A Test of Character for Steering Systems

Developing and fine-tuning electric steering systems with mechatronic HIL tests

Is it possible to test-drive the steering behavior of a vehicle realistically under laboratory conditions? It is. With a suitable mechatronic test rig. This is exactly what the Dr. Ing. h.c. F. Porsche AG did, efficiently optimizing the behavior of new steering systems already in early development phases.

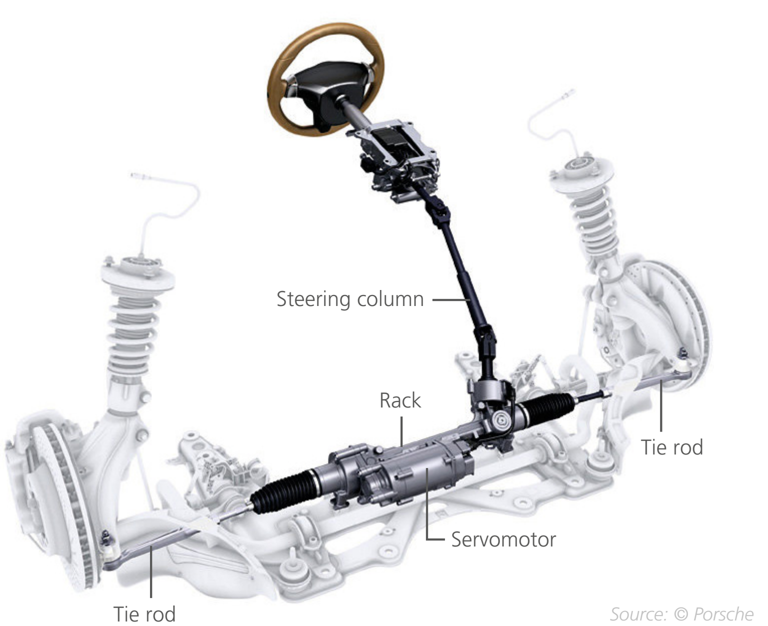
Source: © Porsche

Steering systems of today's vehicles are much more than simple components for changing directions. Supported by servomotors and plenty of assistance systems, they have become an integral part of the safety system and take stress off the driver in road traffic. On the race track, they often even determine whether it's win or lose. This is why sports car manufacturers like Porsche pay special attention to the development of steering systems. And they are not just investigating the precise and quick transmission of the steering movement to the wheels. It is also about direct feedback on the driving state – transferred exactly in the opposite direction. These two factors combined make for intuitive and safe driving. Since the driver experiences the steering system firsthand, the component is also ideal to set the company apart from competitors. Achieving a Porsche-typical steering feel, characterized by an agile and direct steering behavior, is therefore at the top of the developers' specifications. Of course, motor racing places many more, and more specialized, demands on steering torque and steering characteristics than configurations for everyday driving – above and beyond the limits of vehicle dynamics of street-legal vehicles.

Electromechanical Steering

State-of-the-art steering systems are electromechanical, often called electric power steering (EPS) systems (figure 1). In such systems, a servomotor provides additional power to the tie rods and thus actively supports the steering angle demanded by the driver. In comparison to previous generations, i.e., hydraulic steering systems, EPS systems consume much less energy and are easier to control. For example, developers can implement steering, convenience and assistance functions on the electronic control unit (ECU) integrated in the EPS system. This includes speed-dependent steering support, active steering returnability, lane keeping assistants, etc. However, one drawback of EPS systems is that the driver does not receive enough feedback about the driving states, due to the mass inertia of the assist unit and the transmission to the rack. This creates special challenges for designing the crucial feedback behavior and thus keeping the characteristic Porsche feel.

Figure 1: Setup of an electromechanical steering system. The electric motor for steering support is installed in parallel to the rack and exerts a translational force on the tie rods.



