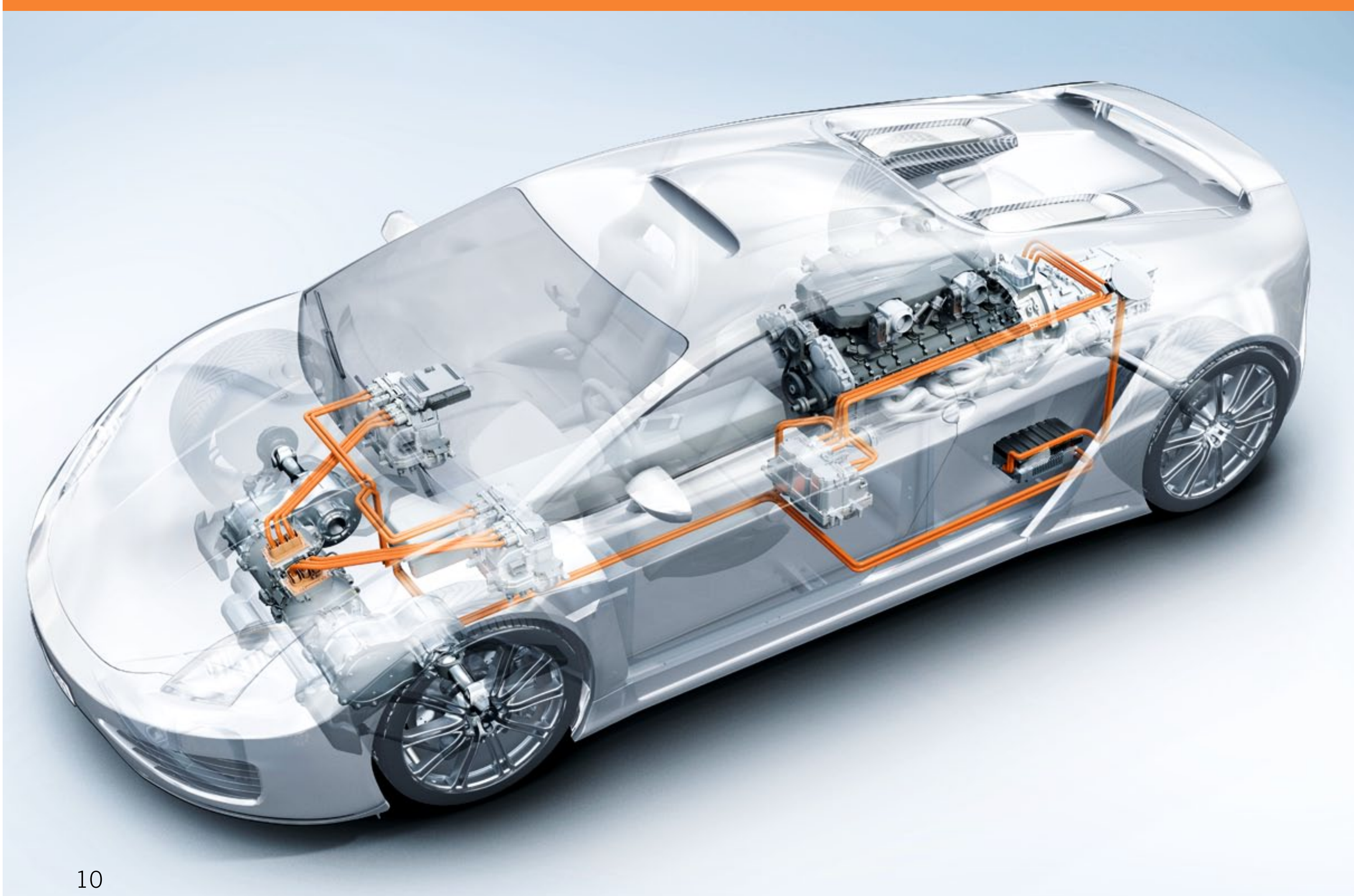
COMPREHENSIVE SIMULATION FOR POWERTRAIN ELECTRIFICATION

Bosch has developed a cross-domain simulation environment for the development of hybrid powertrains. The approach can be applied continuously from the concept phase and system design through to vehicle calibration, thus reducing development time and costs. The simulation platform was used for the first time in the development of a hybrid system for a sports car. Both emissions-relevant and racetrack-related requirements were taken into account.



