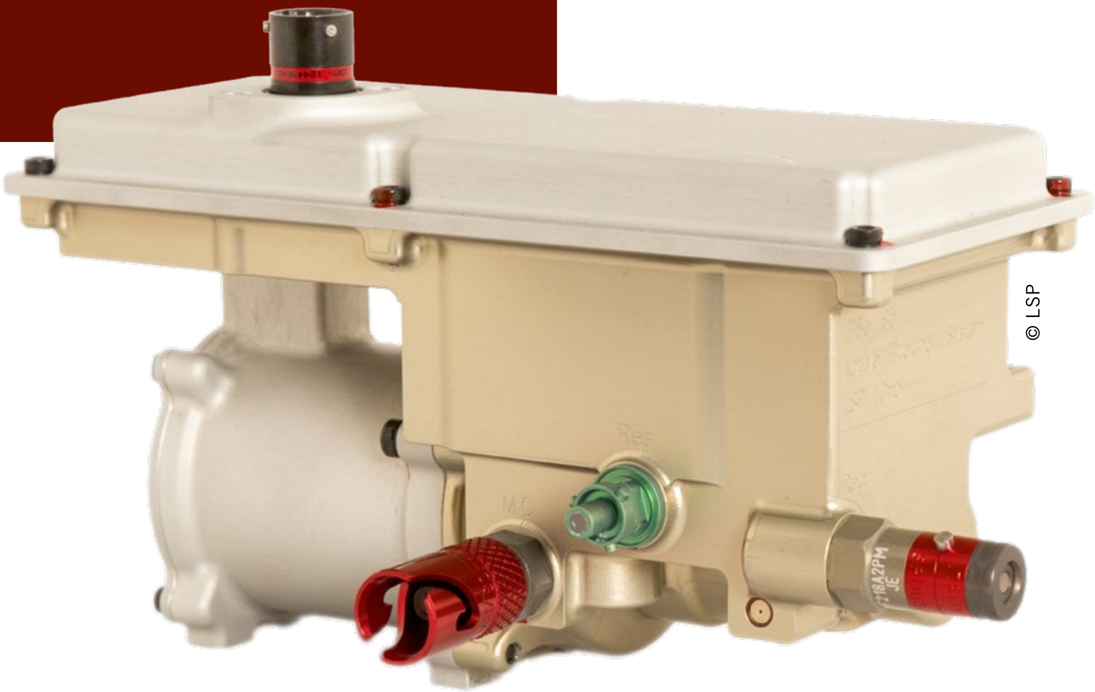
Brake-by-Wire – From Formula E to Concept Development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LSP developed brake-by-wire systems not only to meet Formula E requirements for maximum recuperation capacity in vehicles but also to optimize braking. These systems are now being used by OEMs and suppliers in the advance design of new vehicle architectures.

NEW DEMANDS ON VEHICLE ARCHITECTURES

With the advent of electric and autonomous cars, new demands are being placed on vehicle architecture, which has in turn forced designers to completely rethink the interplay of drive trains, steering and braking [1]. Some manufacturers are already developing unified electric/electronic (E/E) systems as well as domain-independent vehicle control units (VCUs) for future generations of vehicles. Yet none of this will be possible or even testable without the appropriate development tools. That's where LSP comes in. A specialist in braking systems, the company's IBSe braking control concept is a safe and simple brake-by-wire system that is suited to the analysis and design of new drive architectures. Originally developed for Formula E, the system offers something different to series production options, namely, a large degree of flexibility for quick and reliable integration.

The Formula E championship began in 2014 and has constantly grown in importance on the international motor sports scene. In order to complete a race without changing vehicles or stopping to recharge, the FIA not only introduced a new chassis with 250 kW traction motors and larger batteries (52 kWh) at the end of 2018, but also put in place the brake-by-wire (BBW) technology. The system is intended to maximize recuperation capacity in vehicles, that means the usage of braking energy for the drive train. Like this, up to half the energy expended is recovered during one lap.

