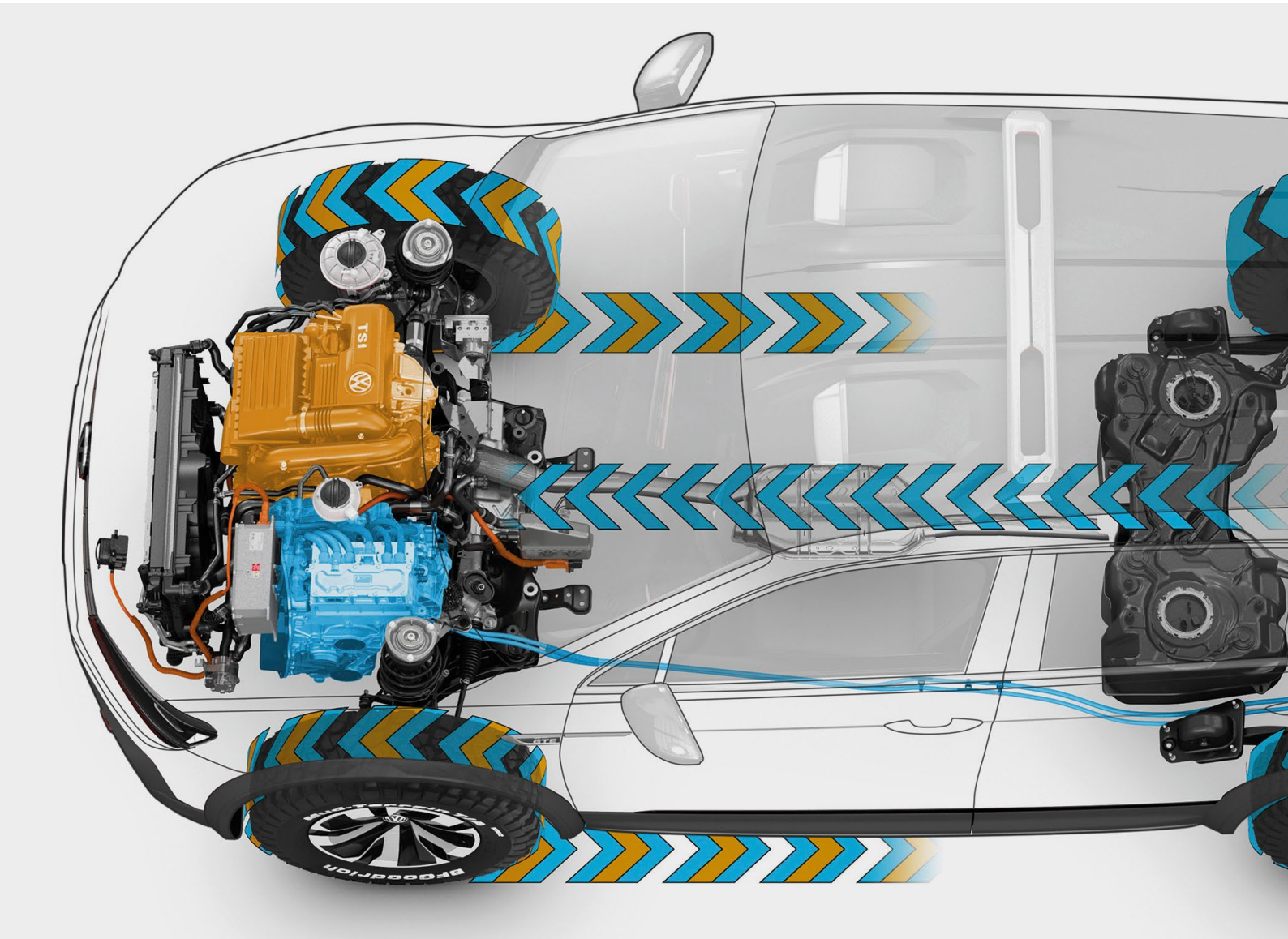
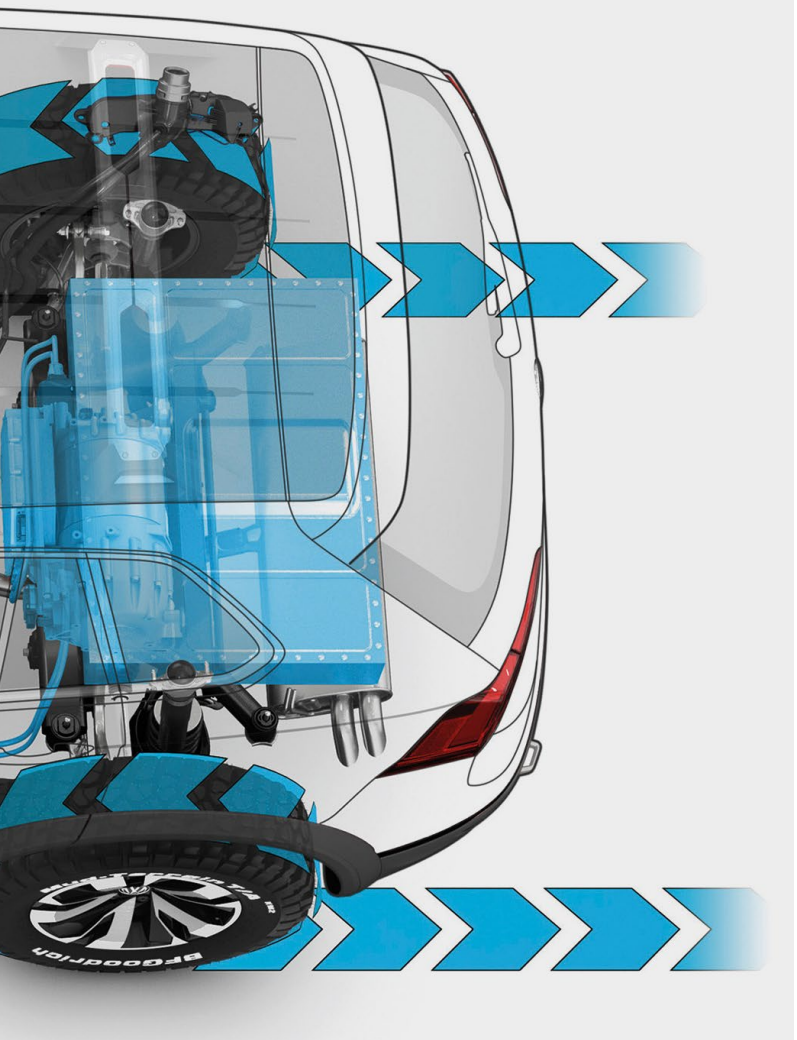
Mastering Complexity – Pre-competitive Collective Research in Hybrid Powertrains

