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► **To cite this version:**

Matthias Schneider, Adrian Thomys. PREDICTIVE POWERTRAIN – NEW OPPORTUNITIES BY NETWORKING SYSTEMS. Embedded Real Time Software and Systems (ERTS2014), Feb 2014, Toulouse, France. hal-02272443

**HAL Id: hal-02272443**

**<https://hal.science/hal-02272443v1>**

Submitted on 27 Aug 2019

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## PREDICTIVE POWERTRAIN – NEW OPPORTUNITIES BY NETWORKING SYSTEMS

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### Keywords

ACC, Connected Cruise Control, Connected Systems, Hybrid Control Strategy, Control Unit Interaction, Cross-Systems Networking, Electronic Horizon, Hybrid System, Predictive Powertrain

### Abstract

These days it is not enough to think about downsizing of engines or the use of hybrid systems to keep upcoming CO<sub>2</sub> regulations as well as customer demands. Furthermore most of the vehicles' components are highly optimized. The realization of further significant optimizations is only possible through a connection between these components.

Intensive research activities play a major role in making Bosch a market and innovation leader in electronic powertrain and safety systems. And in diesel and gasoline engines as well, there are technological possibilities for reducing consumption even further. What all powertrains have in common is the potential to reduce emissions and fuel consumption even further through networking of existing vehicle systems across all vehicle domains. The advent of electromobility is bringing together two areas of automotive technology that were traditionally regarded in isolation from one another – powertrains and chassis. Furthermore Bosch links automotive systems with data from the electronic horizon, which senses the vehicle's environment and provides a detailed preview of the road ahead.

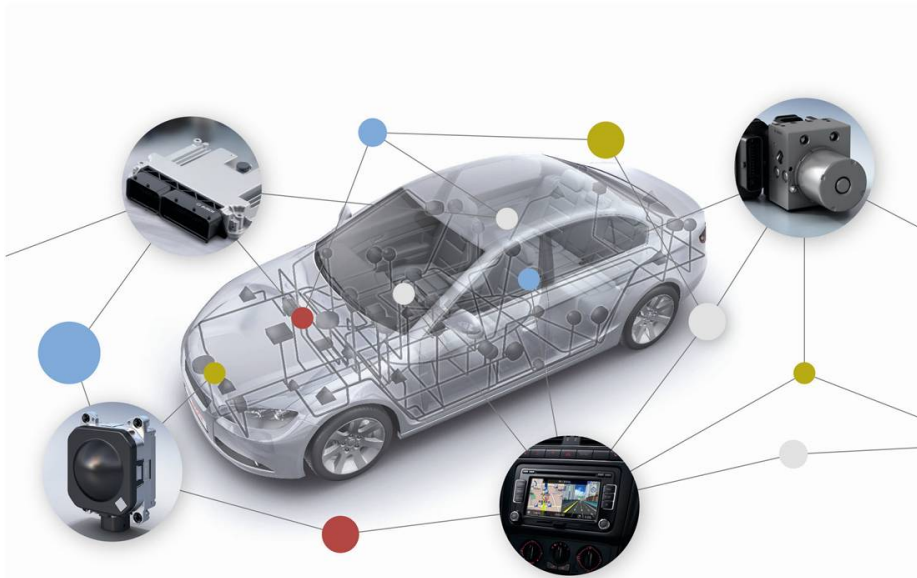
Bosch Engineering GmbH is using cross-system networking within a concept vehicle as well as with external systems to develop new functions. The networking of vehicle systems encompasses the ACC (Adaptive Cruise Control), the electronic stability program ESP® and the whole powertrain (ICE and hybrid). Going beyond vehicle systems, automotive systems are also linked to data from the electronic horizon (interface to navigation system), this feature acts as a sensor to the environment to provide a detailed virtual preview of the route ahead. New functions thereby reduce fuel consumption and increase the level of comfort and safety. This paper provides an overview on the system approach and practical developments of Bosch Engineering in this area.

### Introduction

The steady increase in the number of intelligent vehicle systems means that the networking of these systems is playing an increasingly important role. In addition to the challenge of ensuring that these different electronic systems can co-exist effectively, there is also an opportunity to use the networking and interaction of the sensors, actuators and control units to add value in the areas of driving comfort, safety and driving pleasure.

These new system solutions are increasingly gaining importance with OEMs and are forcing suppliers to rethink certain areas: Products can no longer only be produced within a development division — they must be developed across domains. Bosch Engineering GmbH is acting on this idea and using its advantages as a development service provider with various skills concentrated in one location — this approach is based on the development expertise for Bosch systems in the fields of vehicle dynamics and driver assistance, as well as engine management, hybridization and passive safety.

System solutions require an interplay between a wide variety of components; only rarely are these components developed and provided by one supplier. For a service provider to do this, it is crucial that, in addition to networking its own subsystems, it enables integration and interaction with third-party systems so that it can offer the customer the best possible overall system.