BRAKE-BY-WIRE REQUIRES MAXIMUM RECUPERATION

Implementing an optimized recuperation strategy, however, is a loftier goal than one might think because the amount of energy that can be recuperated varies greatly. The most important parameters for this include charge level, temperature and race tactics. Even during a single braking action, recuperation is not constant due to the specific rpm-torque characteristics of the traction motor. It also needs to be ensured that vehicle stability is maintained during the interaction between the traction motor and the brakes [2]. In the early days of Formula E, recuperation was initially set manually before each braking operation. The driver had to compensate for additional braking torque from the traction motor by changing his pedal actuation – not an easy task even for professional drivers.

FIGURE 1 shows an example of the required distribution of braking torque from a friction brake and the traction motor on the rear axle in order to generate a constant vehicle deceleration of 2 g. What is striking here is that in the range from 125 km/h to 25 km/h the braking torque generated by the traction motor is sufficient to decelerate the vehicle according to the request. The system needs to thus respond as quickly as possible at the start of braking and must also be able to achieve braking pressure of 0 bar. LSP developed the customized BBW IBSe system specifically for the requirements of Formula E [3].

SIMPLE HYDRAULIC LAYOUT

LSP has the competence to design, develop and produce the core components – motor, valves and electronics – at its own facility, which made it possible to approach the system design process in a holistic way. Multifaceted optimizations and the targeted use of high-performance materials resulted in a system size of just 80 x 100 x 180 mm that weighed in at only 1.5 kg.

The braking system is installed directly between the master cylinder and the wheel brakes and consists of the following integrated modules: pressure supply unit, valve block and electronics, **FIGURE 2**. A hydrostatic piston actuator serves as the pressure supply unit. A weight-optimized EC motor actuates the hydraulic piston hydrostatically in a closed brake circuit through an efficient ball screw drive. Leakage-free and low-resistance ball seat valves provide the hydraulic connection for the various operating modes. It is controlled via an open CAN bus interface.

INTEGRATED FALLBACK LEVEL FOR MAXIMUM SAFETY

To ensure maximum safety, the IBSe has a hydraulic fallback. When in operating mode, the wheel brake is separated from the master cylinder and brake pressure is set by the piston actuator. If a fault occurs in the brake system or in the VCU, the system switches over to fallback within milliseconds. The piston actuator is separated from the hydraulic circuit and the wheel brakes are connected directly to the hydraulic chamber of the master cylinder. The IBSe is designed such that, in its non-actuated state it is in fallback and only switches to operating mode when each braking operation is initiated. It is thus in a safe system state when not in use. Numerous tests on the racetrack have confirmed that the driver can easily control the shift to the fallback level even during braking.

CONSISTENT DECELERATION AND PEDAL FEEL

Conventional systems only allow limited brake pressure-to-pedal pressure decoupling, that means setting different pressures on both axles. If a lot of energy is to be recuperated via the traction motor during braking, the axle in question would be overbraked. This leads to brake balance trimming and reduced braking performance as the braking potential of the vehicle can no longer be fully exploited. In order to remain within vehicle stability limits it is therefore not possible to make use of the traction motor's full recuperation potential. These are unacceptable restrictions in both motor sport and road traffic.