Validating the Steering System

In addition to the subjective comfort and response behavior, steering systems also have to fulfill very strict requirements. After all, they are a safety-critical vehicle component, because their failure can lead to a dangerous driving situation. The validation of the mechanics and electronics therefore complies with the most stringent safety standards. Growing amounts of software, new driver assistance systems, and the optional feature of rear-axle steering dramatically increase the need for tests in the development of steering systems. Therefore, suitable methods are needed to efficiently supply the required quality despite the high complexity. Reproducible tests, an easily extendable test scope, and a test depth that can be adjusted to each individual case can all be achieved with the industry-proven hardware-in-the-loop (HIL) method for ECUs. Efficiency can be improved even further by testing the overall system and supporting the controller design early with tests throughout the entire development process. This is why Porsche uses a mechatronic test rig to test the steering system, including the ECU, in its own lab. Suitable actuators stimulate the steering system mechanically, making it possible to test a system behavior that is very much like the behavior during a real test drive in a vehicle prototype. But it is also possible to insert synthetic stimuli at all mechanical interfaces of the steering system. This means that comprehensive tests can also be performed on the test rig. For example, developers test new functions early on, identify important parameters,

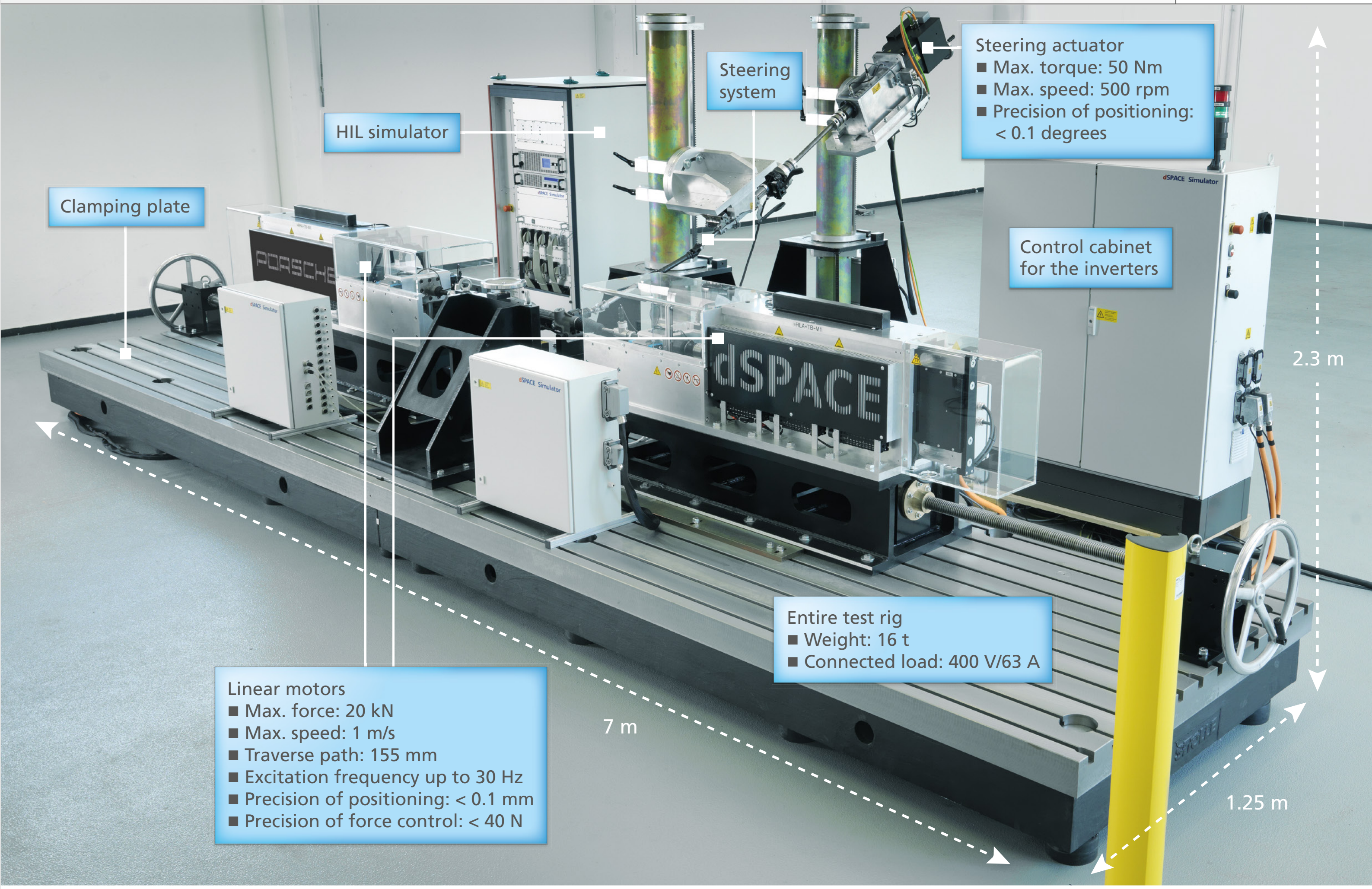


Figure 2: Setup and technical data of the steering system test rig.

and assess the limits of vehicle dynamics without running any risk at all. This also builds up valuable know-how in the company.

Flexible Test Rig Setup

The steering test rig that was developed by dSPACE and Porsche is set up so that it can hold an entire steering system, including the steering column, servomotor, rack, and tie rods (figure 2). It stands out for its variable clamping plate with various scales for positioning the individual components. Moreover, there are interfaces for energy and signal transmission between the steering system and the test rig. All this makes the test rig highly flexible, letting users adapt it perfectly to different steering systems while ensuring extremely short setup times and, thus, efficient operation.