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MEETING CO_2 TARGETS THROUGH HYBRIDISATION

The introduction of emission limits and their increasingly strict updates means that conventional internal-combustion engines are going through constant change. In recent years, one of the focal points of development work has been on compliance with the strict Euro 5 and Euro 6 emissions standard. Following the introduction of CO_2 legislation, reducing fuel consumption is gaining rapidly in importance. Today's automakers have their sights fixed on 2020, and the 95 g/km CO_2 limit for passenger cars that is under discussion for that year. Even the 130 g/km target that will apply from 2015 calls for additional technical measures to bring fleet CO_2 emissions in line with the targets set.

For sports car manufacturers, this poses a much greater challenge than it does for, say, manufacturers of passenger cars in the large/SUV class. In the past, the sports car segment's development focus was on maximising engine performance while keeping vehicle weight to a minimum, not on meeting future emissions and CO_2 targets. Today, however, manufacturers of sports cars are already applying traditional CO_2 reduction measures such as downsizing and de-throttling. Combining these with other measures outside the engine, such as minimising rolling resistance, reducing vehicle weight, and optimising aerodynamics, can significantly contribute to meet the emissions targets for 2020. What's more, electrification of the powertrain offers the potential to achieve or even exceed these targets.

In hybridisation, which combines internal combustion engine (ICE) and electric motor(s), systems expertise is needed to control the interaction of powertrain, vehicle dynamics, body electronics, and chassis systems. Because when it comes to guaranteeing a sports car's success, it is not just a question of reducing CO_2 emissions but above all one of vehicle performance and vehicle dynamics. Hybridisation must be able to preserve and enhance these characteristics. How best to design the hybrid powertrain, how many electric motors to include, and where to place them is the subject of lively debate in this segment. Common topologies see electric motors either integrated into the internal combustion powertrain (parallel or power-split hybrids) or located on one of the vehicle's axles as a separate drive (axle-split hybrids). Attention must also be paid to the positioning of the ICE and of high-voltage components, as this has a direct impact on weight distribution. Optimum positioning of the components can shift the vehicle's centre of gravity to improve its dynamics.

CHOICE OF HYBRID CONCEPT

In the future, if it is to achieve the CO_2 limits under discussion for 2020, the sports car segment will have to move beyond measures that target the ICE alone. It will be absolutely necessary to electrify the powertrain, for instance by adopting a plug-in hybrid concept. Bosch offers various hybrid systems and components, ❶. To identify the optimum powertrain topology, Bosch Engineering GmbH studied a variety of hybrid concepts, like axle-split hybrid, parallel hybrid, serial hybrid and power-split hybrid, ❷. One criterion in this study was that it had to be possible to integrate the components needed for hybridisation into an existing sports car architecture with a conventional ICE, without having to completely redesign the vehicle. The most suitable concept proved to be the axle-split hybrid with two electric

❶ Bosch hybrid components: electric motor SMG 180/120 (left) and power electronics INVCON 2.3 (right)

	AXLE-SPLIT- HYBRID WITH ONE EM	AXLE-SPLIT-HYBRID WITH TWO EM	PARALLEL HYBRID	SERIAL HYBRID	POWER-SPLIT-HYBRID
Power density	+	0	++	−−	+
Efficiency	++	+	++	0	++
Packaging flexibility	+	++	0	−	0
Vehicle dynamics and additional functions	+	++	0	0	0
Costs	++	+	++	−−	++
Ranking	**2**	**1**	**3**	**5**	**4**