**Figure 1** Illustration of networking between various components in the vehicle (VCU, ACC, HMI and PDC)

The Bosch Engineering GmbH approach of creating added value through intelligent networking within the vehicle places a primary focus on using only the existing systems in the vehicle and thereby representing new and/or improved functionalities without the need for additional hardware or components. Rather than being restricted to premium-segment vehicles as an optional package, a large number of electronic systems are now increasingly included as standard in mid-range vehicles available in the market. This increases the potential for system solutions, as well as the motivation for new and intelligent approaches that make tangible yet cost-effective functions a reality for end customers. The following figure shows some of these systems, which are currently being used in many vehicles.

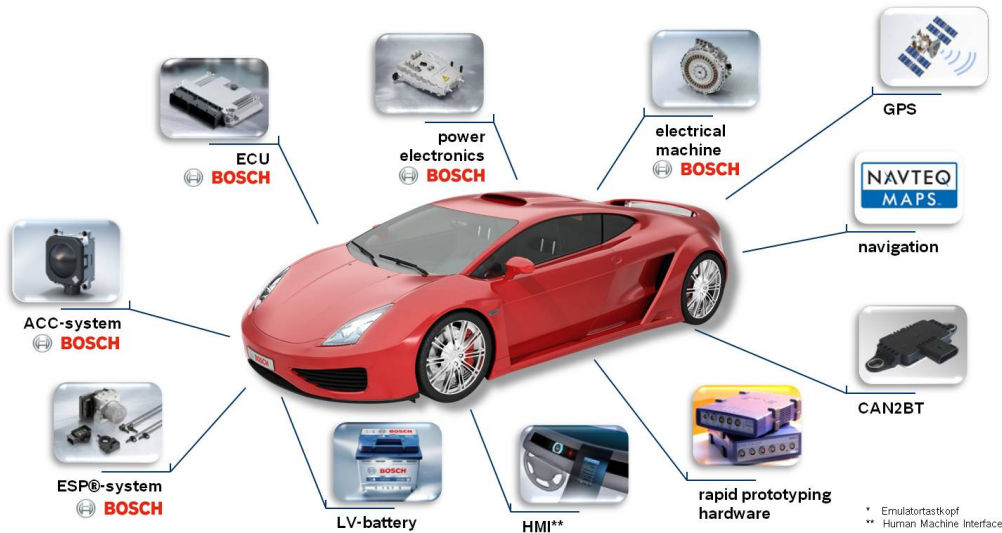
In reference to the powertrain, the integration of environment information is one way to increase the efficiency of the vehicles during actual driving cycles. Information from a radar and video system can provide information on upcoming events in just the same way as map data stored in a navigation system in combination with the current position, which is determined by GPS. Through this type of interaction between multiple control units, the vehicle can support the driver during anticipatory driving or can itself access the system within the driver's specifications. For example, it can influence the engine start/stop behavior and the loading strategy of hybrid vehicles, comfort optimization of cruise control and speed limitation functionality, as well as the diagnostic cycles and component protection measures.

Intelligent networking of systems in the area of driver assistance also creates potential for optimization and enhancement of safety and comfort functions. Interaction with the navigation system plays a crucial role in this regard: Information from the peripheral sensors is combined with information from map data and prospective routes, enabling an anticipatory and thus optimized driving strategy. This allows such factors as speed zones, cornering characteristics and the course of roads to be taken into account, thereby enhancing driver assistance functions or even making them a possibility for the first time.

As part of an internal innovation project at Bosch Engineering GmbH, a test vehicle was set up to make intelligent system networking a tangible reality using example functions.

### **Connected Systems**

To illustrate the possibilities of networking in the area of the powertrain, a Porsche Panamera S Hybrid series-production vehicle was used as a platform as part of the "Control Unit Interaction" innovation project. Based on the installed series components, a wide variety of functions in the area of operating strategy, GPS connection and driver assistance have been developed, implemented and tested. This section describes some of these functions and their added value, which is created solely by networking the various existing systems.



**Figure 2** Components of the test vehicle

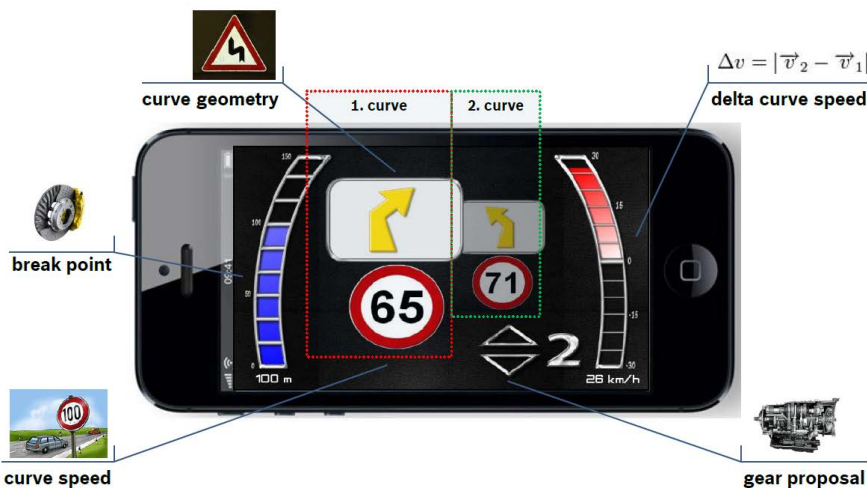
Figure 2 illustrates the components of the test vehicle that were used for functional expansion and thus for networking the systems. Only a navigation PC and rapid prototyping hardware were added to the test vehicle. These components offer quick access to the development platform and would not be required for in series production of the functions presented below, as these components would be replaced by the series control unit and an integrated navigation system.