Efficient Electric Drives

The dynamic electric drives, consisting of two linear motors that mechanically stimulate the steering system, are the heart of the test rig. They simulate forces that, in a real vehicle, are transmitted from the wheels to the two tie rods. The steering actuator (electric motor) at the other end of the steering column dynamically sets the steering angle, thus imitating a driver. Controlled drive-inverters supply power to the two linear motors and the steering actuator. The control of the linear motors is designed so they can represent high forces and precise resolutions. The inverters of all the motors are connected by a shared voltage DC link. The DC link is fed energy from the electrical grid via an active feed-in unit. Because the inverters are connected, only the current losses of the test rig have to be covered. The majority of the energy continues to flow in the circuit. This makes the test rig much more energy-efficient than the hydraulic test rigs that Porsche used until now. The external power supply works with only a standard three-phase plug (63 A). Other material, such as coolant and compressed air, are not needed.

Setup and Function of the Simulator

The motor control, test rig monitoring, and measurement data capturing are all performed by a dSPACE HIL simulator. The simulator contains the real-time processor, the required I/O, and the appropriate signal conditioning. The drive inverters are controlled via the LTi Motion TWINsync protocol which ensures that the setpoints are transmitted to the inverters in intervals of 125 µs. This control concept provides high accuracy even for highly dynamic stimuli up to 30 Hz, which corresponds to a fast drive on a cobblestone road. The HIL system also simulates the restbus, which can be based on either CAN or FlexRay,

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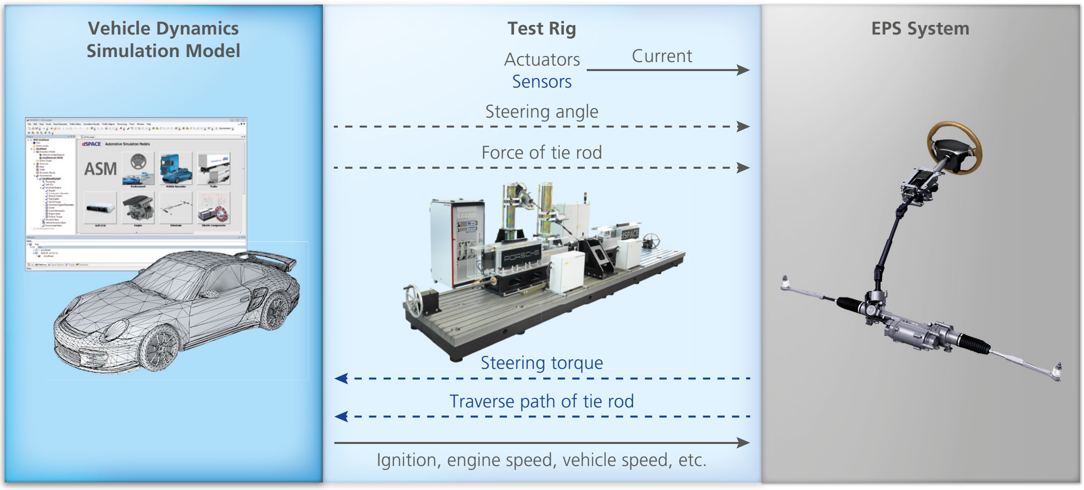