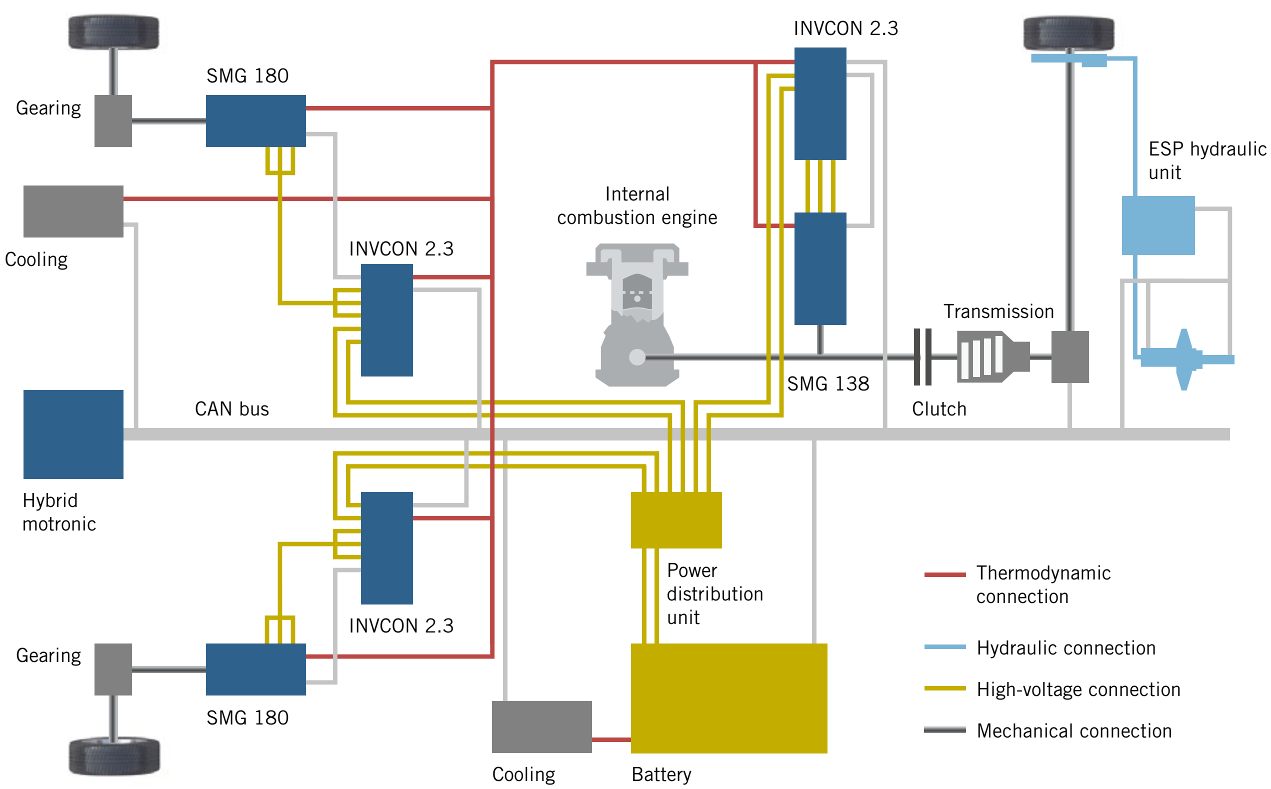
❷ Evaluation of various hybrid topologies for the Aston Martin DB9 concept car (EM: electric maschine)

motors, which performed particularly well in terms of vehicle dynamics and additional functions as well as packaging flexibility – two categories of special relevance to sports cars. The weighting of criteria can be tailored to customer preferences and to the base vehicle.

In order to highlight the potential of hybridisation to reduce emissions and improve driving dynamics, Bosch Engineering converted an Aston Martin DB9 with a six-gear manual transmission into a hybrid vehicle, ❸ and ❹. Each of the concept car's front wheels is driven by an electric motor following the axle-split hybrid concept. The ICE drives the rear wheels and the high-voltage generator, which can start the IC engine and charge the battery. However, the additional components make the hybrid concept car weigh more than the base model, ❺. As a result, the challenge in converting the powertrain was to fulfill CO_2 emissions limits despite the extra weight while also improving performance. Even though hybridisation increases drive power by 169 kW and delivers high torque, it is the extra weight, the change in the centre of gravity, and the suspension characteristics that determine the sports car's handling. Analysis of these cross-domain dependencies was done by way of comprehensive vehicle system simulation. This makes it possible to simulate and evaluate the boundaries of dynamic performance for the relevant vehicle and each engine option over defined parameters while taking account of lateral dynamic performance and compare them directly with those of the series-production model.