The electrification of combustion engine powertrains enables emissions of both greenhouse gases and exhaust pollutants to be reduced significantly. However, the growing level of complexity that accompanies hybridization is posing new challenges for the development process and the simulation tools used. Through several projects, the FVV Research Association for Combustion Engines is aiming to provide its members with such tools and create a more comprehensive foundation for small and medium-sized industrial businesses.



1 HYBRIDIZATION

The electrification of conventional powertrains plays an important role on the path to carbon-neutral mobility for several reasons. Thanks to the higher powertrain efficiency, greenhouse gases can also be reduced in cases in which the necessary ranges cannot be covered by purely electric vehicles – whether due to the current lack of an extensive charging infrastructure, or due to forms of mobility for which sufficient energy stores are not available. As well as reducing the emission of exhaust pollutants in electric driving mode, by shifting the load point, hybrid powertrains also avoid the combustion engine operating ranges in which particularly high raw emissions are generated. If the electrical range is sufficiently high, modern hybrid powertrains can make an immediate and significant contribution towards lowering pollution in busy urban areas. Even in applications such as construction machinery, in which engine operation frequently switches between full load and idling, fuel consumption can be lowered considerably



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"For future generations of hybrid powertrains, the variety of technologies employed poses fundamental technical questions that need to be answered scientifically."

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"The development method is becoming increasingly important in view of the high complexity of hybrid powertrains. Therefore, small and medium-sized enterprises particularly benefit from generic methods."

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"An electrification of ship propulsion systems operated with alternative fuels can not only lower emissions, but also improve maneuverability."