Figure 3: Components, signals, actuators and sensors of the test rig.

depending on the steering type. The tool suite dSPACE Automotive Simulation Models (ASM) is used to simulate the vehicle dynamics of a vehicle in real time. The real steering system can be connected to the ASM Vehicle Dynamics Model for closed-loop operation (figure 3). The graphical user interface of dSPACE ModelDesk is used to parameterize the various Porsche vehicle models. The software also lets developers define roads and maneuvers for the virtual test drives. To immediately visualize the vehicle behavior, the 3-D animation software dSPACE MotionDesk is used (figure 4). The experiment and instrumentation software dSPACE ControlDesk is used to control the test rig. With the test automation software dSPACE AutomationDesk, Porsche can also automate the test sequences for more convenience.

Parts of the EPS Tests

At Porsche, the steering test rig is used to identify mechanical steering parameters and analyze the transmission behavior of the steering system. The tests for parameter identification are used to understand how the supplier of the steering system implemented the mechanical requirements. In addition, repeated measurements with the same part provide information about the wear-and-tear properties of this part. The following parameters are identified during the tests:

- Transmission behavior between the pinion angle and the rack movement
- Transmission behavior between the motor angle and the rack movement
- Stiffnesses of the steering rod (torsion bar and steering column)
- Stiffness of the motor transmission (belt drive and ball screw)
- Friction of steering box and steering column
- Motor look-up table (performance, energy consumption, and efficiency)

By using AutomationDesk, Porsche can conveniently automate measurement sequences. A good example for this is the identification of the friction in the steering box and the steering column and the identification of the motor look-up table, which each require different measurements. For example, to determine the stiffnesses of the steering rod, the steering actuator starts a torque-controlled triangular signal by using automated tests. The stiffness c can be derived from the measured variables ‘steering wheel torque’ M_L and ‘steering wheel angle’ δ_L (figure 5, (3)). The analysis of the transmission behavior of an electric power steering system makes it possible to identify the properties of the servomotor. It is used to examine how well the servomotor fulfills the assist requirements for different stimulus frequencies. It is also possible to analyze the feedback behavior of the steering system. The developers influence it mainly via the software of the steering controller and design it to match the Porsche feel. The transmission behavior of forces on the rack to torques on the torsion bar is analyzed for various frequencies. The analyzed transmission criteria are:

- Transmission behavior from motor torque to rack force
- Transmission behavior from rack force to torsion bar torque

Figure 5 (4, 5) shows how a stimulus at the rack translates into a reaction of the torsion bar torque. The ‘passive’ curves describe the purely mechanical transmission behavior of the steering system without EPS assist. The ‘active’ curves describe the behavior of the steering system with activated support. The ‘active’

curves have markedly lower amplitudes than the 'passive' curves. This is caused by the assist function of the steering system, which reduces the manual torques the driver has to exert to a comfortable level. The large agreement of curves #1 and #2 illustrates the high reproducibility of the measurements with the steering test rig by dSPACE.