### Curve Assistant

The basic concept of the Curve Assistant is to prepare the driver for the course of the route ahead using map data information. In specific terms, this means providing a visual and acoustic representation of relevant speed limits, curve geometry and curve speeds, as well as the next brake and acceleration point. A smartphone is used here as the HMI (human-machine interface), as shown in Figure 3.

Although GPS-based map navigation technology has been established in vehicles for over a decade, it is only recently that map data has started to be used across control units. The basis for this development is the standardized ADASIS protocol created by a range of manufacturers. It provides the control units with data on the route ahead via CAN ("electronic horizon"). In the Bosch innovation, the provider of the ADASIS data stream runs in this case as a prototype on a powerful car PC in the vehicle's trunk. A GPS receiver connected via USB provides the location information.

The lack of accuracy and stability of the GPS signal, particularly in forested areas or tunnels, represented a challenge in the implementation of this solution. This was tackled with an intermediary application developed in-house. When used via a Kalman filter in combination with vehicle sensors (speed and acceleration), this enabled precise positioning even when the GPS signal was poor.



**Figure 3** HMI of the Curve Assistant

Curve Assistant processes data on an ES910; a control unit for rapid prototyping from the Bosch subsidiary ETAS. This receives the ADASIS protocol of the car PC via CAN and is connected to the vehicle CAN via a second bus. The data output for the display is also completed via CAN, with subsequent radio transmission via Bluetooth to the smartphone. The visual representation and the voiceovers are provided by a specially developed Android app.

The Curve Assistant can be set by the user as desired, ranging from comfortable to sporty.

In practice, the Curve Assistant has now demonstrated the performance and the range of the concept on numerous customer journeys. This assistant not only offers significant comfort, but can also increase safety and efficiency, particularly on winding country roads with changing speed limits.

*Connected ACC*

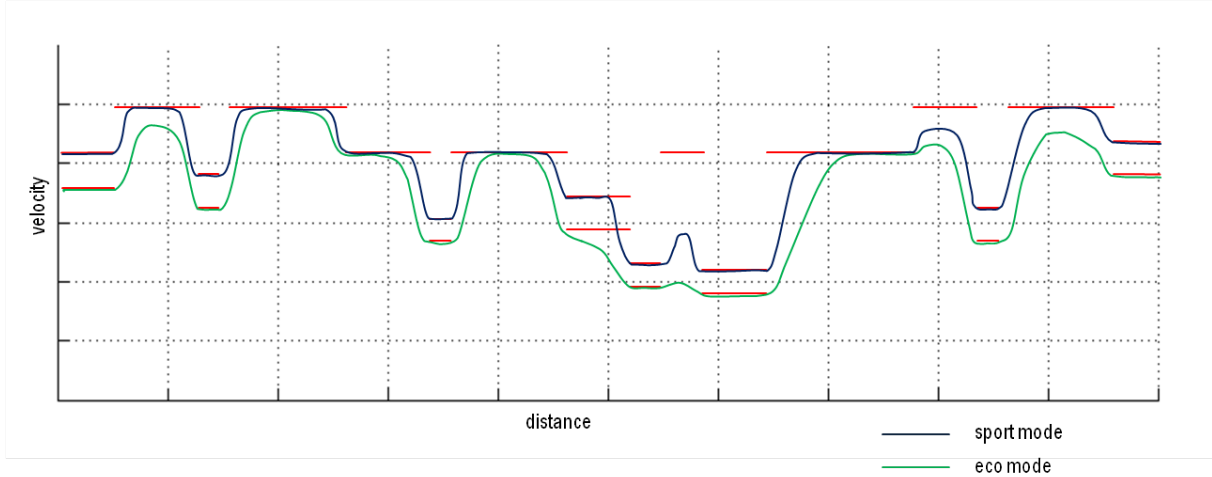
In recent years, the importance of driver assistance systems has risen steadily. Better sensors and more powerful control units have enabled new assistance functions to be developed that support the driver and remove certain driving tasks. One such example is the "Adaptive Cruise Control" (ACC) driver assistance system from Bosch. ACC uses radar to record the vehicle's environment and adjusts the speed to the traffic situation independently by intervening in the powertrain. During normal driving, the system acts as a conventional cruise control system, i.e. it maintains a speed set by the driver.

As ACC works on the basis of radar data, it has only a limited amount of information about the route ahead. In particular, curves and changing regulatory speed limits may require the driver to adjust the set speed or to brake.

As part of the "Control Unit Interaction" advance development project, Bosch Engineering GmbH has been developing an extension of ACC since 2012 that takes into account information about the route ahead using map data. The system, known as "Connected Cruise Control" (CCC), undertakes full longitudinal control of the vehicle. It does this completely independently in most situations, without the driver, who monitors the function, needing to actively intervene. This makes it the logical next development of the Curve Assistant presented here.