CROSS-DOMAIN VEHICLE SIMULATION

Bosch Engineering developed a simulation platform specifically to allow comprehensive consideration of the cross-



❸ Overview of the powertrain components of the Aston Martin DB9 concept car with axle-split hybrid topology

❹ Aston Martin DB9 concept car with axle-split hybrid powertrain

domain vehicle system at an early stage of a vehicle development. This platform is based on a Bosch standard powertrain simulation environment that takes a generic modelling approach and allows a quick and efficient comparison of various powertrain topologies in respect of their fuel consumption as well as their fundamental longitudinal performance. In order to factor in the vehicle dynamics characteristics to the design of a sports car, the simulation platform was expanded to include these aspects and appropriate sub-models were added. The vehicle simulation also reproduces powertrain components' thermal behaviour, taking into consideration the thermal impact on vehicle performance due to thermal derating (for instance of the battery) that occur when temperature limits are exceeded. This means the cooling circuit can be designed realistically to match the maximum requirements of specific use cases, for instance on race tracks.

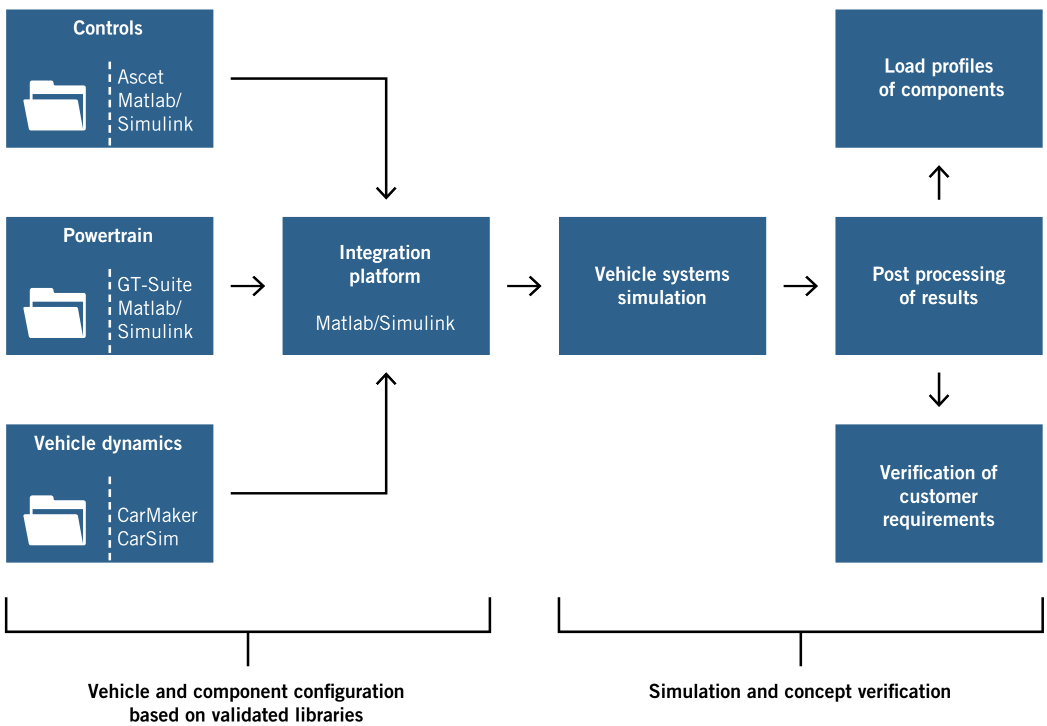
	ASTON MARTIN DB9 BASIC VEHICLE	ASTON MARTIN DB9 HYBRID CONCEPT VEHICLE
Empty-weight	1689 kg	1983 kg
Internal combustion engine (ICE)	V12 front engine, rear-wheel drive	V12 front engine, rear-wheel drive
Transmission	Six-speed manual transmission	Six-speed manual transmission
Maximum power (ICE)	421 kW	421 kW
Maximum torque (ICE)	620 Nm	620 Nm
Electric motors (EM)	–	2 x SMG 180/120 on the front axle (2 x 85 kW) 1 x SMG 138/80 at the ICE (25 kW)
Power electronics	–	3 x INVCON 2.3
High-voltage lithium-ion battery	–	8 kWh usable energy