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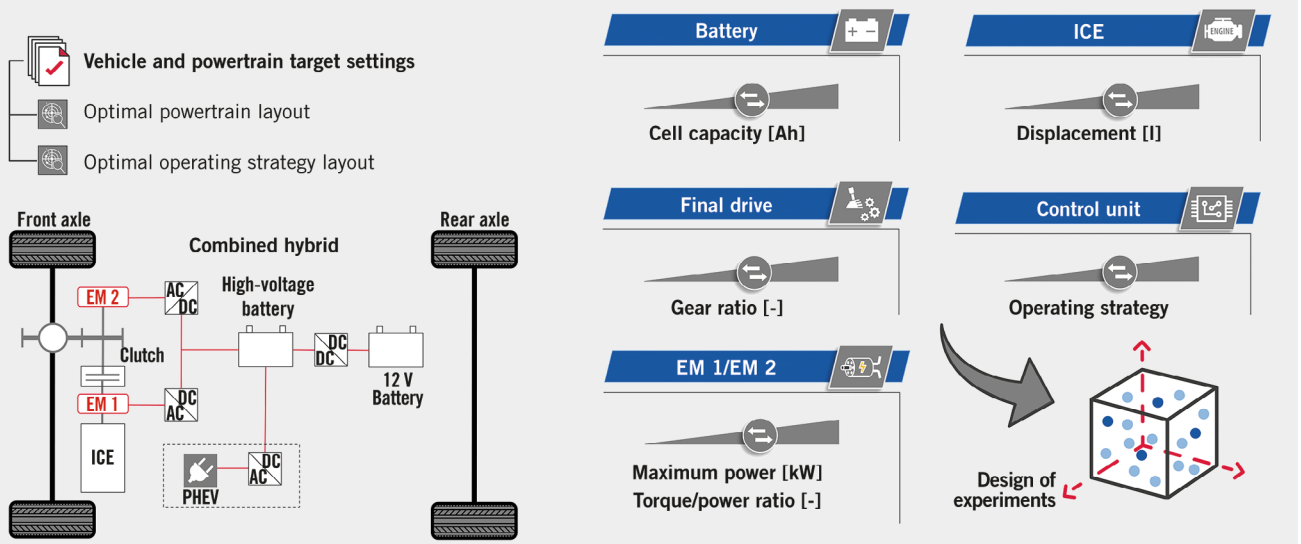

FIGURE 1 Architecture of a serial/parallel hybrid powertrain (left); design parameters for sub-systems (right) (© FVV)

by means of electrical energy recuperation. Ships can be operated in areas near the coast without generating any pollutants, while their maneuverability also improves thanks to electrification.

Current hybrid powertrains possess a broad range of technological approaches, which in part reflect the statutory requirements in individual world regions. It is explicitly not the task of Industrial Collective Research to intervene in the functioning competition among vehicle and engine manufacturers to develop the best technical concept. However, the variety of technologies employed poses fundamental questions that need to be answered scientifically. FVV has identified the following focus areas, among others:

- A large number of technical solutions, the growing number of components and the high degrees of freedom in application are increasing the complexity of the development process, which can only be managed by means of new, software-based methods.
- To enable acoustic optimization when the combustion engine is switched off, the transmission routes of noises that are independent of the powertrain and those that are caused by electrical components must be known, and it must be possible to map these in a simulation.
- Operating strategies must also maintain the full effectiveness of exhaust gas purification when the engine and exhaust system cool down during longer journeys on electrical power.

2 DEVELOPMENT METHOD AND OPERATING STRATEGY

Combining an Internal Combustion Engine (ICE) with one or more Electric Machines (EM) creates powertrain systems for mobility that enable numerous operating strategies, which in turn are significantly influenced by the selected components. In order to also meet interrelated requirements of clients and legislators across the world, the respective operating strategy must also be flexible and function as well as possible. To this end, a holistic development method is needed that enables the powertrain characteristics relevant to real transport applications to be modeled even at an early stage of development. The research project “Highly-flexible internal combustion engines for hybrid vehicles” [1], which has been running since March 2021, addresses precisely this issue; the Chair of Thermodynamics of Mobile Energy Conversion Systems (TME) at RWTH Aachen University was won as a research partner for this project.