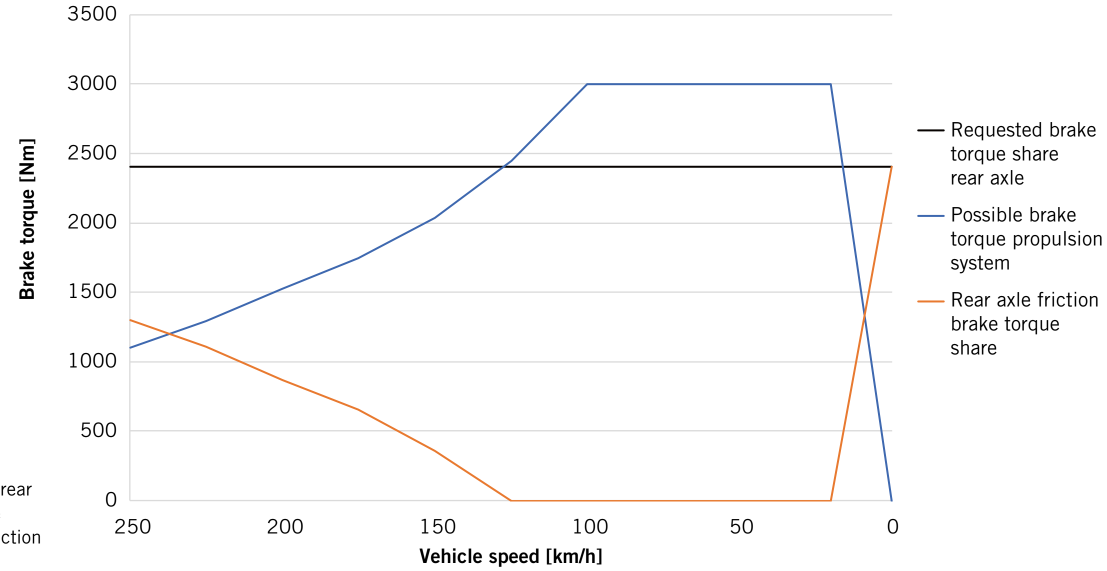


FIGURE 1 Distribution of rear axle torque between the electric drive and the friction brake (© LSP)