The driver has the option to set, as desired, how sporty or economical the vehicle is when driving. It brakes precisely at curves, speed limits and ahead of junctions. This does not affect the normal function of the ACC in any way. If the system detects another vehicle in front of it, then a safe distance is maintained. The function is of course easy to override at any time using the pedal.

The CCC receives the information about the route ahead, also known as the "electronic horizon," from the navigation device via the ADASIS protocol. This is a standardized interface definition that allows the navigation device to be connected to the vehicle control units. The CCC can also access all route information in the navigation device, including speed limits, curve radii, intersections and information on the gradient of the road. This data is available even if the driver has not entered a route in the navigation system, meaning is not clear whether he wants to turn or go straight ahead at intersections and turning points. When this occurs, the system calculates the most likely route and provides the relevant details.



**Figure 4** Example speed curve

Based on this information and the driver's desired vehicle dynamics, the CCC calculates optimal cornering speeds. Together with the statutory speed limits, this produces a top speed band that the vehicle cannot exceed, making for a safe, legally compliant journey. The speed band is composed of different sections of constant maximum speeds, as shown in red in Figure 4 (horizontal bars). It can be seen that the maximum speed for curves depends on the desired vehicle dynamics.

The CCC optimizes the speed trajectory based on the upper speed band. Each section of the speed band is divided into four phases: acceleration, cruise, coasting and braking phase.

Since the target speed is known before the acceleration phase starts, a smooth and comfortable acceleration trajectory can be calculated. Depending on the desired vehicle dynamics, acceleration is performed with high power (sport mode) or an attempt is made to keep the engine in its most efficient operating state (efficiency mode). The braking trajectory in the braking phase is also predicted in this way. In efficiency mode, deceleration procedures are normally completed through recuperation and without applying the hydraulic brake.

In the cruising phase, the vehicle retains the maximum speed specified by the top speed band at a constant level. Short sections of road between two curves are an exception in this regard: To prevent the vehicle from accelerating and immediately decelerating, the cruising phase continues at a reduced speed, which is significantly more comfortable for the driver. The cruising phase is followed by a coasting phase where the powertrain is switched to the torque-free setting so that the vehicle coasts without consuming fuel. The sportier the CCC setting, the shorter the coasting phase.

Figure 4 depicts a typical speed curve using a schematic illustration, and shows the differences between sport mode and efficiency mode.

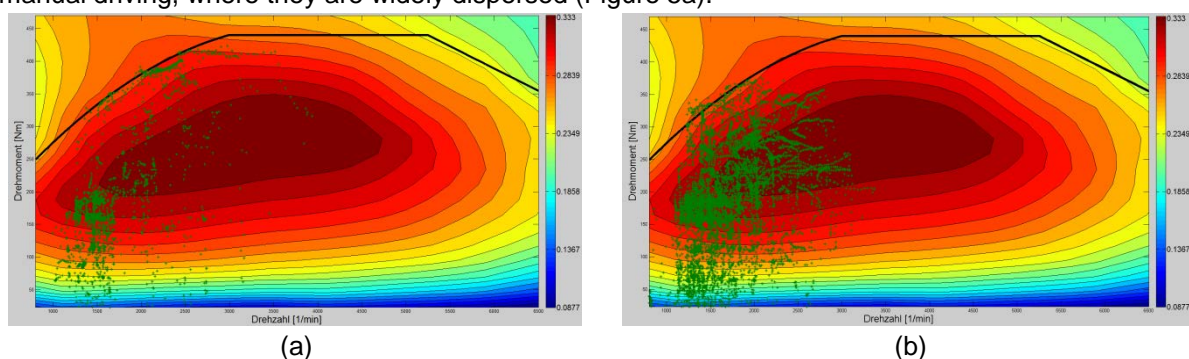
Connected Cruise Control offers the driver a number of advantages:

In normal usage, the vehicle undertakes full longitudinal guiding. It is no longer necessary to adjust the set speed, and the accelerator and brake pedal do not need to be operated. This significantly reduces the driver's workload.

The driver can be confident that the vehicle is complying with the legal speed limit, and so does not need to look away from the road to check the speed or the set speed on the instrument cluster. In addition to increased comfort, this also enhances driving safety. Additional safety is achieved by the fact that Connected Cruise Control complies precisely with the applicable speed limits.

A further advantage is the significantly reduced fuel consumption. Through an adjusted driving strategy and connection to other engine control features, a fuel saving of up to 15% could be achieved. This fuel saving is achieved through a variety of measures: Connected Cruise Control takes into account the circumstances of the powertrain and configures acceleration processes specifically so that the engine is operated in its optimum state. As mentioned above, braking processes in normal conditions are completed solely through recuperation. The extensive coasting phase in efficiency mode reduces fuel consumption further.

Based on the calculated driving trajectory, the vehicle is able to brake specifically at speed limits or curves and to accelerate again once these have been cleared. As soon as the driver switches the Connected Cruise Control to sporty, it offers a new driving experience and level of driving pleasure, as the vehicle drives around curves dynamically and the driver can concentrate fully on steering. This is also evident in the measured load point distribution, which is illustrated in Figure 5. The load points in automated longitudinal guiding are significantly more focused in the effective areas (Figure 5b) than in manual driving, where they are widely dispersed (Figure 5a).