❺ Comparison of vehicle data

The simulation platform, ❻, is divided into powertrain (front and rear axle), vehicle dynamics (chassis, wheels and brakes), and control software. Matlab/Simulink is used as the integration platform, while model and component libraries with varying model depth serve as the basis. This guarantees the optimum level of detail and best possible simulation runtime for a given set of requirements and field of application. Existing component models in Simulink – for instance of the ICE, transmission, electric motor, power electronics, and battery – were integrated into the powertrain model and an interface to the other models was created. In addition, a detailed 1D model of the V12 combustion engine was developed in GT-Power with two aims: first, to evaluate engine-related measures addressing performance and cycle fuel consumption; and second, to transfer these results to the simplified model at vehicle level. This reduces the need to build up engine variants and saves time on the engine test rig. The hybrid operating strategy can be imported from Simulink as part of the model library; alternatively, the ECU code is included directly in Simulink as a so-called dynamic-link library (dll) file. One advantage of including the actual software for the hybrid operating strategy is that it allows realistic load profiles to be deduced for the respective components, which permits reliable predictions of their service life.

The biggest difference between this and the fuel economy simulation tools that have been used in vehicle development to date is in the detailing of the vehicle dynamics aspects and hence the models for the chassis, tyres, and driver. The relevant vehicle dynamics subsystem is realised via a connection to vehicle dynamics software IPG CarMaker, which gives much more detail on vehicle performance. Depending on the use case and the requirements simplified Simulink models can be used. This reduces both parameterisation workload and runtime. In order to respond flexibly to customer requirements, it is also possible to include further specific Simulink models as well as additional software, for instance CarSim from Mechanical Simulation.

In developing the Aston Martin DB9 concept car with hybrid powertrain, comprehensive use was made of cross-domain vehicle simulation in all prelimi-



❻ Cross-domain simulation platform

nary investigations to determine the components' rough design and dimensioning, to predict performance and energy demand, and hence also to calculate the electrical range. Moreover, further simulations were conducted specifically to determine the battery's cooling requirements and the design of its cooling circuit for the race track use case. The simulation demonstrates that the concept car has significant advantages over the basic model, ❼. Fuel consumption was reduced by 50 % despite the extra weight, while sporty performance, measured in terms of acceleration time, was also markedly improved. Fuel consumption was calculated according to the ECE R101 procedure for plug-in hybrid electric vehicles in the New European Driving Cycle (NEDC).

	ASTON MARTIN DB9 HYBRID CONCEPT VEHICLE
Time from 0 to 100 km/h	– 20 %
Time from 0 to 200 km/h	– 13 %
Time to 1000 m	– 7 %
Consumption (NEDC)	– 50 %
Electric range	25 km

❼ Simulation results for the key criteria

CROSS-DOMAIN APPLICABILITY

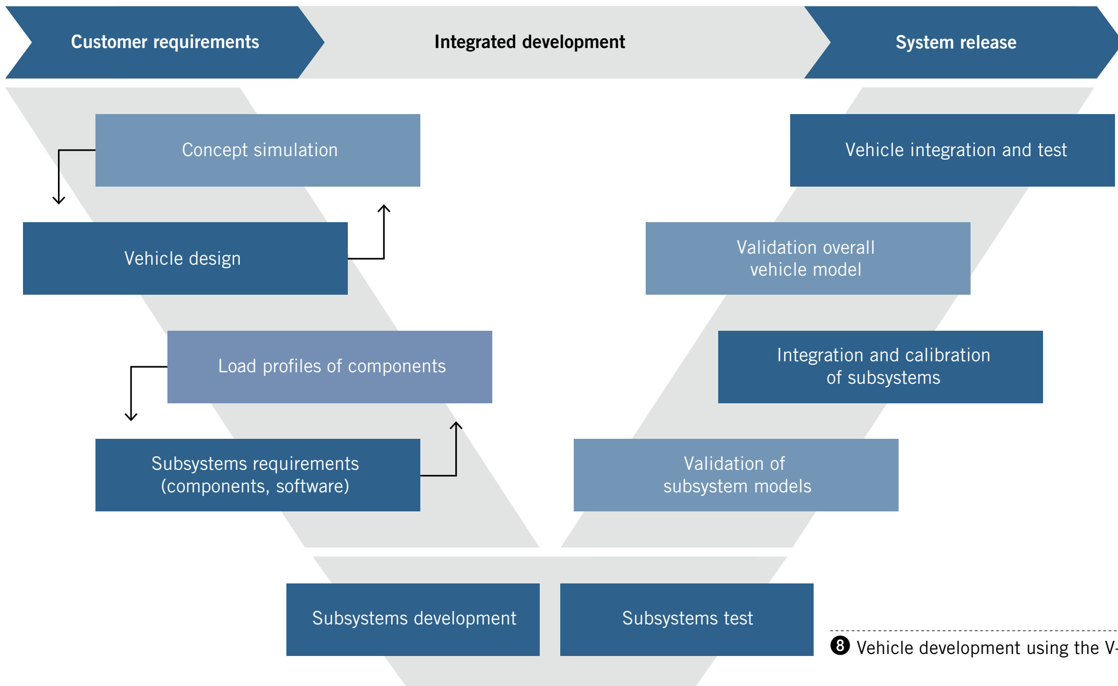
The vehicle simulation described gave rise to a work platform that can be used in a cross-domain way by various areas and project teams. For instance, ESP development and calibration benefit from detailed powertrain models, while powertrain design can refer back to robust performance simulations in detailing vehicle dynamics. This puts more extensive and more detailed data at the disposal of vehicle design earlier on in evaluating various concepts. Although creating the models and precalibrating them adds to workload, applying them comprehensively makes up for this in subsequent development stages, from prototype construction to series development and calibration, ❽.