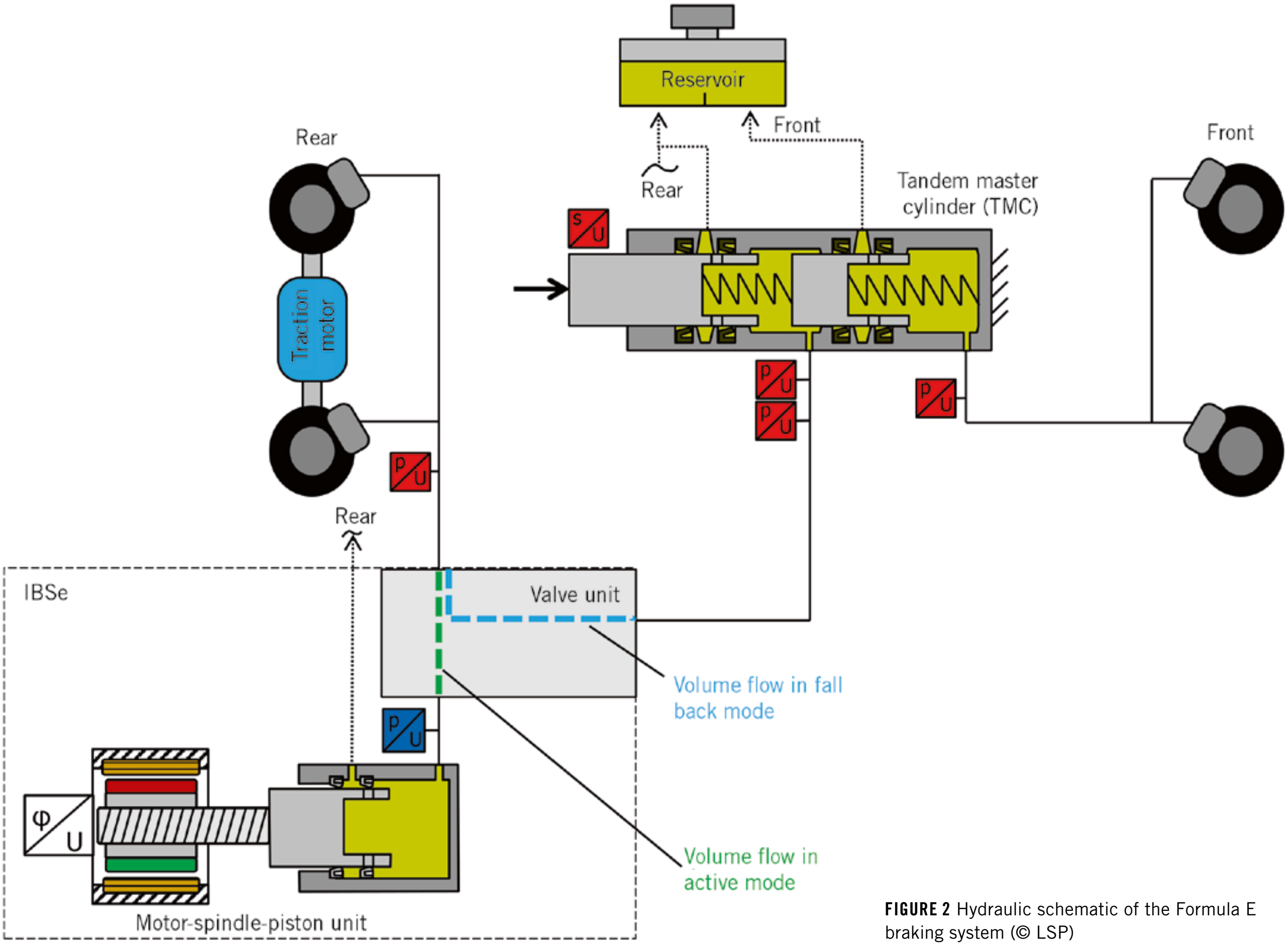


FIGURE 2 Hydraulic schematic of the Formula E braking system (© LSP)

The IBSe, on the other hand, disconnects the driver from the wheel brake. This allows the system to fully modulate brake pressure between 0 bar and maximum pressure. Based on pedal pressure, the VCU calculates in real time the deceleration desired by the driver, splits it into torque values for the traction motor and the friction brake, and then sends the corresponding control commands to the appropriate actuators. This results in the full exploitation of recuperation potential from the traction motor while maintaining the desired vehicle brake balance and power. For the driver, pedal feel and vehicle deceleration remain constant regardless of how much the traction motor intervenes.

In Formula E, as in most vehicle categories, the traction motor only drives one axle. This means the BBW system is only installed in the relevant brake circuit. The second brake circuit retains its conventional direct connection to the corresponding chamber in the master cylinder and thus creates the familiar pedal feel for the driver. If the vehicle has two electrically driven axles and requires brake torque balance, the IBSe is installed in conjunction with a pedal travel simulator.

HIGHLY DYNAMIC PRESSURE CONTROL AND INTEGRATED DIAGNOSIS

In terms of control strategy, PPC (Piston Pressure Control) is utilized [4,5,6]. The core elements of PPC are the use of the wheel brakes' pressure-to-volume curve and a pressure estimate based on the electric motor current. PPC control has been optimized over the course of 15 years and now possesses self-calibrating models that allow the regulator to consistently, efficiently and accurately manage the desired braking pressure even given changes in the operation of the system (temperature, wear and tear). **FIGURE 3** shows the Bode diagram of the IBSe unit for pressures between 10 and 70 bar (60 bar amplitude peak to peak). Pressure curves of up to 10 Hz can be displayed with damping of less than 0.5 dB and a phase delay of less than 45°. In practical terms this means that with a maximum gradient of 860 bar/s, pressure can increase from 0 bar to 80 bar within just 110 ms. To do this, the IBSe requires 450 W at peak. Since power consumption between braking is only 7.5 W, the system has an average power consumption of less than 15 W during a Formula E race.

Piston actuator systems provide a wealth of information about pressure and volume consumption in the hydraulic circuit in real time and without additional sensors. That brings with it significant advantages for diagnostic purposes and for the safety of the braking system. For example, wear and tear as well as the venting status or leakage in the brake system can be monitored online. This will be essential for future applications such as autonomous driving.

VARIABLY APPLICABLE IN MECHATRONIC DESIGN

Combining different BBW modules allows for an expansion of the system and thus a significant increase in the scope of its functionality, **FIGURE 4**. Depending on the number of brake systems in place, pressure can be set on one axle, on two axles at a time or individually for each wheel.

Thanks to highly dynamic pressure modulation, even vehicle stability functions such as Traction Control (TC) and Electronic Stability Control (ESC) can be precisely mapped, including all of their relevant subfunctions. A further application includes evaluations in the field of torque vectoring (TV) and steering by individual wheel braking action, for example as a replacement for electric power steering.