First of all, the requirements placed on a car with a plug-in hybrid powertrain (Plug-in Hybrid Electric Vehicle, PHEV) are defined on the basis of market studies, databases and a comprehensive interest group analysis. A reference architecture is derived on the basis of the criteria catalogue compiled through the aforementioned steps. Thanks to two EMs and an intermediate clutch, the dedicated hybrid powertrain enables both serial and parallel drive, **FIGURE 1** (left). The design parameters are defined for all main hardware components, **FIGURE 1** (right). Existing and enhanced simulation models are used to make an exemplary evaluation of the powertrain, which are retained as replaceable tools. For the optimum design of the powertrain, requirements such as low CO_2 emissions, acceptable costs and the acceptability of Noise, Vibration and Harshness (NVH) are taken into account. The limits of the reference architecture are then identified based on simulations of four particularly challenging scenarios, such as a winter drive in Sweden or a journey on German motorways in summer. Individual driving styles and ambient conditions, such as the outside temperature, are also taken into account. The potential for optimizing vehicle operation is investigated using a predictive journey manager, which aims to enable a route-specific operating strategy on the basis of the navigation goal. Furthermore, the potential held by individual technologies and combinations of technological mea-

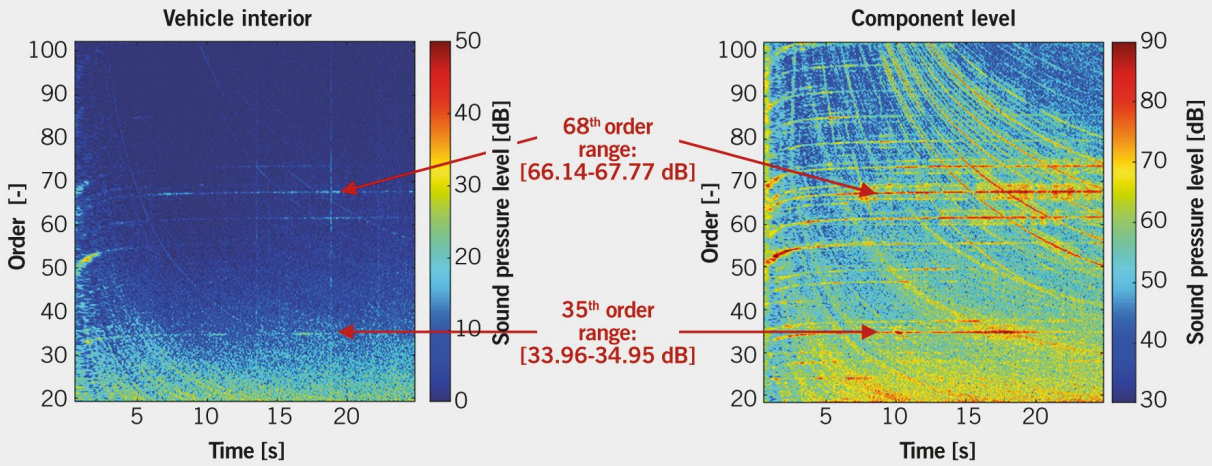

FIGURE 2 Automated analysis of individual noise components from vehicle interior noise using the example of an electrical asynchronous engine (© FVV)

sures is evaluated. Finally, the applicability of the holistic and manufacturer-neutral development method to other hybrid topologies and vehicle classes is to be demonstrated.

3 ACOUSTICS

Alongside sounds emitted by electrical powertrain components, noise components are also audible in electric driving mode that are masked when using a combustion engine. While the noises perceived as being pleasant or unpleasant in combustion engine operation are well known, customer expectations regarding the sound of electrical vehicle powertrains have not yet been described in sufficient detail. Moreover, the acoustic pattern in the vehicle interior cannot be attributed directly with individual powertrain components due to a lack of knowledge of the transmission paths. For this reason, a current research project is investigating characteristics for the subjectively experienced annoyance factor and developing automated methods for allocating individual noise components to the powertrain components that cause them [2]. These psychoacoustic investigations carried out by Industrial Collective Research can thus boost the competitiveness of small and medium-sized companies, which often supply these components.

In the first step, the Department of Experimental Audiology at the Otto von Guericke University of Magdeburg and the TME at RWTH Aachen University are building a noise database that is representative for today's hybrid vehicles. Alongside interior noises, structure-borne and airborne sound signals from the near sound field of the sound sources are recorded for various load scenarios. At the same time, listening tests are conducted using synthetically altered example noises from previous projects in order to quantify the disturbing effect of partially masked noise components. New noise separation algorithms based on image processing methods are then developed so that the components that contribute to the acoustic pattern can be clearly identified. The extracted noise components are sorted by signal characteristics using a classification method and are assigned to the individual powertrain components. In extensive listening tests, test subjects are then to evaluate the overall noises and the effect of individual noise components on the overall noise. While doing so, the audibility of individual noise components can be determined by simulating a psychoacoustic laboratory experiment with a virtual subject. The results of the noise analysis and the listening tests are used to define target noises and program a software solution that enables the automated allocation of measured noise components, **FIGURE 2**, and a noise prediction for technical variants. It is planned to expand this software to cover sound radiation of an asynchronous machine.