The comprehensive, cross-domain simulation environment offers full coverage of all areas, from system and component design through software and function development to calibration of the hybrid operating strategy. The modelling depth of the simulation can be tailored to the field of application and the goal of the simulation. The result is always a comprehensive simulation platform that can help various teams increase their development speed, their efficiency, and the quality of their output. The cross-domain simulation platform can be applied at any point in time in a vehicle's development and it can be flexibly tailored to the requirements of individual phases. This allows a major reduction in the number of tools applied and in the parameterisation workload throughout the entire V-Model. Much of this reduction is made possible by a thorough validation of the overall model. A validated model can be used as an efficient way to evaluate functional safety and can reduce the test catalogue for development vehicles. This in turn can significantly cut development time and costs.

CALIBRATION OF THE HYBRID OPERATING STRATEGY

One application of the simulation platform is to calibrate the hybrid operating strategy. Simulation is absolutely necessary for modeling certification driving cycles such as the NEDC for the EU market or FTP75/US06 for the US market. It permits simulation of minimised CO_2 emissions, maximum range, or the achievement of a predetermined energy balance. The results of the simulation serve as an important basis for more efficient precalibration of prototypes.

A hybrid operating strategy including the parameterisation of components, previously developed by Bosch, based on a



❽ Vehicle development using the V-Model

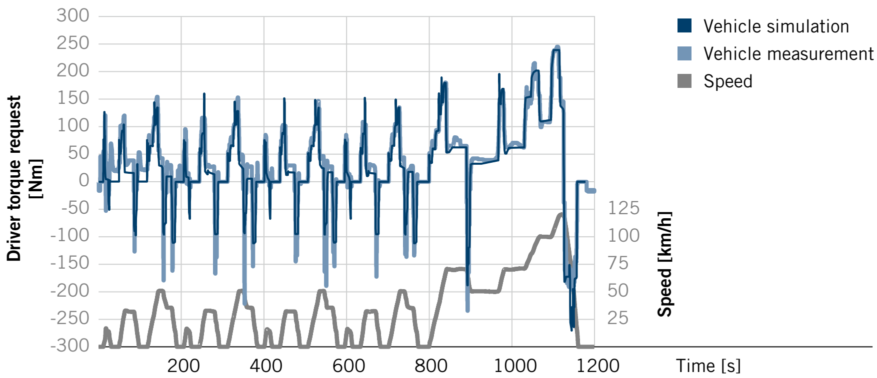
production sports car with parallel hybrid powertrain was integrated. A dll-file was included to allow rapid replacement of individual functions at a later stage. This means it takes very little time to take functions from the hybrid operating strategy and integrate them into the simulation environment or update them. Basic precalibration of the operating strategy is carried out and optimised using the design-of-experiments (DoE) method. The range of parameters is limited to include only the most important. Following simulation of the sets of parameters, a software called Ascmo (advanced simulation for calibration modeling and optimisation) from ETAS GmbH is used to define the optimum precalibration of the operating strategy based on criteria such as CO_2 emissions, range, or energy balance. The result is a basic precalibration of the operating strategy that can be tested in the concept car and calibrated in detail. This method allows computer-aided basic precalibration to be started earlier in the project. This saves development time in the period before construction of the prototype. It also permits a reduction in the extent of calibration in prototype vehicles by employing simulated driving cycles. This makes vehicle development more independent of prototype availability and cuts costs for testing on test rigs.

