperature and exhaust backpressure. The mathematical representation of the physical relationships in the combustion engine in conjunction with algorithms in a Matlab or Simulink environment is so accurate that the precision requirements for parameterization are actually exceeded. At the same time, the methodology of the calibration is highly efficient because it is possible to proceed in a shorter time and with a smaller number of tests compared to solver methods. ■

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