Testing the Overall System Behavior

The test rig provides two methods for analyzing the behavior of the overall system. First, predefined signals, e.g., from a test drive measurement, can be passed to the test rig as test vectors and then started. The advantage of this method is that the test vectors have to be recorded only once and can be reused any number of times. It is therefore not necessary to perform the driving maneuver again with the real vehicle to analyze different software states. Second, the ASM Vehicle Dynamics Model can be used to analyze the behavior of the steering system in the context of the overall system, the vehicle. For this, the ASM Vehicle Dynamics Model has to be parameterized with the data of the Porsche vehicle to be tested. In addition, ModelDesk can be used to define various driving situations. The developers can modify several variables, such as the topology of the track and the friction properties of the road surface. Both the use of test vectors and the simulations with ASM Vehicle Dynamics can support the system analysis of the test drive in the real vehicle. One main reason why the tests are so reproducible and precise is that they are independent of driver and environmental factors (figure 6).

Project Progress and Coordination

During the entire project, from the first talks in the quotation phase to the commissioning and final check,

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> "Because it is highly dynamic, the mechatronic test rig from dSPACE is an important development tool for us that perfectly integrates into the highly demanding Porsche steering system development."
>
> *Anton Uselmann, Porsche AG*

Figure 4: The mechatronic test rig, including the operator workstation with ControlDesk for controlling the tests (left) and MotionDesk for visualizing the driving maneuvers (right).

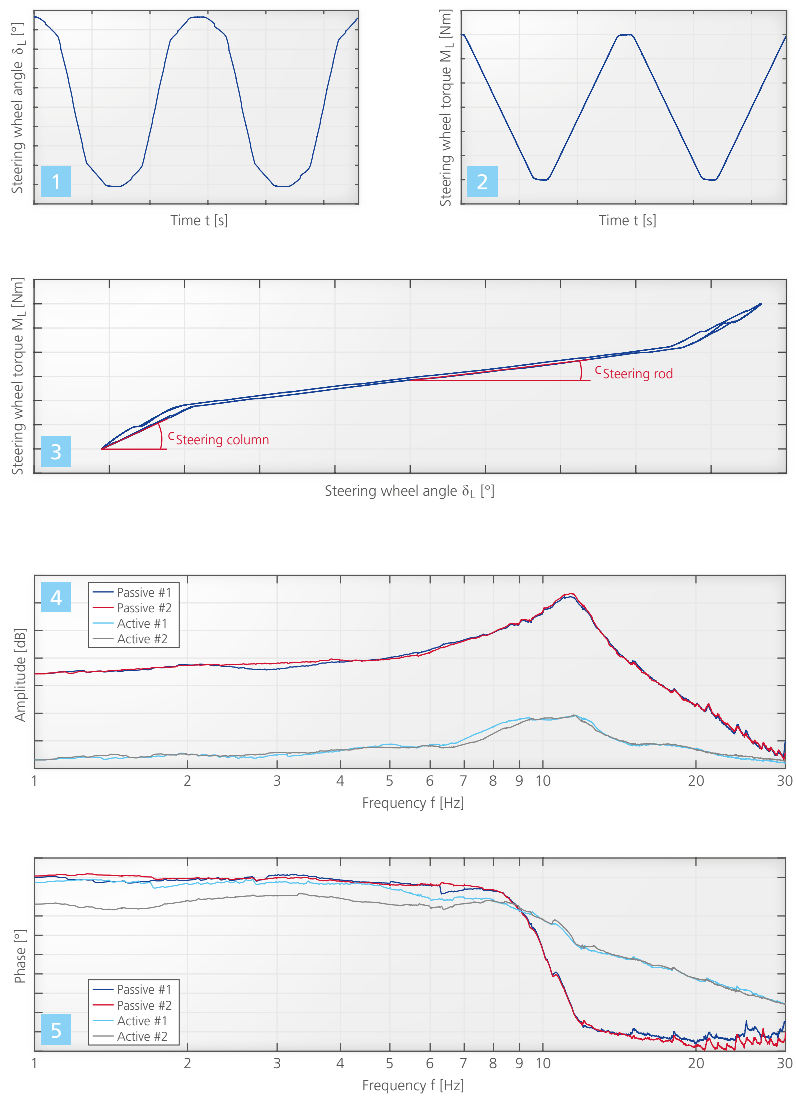

Figure 5: Various measurement values recorded during the steering wheel tests.
1, 2: Stimulation of the steering rod with steering wheel angle δ_L and steering wheel torque M_L over time t.
3: The stiffnesses of the steering rod can be derived from the gradient of the steering wheel torque M_L over the steering wheel angle δ_L.
4, 5: Transmission behavior of the steering system with purely mechanic transmission (passive) and activated assist unit (active). The curves #1 and #2 illustrate the high reproducibility of the measurements with the dSPACE test rig.