VALIDATION CONCEPT

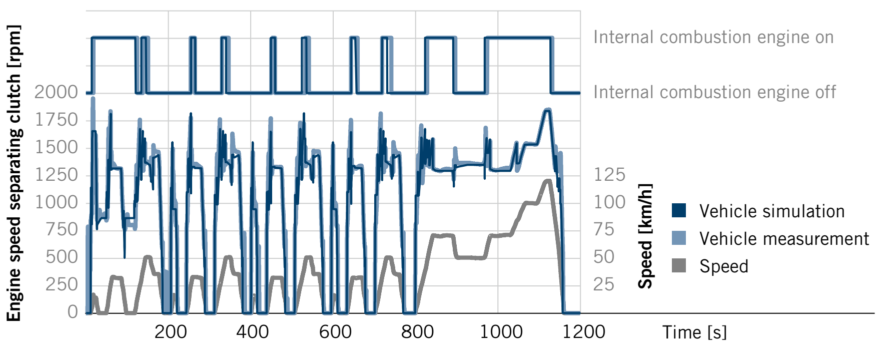
When validating the hybrid operating strategy, the determining factor for the necessary degree of detail of individual subsystems is how well the model predicts physics. This is why the validation concept for cross-domain vehicle simulation is divided into two steps. In the first step, all subsystems or component models are validated separately. To this end, each sub-model is validated against the applicable measurements in its own specialised test environment. Likewise, the ECU code imported to Simulink is validated in its own right against vehicle measurements. This first step ensures that predictions of concept evaluations are as accurate as possible, even before constructing demonstrators and carrying out hardware tests. In the second validation step, the simulation of the entire vehicle – in other words, the overall model – is compared to measurements taken from the vehicle or the prototype. This validation was already performed for a sports car with parallel hybrid powertrain. For the calibration of the hybrid operating strategy, the simulation results were compared to actual measurement data collected on a chassis dynamometer.
❾ and ❿ show the comparison of simulation and measurement data for a parallel hybrid topology in the NEDC. A high degree of correlation between the two data sets can be seen in the engine speed behaviour at the separating clutch, for instance, or in the engine start requests during the cycle. This request depends on factors such as the driver's desired level of torque, the temperature of the catalytic converter or cooling water, and the status of the battery. Here, the simulation data are a perfect match for the required engine starts and detail engine speed at the clutch. The minor discrepancies in engine start requests are a result of the "human" driver's pedal dynamics and the consequent breaching of specific limits that cause an early engine start request. After further development of the ICE model focusing on the warm-up period, with parameters such as cold-start enrichment, secondary air, and heating of the catalytic converter, the simulation results for CO_2 emissions and fuel consumption in the driving cycle are now accurate to 1 %.

OUTLOOK

Future CO_2 regulations pose a major challenge to the sports car segment in view of the powerful engines that are its hallmark. In order to highlight the



❾ Comparison between NEDC measurement and simulation of driver's torque request



❿ Comparison between NEDC measurement and simulation of engine speed, separating clutch, and engine start request

potential of hybridisation to reduce emissions and fuel consumption while also improving vehicle dynamics, Bosch Engineering converted a premium sports car by applying a hybrid powertrain concept to it. In preparation, various powertrain topologies were studied during the simulation's concept phase. Cross-domain vehicle simulation was developed in order to cover the entire vehicle development process with a single simulation platform, bringing together the traditional domains of powertrain, electrical systems, and vehicle dynamics. This allows not just fuel economy cycle simulations but also race track simulations to be carried out with detailed powertrain and vehicle dynamics models.

The cross-domain simulation approach is applied comprehensively, from the concept phase and system design through to vehicle calibration. The platform can for instance be used to integrate ECU software and calibrate it virtually. Implementation of a hybrid operating strategy was the first application selected, with remarkable results. These methods and the knowledge gained will be employed in future projects not only in the sports car segment but also others, for instance off-highway applications. This means the new simulation platform allows cross-domain system projects to be carried out quickly and effectively in a variety of sectors.