**Figure 5** Load point distribution in manual driving (a) and with activated CCC (b)

For the top speed band, the function in its prototype version has until now used speed limits and curve information. The plan for future versions is for them to take into account traffic circles and intersections. In addition, based on the data relating to road gradient, it should be possible to calculate the coasting processes with even more precision so that fuel efficiency can be further improved.

An additional networking step is also already under analysis: In addition to the Robert Bosch GmbH video systems for example, smartphone applications already exist that recognize traffic signs and make this information available. With reliable traffic sign recognition and transfer, Connected Cruise Control would also be able to respond to temporary speed restrictions that are not noted on the maps of the horizon providers.

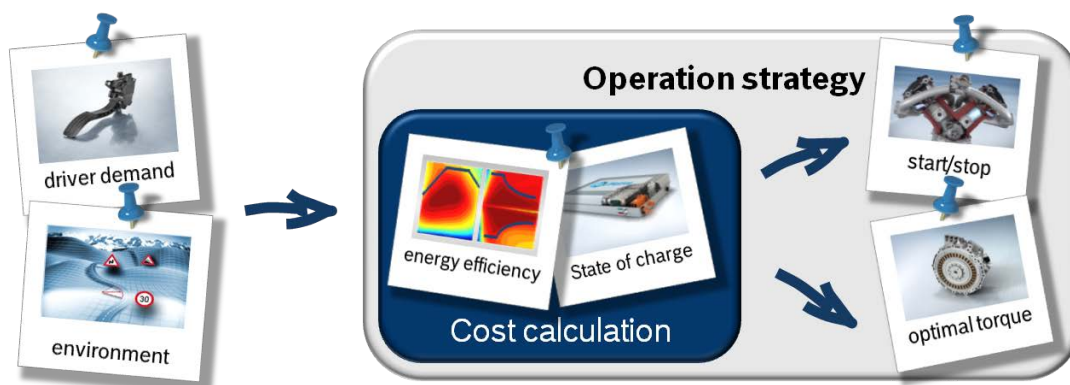
### *Operating Strategy*

In a parallel hybrid vehicle, two operating states with sub-states can be distinguished. The first operating state is hybrid driving. This offers the possibilities of load point shift (load point raising and lowering) as well as pure combustion engine operation. The second operating state is pure electric driving. The relevant choice of optimum operating state is described as the operating strategy. The solution to this problem can be split into two related sub-problems: start/stop of the combustion engine as well as determining the optimal torque of the electric machine. This is possible because each operating state is characterized by exactly one permutation of these sub-problems.

The ECMS procedure [1] offers one possible solution. In this procedure, the "costs" of electric driving or hybrid driving (with the optimum torque of the electrical machine) are calculated and compared with one another. The more favorable variant at a set point in time is then set by the hybrid control. The most important input variables are the driver's request and the battery charge level. To calculate the "costs," the efficiency characteristics of the combustion engine, electric machine, pulse inverter and battery are also used.

As electric driving requires that sufficient energy is always stored in the battery, the recuperation potential cannot always be fully exploited when operating a hybrid vehicle. This is especially true for long descents or very frequent braking. The battery is then becomes "too full" prematurely if it has not previously been emptied. One example shows driving on the flat at a speed at which electric driving would be possible. If the flat is followed by a descent, then purely electric driving is more efficient on the flat as the energy required for this can be recuperated on the subsequent descent. However, the data in the hybrid control is not sufficient to make this decision.

The predictive operating strategy developed by Bosch Engineering GmbH can determine the sections that are suitable for the recovery of braking energy using topographic data from the navigation system such as inclines, descents or curve radii. Long before these situations are reached, the battery charge status is adapted on a predictive basis, e.g. through electric driving, so that optimum recuperation can be achieved.



**Figure 6** Predictive operating strategy

The Bosch development constitutes a CO<sub>2</sub>-reducing measure under EU certification. By connecting the navigation system to the operating strategy of the hybrid vehicle, the Bosch system therefore delivers a creditable, vehicle-specific advantage for the respective automotive manufacturer's fleet usage and can thereby counteract the threat of penalties for exceeding the legally prescribed average CO<sub>2</sub> emissions [2].

### *Inverter DCS*

In hybrid and electric vehicles, the electric motor adds another braking option. The recuperation is particularly useful with regard to energy recovery, as the energy fed back in relieves the battery and thus reduces the system costs. Essentially, this is relevant for topologies where the electric motor is permanently connected to the wheels. The objective is therefore to regain as much energy as possible. But what happens during recuperation with an electric vehicle on a slippery road? And what possibilities are there for getting as close as possible to the goal of the maximum, electrical brake energy exploitation?

It must first be considered how the driver can report the recuperation requirement as this can be done in various ways: via the brake pedal, the accelerator pedal or a new interface.

Conventionally, the brake pedal would be the suggested input method, as the driver has a braking requirement. This is also the approach in the ESP hev and iBooster systems. In the former, a vacuum-based brake booster is used and the brake interventions are decoupled in such a way that the rear axle can brake purely electronically. In the iBooster, the brake pressure is built up in a vacuum-independent process via an electrical actuator. The brake pressure for the friction brake can therefore be withdrawn and assigned to the electric motor. The advantage of inputting via the brake pedal is the familiar user interface and the integration of all braking interventions relevant to vehicle dynamics.