the Porsche and dSPACE employees involved in the project cooperated closely. The first project phase was about creating a test rig setup according to Porsche's requirements. It was created on the basis of a 3-D model of the mechanical setup that was revised in several steps. For example, measures concerning the construction ensured that the natural frequencies of the test rig are compatible with all the planned use scenarios, i.e., they do not lie in the frequency range of the excitation. The rotor of the linear motors also had to be optimized for the required high dynamics. Regular conference calls and on-site meetings, both at dSPACE in Paderborn and at the Porsche development center in Weissach, were an integral part of the project, making the project status transparent at all times. The test rig was delivered and commissioned on schedule. Because the entire test rig comes from a single source and was delivered turn-key, there was no coordination overhead or communication problems with third parties.

Conclusion and Outlook

The steering test rig gives Porsche greater flexibility and lets them reproduce tests with high precision, making the development and validation of the steering systems more efficient. Even after project completion, the two companies have remained in close contact. For example, dSPACE is currently working on further optimizing the control algorithms for steering test rigs. In the next phase, the two companies will integrate a

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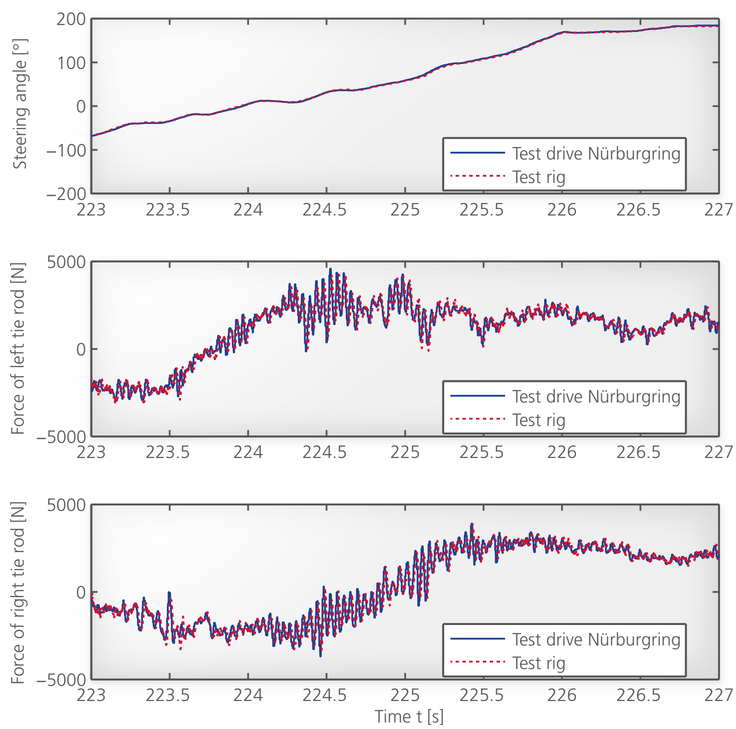

Figure 6: Measurement data recorded during a real test drive on the Nürburgring race track for the steering angle and the corresponding tie rod forces (blue), and for the values measured at the steering test rig (red).

> "We are using the real-time simulation model ASM Vehicle Dynamics to analyze the behavior of a real steering system in a virtual vehicle."

Benedikt Schrage, Porsche AG

rear-axle steering system in the test rig. Including a steer-by-wire architecture could be another project. In addition, Porsche is planning on integrating a temperature chamber for the unit under test. The necessary interfaces are already included on the HIL simulator. ■

Anton Uselmann, Eric Preising, Benedikt Schrage, Dario Düsterloh, Porsche AG

Watch the video to learn more about how the test rig works: www.dspace.com/go/dMag_20162_mHIL_E

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