The clearly structured CAN bus interface, which is protected against false operation, allows for a fast and uncomplicated connection to the existing vehicle communications network. This also incorporates the replacement of conventional control structures in vehicles with a central VCU that controls all existing subsystems such as brakes, steering and drive trains [6,7].

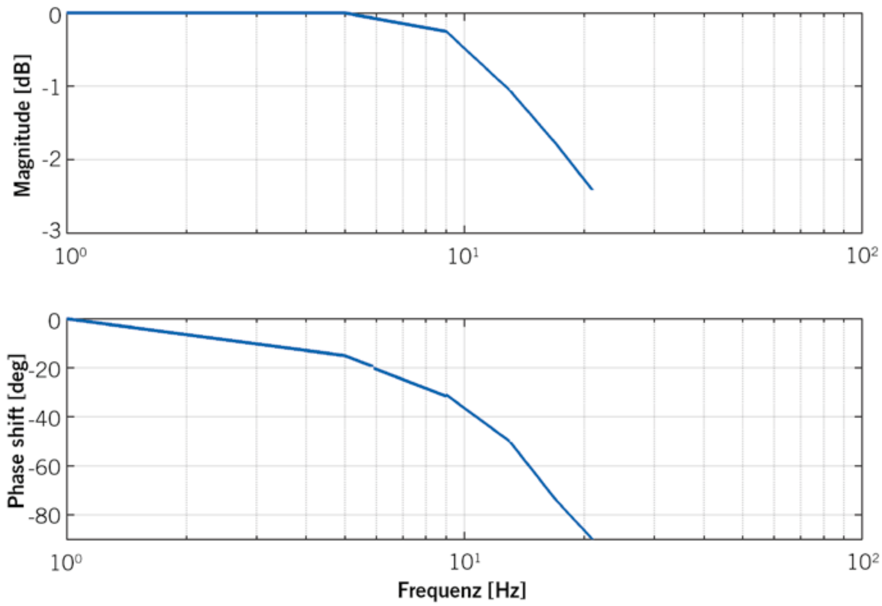


FIGURE 3 Bode diagram of the IBSe brake system with pressure rising from 10 to 70 bar (© LSP)

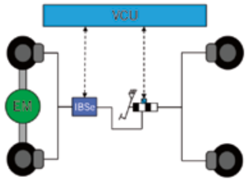
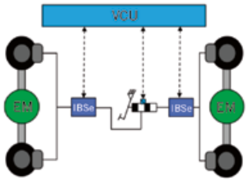
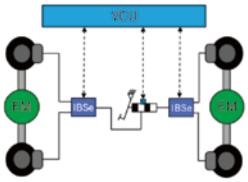
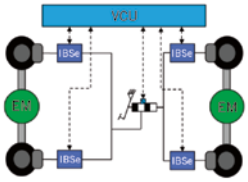
System layout	Brake boost, EBD	Brake blending	Propulsion system	ESC, TC, Torque-vectoring
a) 	✓	1 axle	1 x Electric motor	–
b) 	✓	2 axle	1-4 x Electric motor	–
c) 	✓	2 axle or 4 wheel	1-4 x Electric motor	✓
d) 	✓	2 axle or 4 wheel	1-4 x Electric motor	✓

FIGURE 4 Overview of different IBSe-based brake system layouts (© LSP)

Installing an IBSe system in the vehicle is simple because it does not have its own pedal interface. Instead, it is simply inserted into the existing brake circuit by means of a hydraulic quick coupler. No time-consuming conversions have to be carried out on the firewall. The IBSe brake system originally developed for Formula E is thus a good example of the move from racing applications to series development. The first developments in the areas of highly automated driving, drive architectures, vehicle dynamics and uniform vehicle E/E architecture have already been successfully implemented.

SUMMARY AND OUTLOOK

Currently available mass production brake systems do not meet the specific requirements of motor sports nor do they reflect the latest concepts in drive and vehicle dynamics. LSP's IBSe is a failsafe brake system that can be quickly integrated and provides an open control interface. In the near future, a modular BBW kit that is already being developed will offer a fast and flexible research platform for new control strategies for driving dynamics as well as redundancy concepts for highly automated and autonomous driving.

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