If you want to take advantage of the opportunity to read the recuperation requirement using the accelerator pedal, this can be done through replication of the drag torque, for example. In practice, this means that if the driver takes his foot off the accelerator and does not release the clutch, the vehicle will be braked via the (electric) motor drag torque. The advantage here is that this torque can be freely changed via the electric motor, provided the motor is connected directly to the axle.

The use of new interfaces involves using such features as an additional rocker switch that reads the recuperation requirement individually and directly. Alternatively, entries could be made by briefly pressing the accelerator or brake pedal in order to vary the recuperation level.

While a new interface does require an initial rethink, it also separates safety-critical braking maneuvers from a request to recover energy during non-critical coasting. But how do these input types differ in terms of their recuperation level? If we consider the request for each brake pedal, combined braking demonstrates a certain time delay in the electrical part in comparison to conventional braking via the friction brake. The recuperative share must be requested via CAN from the superordinate Vehicle Control Unit (VCU). The VCU uses this to generate the target torque which, in turn for each CAN, is sent to and set by the power electronics. This does not initially present a problem when setting the brake requirement as the down time can be taken into account using the brake actuator. However, if the objective is as high a share of recuperation as possible, the following may occur: The wheel locks on a slippery road, but the complete braking power is applied via the electric machine. This means that the braking power cannot be immediately withdrawn as the aforementioned down time still needs to be taken into account. In order to respond with the brake flexibly and in the safest possible way, it is usually only a small proportion of braking that is completed in a recuperative process. For maximum recuperation, however, a different method is more appropriate.

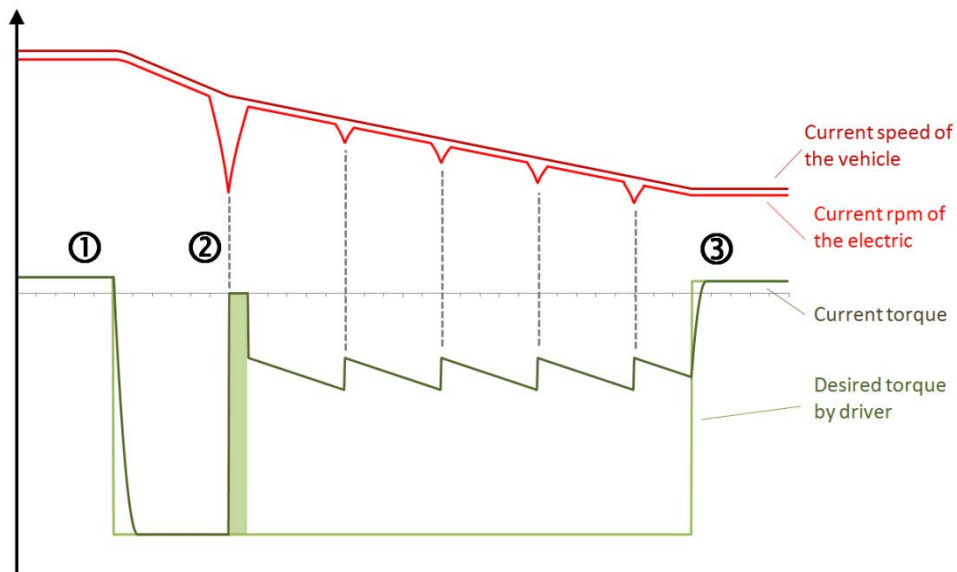
When there is a recuperation requirement, the aim of the recuperation stability system (RSS) is initially to recover as much electrical energy as possible in a non-critical driving situation. Any locking of the wheels and thus instability must be avoided.

To ensure safety is not compromised and to avoid any change to the vehicle and ESP, the RSS intervenes in the torque of the electric machine sooner and more rapidly. It can do this as it monitors the engine parameters directly in the software of the INVCON power electronics.

To detect wheel lock, it is important to consider three parameters: the relative speed difference between the wheel and the ground, the braking force relative to the normal force, and their maximum value that is still just permissible on the current ground composition.

If we consider an electric vehicle braking on a slippery road, the driver will report the braking request between point 1 and point 3. The electric motor sets this request as quickly as possible. Provided this is permitted by the adhesion coefficient, the vehicle speed is then reduced. Shortly before point 2, however, the vehicle reaches the slippery ground and as the braking force is too strong, the wheels start to lock. This can be clearly detected from the speed of the electric motor. In the figure, it would be reduced to half (axle-specific drive) or to zero (wheel-specific drive) without any intervention.





**Figure 7** Sequence of an RSS intervention. During the braking request (1-3), wheel lock is detected internally in the inverter and is counter-steered by withdrawing torque. The control system attempts—provided there are no interventions by the driver or ESP—to drive as closely as possible to the slip limit.

Based on a power and slip model, as well as a vehicle model, the RSS is able to detect this situation and trigger an intervention (Figure 7). This reduces the torque and the wheel can rotate freely again. A modeling approach reduces the wheel lock period. The intervention means that the friction coefficient is also now known, allowing the maximum permissible torque to be predicted. The controller now attempts to oscillate around this value (e.g. as shown as a two-position controller).

In the additional interventions, the calculated parameters can be used as a reference point so that interventions can be made more quickly.

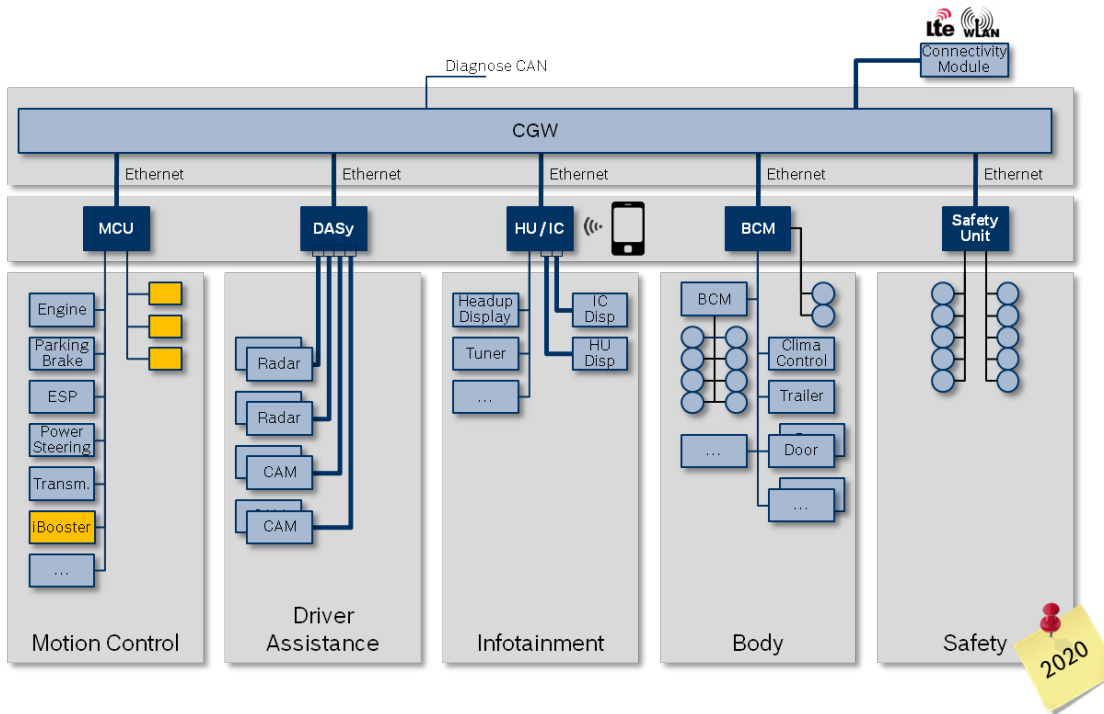
For the RSS—in contrast to the ESP calculations—the absolute values of slippage and adhesion coefficient are not known accurately enough as speed and torque are not measured at the wheel. However, value generation is completed much more frequently in the inverter, so that an intelligent filter can be used, taking the history into account. In addition, the implementation does not require target slippage formation, as is completed in ESP.

### Future System Technologies

In future vehicle architectures, the internal and external networking of the control units will play an even greater role. The different domains in the vehicle will be connected via a rapid communication line and the respective domain controllers. This forms a backbone structure that enables additional new functions to be implemented that are the result of intelligent linking of different domains. Special requirements are placed on these central nodes in terms of hardware and software.

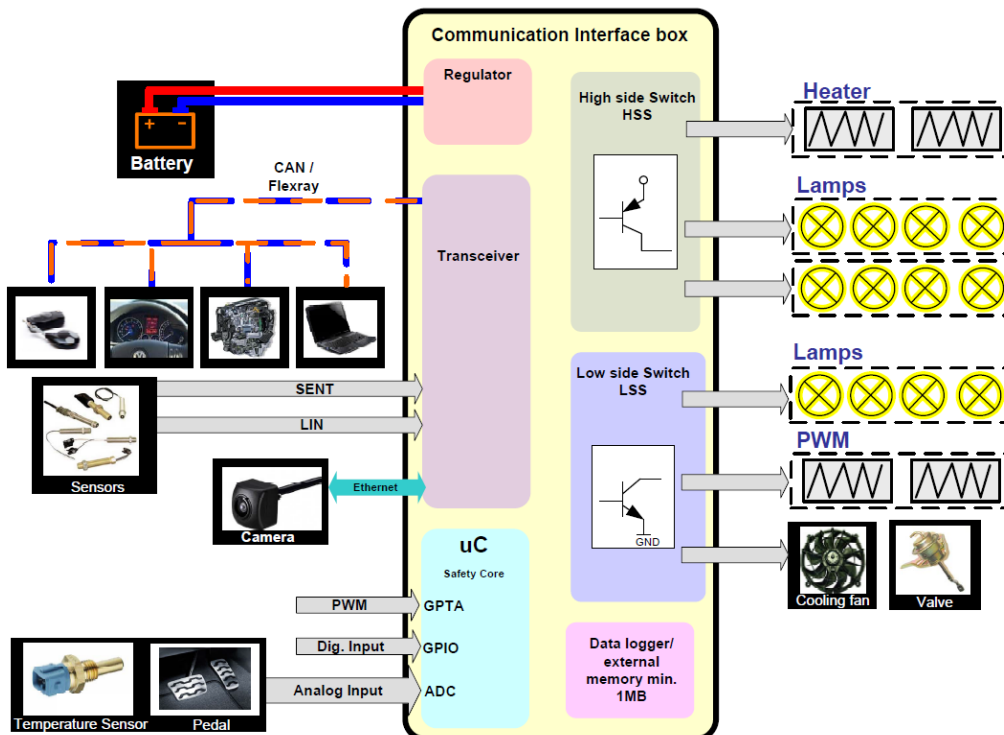
The hardware of such a domain control unit must have high computing power and a large capacity of permanent and non-permanent memory for a wide variety of tasks. For flexible usage, many different communication interfaces with medium to high data rates are required, ranging from today's widespread CAN, LIN, and SENT interfaces, to the increasingly emerging and future-oriented FlexRay and Ethernet buses. The task here is to use the available and proven automotive technology from large-scale production to minimize costs and installation space. The compact design and the high density of high-frequency signals and computing power offer particular challenges with regard to loss of power and electromagnetic compatibility (EMC).

The device should be prepared for a wide variety of energy management roles of future network topologies in the overall vehicle assembly. It should therefore be available for activation through various channels (CAN, Flexray, digital inputs) or even via its own clock (internal downtime counter) so that it can activate other parts of the network or control units as a master if required. The device must only have extremely low standby power consumption. To allow further functions to be adopted that cannot be assigned to the existing subsystems, it is useful to have some digital and analog inputs and outputs available.



**Figure 8** Scope of future domain control units

The highly flexible functional scope described above is achieved by quickly adapting a wide base unit as an assembly option to the required functional scope. This also allows several different functions to be generated in a network from the same base. This flexibility offers the customer the advantage of converting existing topologies step-by-step to the future target topologies, without the need to convert each individual participant immediately in a time-consuming process. Existing bus networks can therefore be connected to the new bus architecture via the communications interface. The functionality can be further expanded by connecting connectivity modules, such as any number of "CAN to wireless" extensions. This allows networking to be opened up for the Internet of things and services, for example.



**Figure 9** Interfaces of a Communication Interface Box

Hypervisor allows various operating systems to run on the domain controllers, enabling different functional safety levels to be implemented on an ECU. Connecting to the Internet means that special security measures are necessary in the backbone. In future, it will not be possible to achieve security through a strict separation and encapsulation of the vehicle from the Internet, as the connection itself will make new functions possible.

On the one hand, system and vehicle data will be transferred into the Cloud in order to supply crowd services with data and to cover car-to-car and car-to-infrastructure issues. On the other hand, information from the Internet can have a direct influence on the parameterization of vehicle functions (location-based services, software updates, remote access to vehicle functions). Through integration of smart connections from smartphones, functions can also be removed from the vehicle and computed on the ever-growing computing power of mobile devices. Additional comfort features or functions with extremely complex calculations can also be made available, and can be used retrospectively in older vehicles.

### **Conclusion**

By networking vehicle systems with electronic horizon data, Bosch is able to develop numerous new functions that are made for a safer, more comfortable and efficient driving experience. Information such as curve radii, inclines and speed limits are directly integrated into vehicle systems using the standardized interface protocol (ADASIS v2). Thus with the resulting functions, vehicle manufacturers can differentiate between vehicle features and characteristics specific to each brand.

### **Outlook**

The illustrated functions demonstrate the opportunities created by intelligent networking of existing components within the vehicle with regard to safety, comfort and efficiency. The possibilities offered by connecting map information to the engine control system and the ACC are illustrated in particular.

In future, the subject of environmental sensor systems and sensor fusion will play an increasingly important role in this regard — the combination of radar, video, ultrasound, and map information will provide the data mix required to illustrate the functions described in this paper or other, similar functions in a safe and reliable way. One possible extension here is the use of clouds, which enable data to be collected and thereby provide other vehicles with additional information. This requires an Internet connection, which can be realized via a smartphone or a control unit with a corresponding interface.

Another important issue in future will be the use of smartphones as external processing units with a great deal of storage capacity and high-performance processors. End-customers can always install new applications on their smartphones, as well as view the information from the vehicle and even intervene in the vehicle behavior using appropriate secure interfaces.

In general, innovations demonstrate the possibilities and potential for future series applications and are therefore only the first step of the product development process. For this reason, the focus at BEG now lies in working with the OEMs to address, discuss and develop the illustrated ideas so that they can be brought to market together.

[1] Ambühl, Daniel: *Energy Management Strategies for Hybrid Electric Vehicles*. Zürich: ETH/ Measurement and Control Laboratory, 2009.

[2] [http://www.bosch-presse.de/presseforum/details.htm?txtID=6350&tk\\_id=108](http://www.bosch-presse.de/presseforum/details.htm?txtID=6350&tk_id=108)