4 SHIP PROPULSION SYSTEMS

A complete electrification of maritime transport is still a long way off. In order to contribute to climate neutrality, the use of renewable fuels such as ammonia or methanol will therefore be discussed in the Industrial Collective Research project "Hybrid powertrains for alternative fuels," which has already been applied for. However, this leads to a deterioration in transient behavior in the combustion process in spark-ignition engines. EMs can compensate for this lack of performance when maneuvering in ports and help reduce emissions of exhaust pollutants both here and in areas near the coast. Verified simulation models can achieve a high level of control quality in the hybridized powertrains of special vessels, which are often only built once; these models can replicate the complexity of such ships instead of a prototype, **FIGURE 3**. Therefore, a simulation model covering all maneuvers and the engine model required for these are to be developed in two sub-projects initiated by FVV in collaboration with the Research Association for Shipbuild-

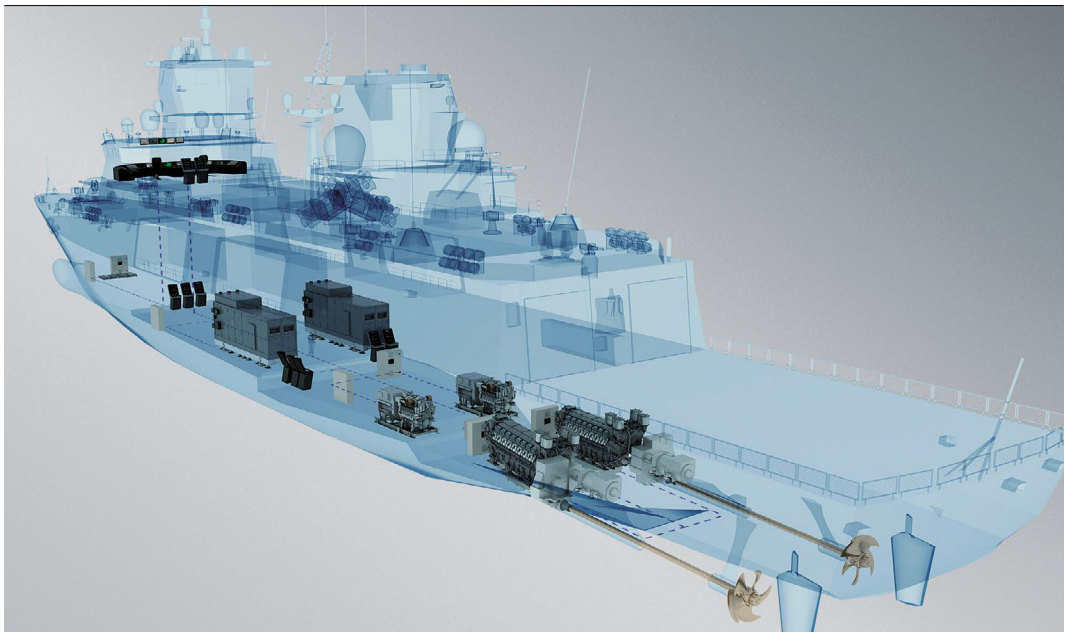

FIGURE 3 Simulation models for hybrid ship propulsion systems to display all system components from the bridge to the rudder (© Rolls-Royce)

ing and Marine Technology (Forschungsvereinigung Schiffbau und Meerestechnik, FSM). The research partners are the Department of Marine Engineering (ASM) and the Institute of Ship Design and Ship Safety (SSI) at the Hamburg University of Technology (TUHH), as well as the Institute for Internal Combustion Engines (ivb) at TU Braunschweig.

In the first sub-project, "Design and maneuvering simulation of ships with hybrid propulsion systems," an end-to-end simulation tool is being developed that maps the behavior of the propulsion system, including propellers and rudders and the ship automation systems. This focuses on safety-relevant maneuvers such as changing course in poor weather or entering and departing docks. The main new features are the lack of predefined time series for individual maneuvers and a detailed description of the individual components of the propulsion system, in particular propeller behavior. In the second sub-project, "Development of engine models for alternative fuels and superordinate control strategies for embedded hybrid propulsion systems," existing knowledge of engine process calculation is to be transferred into a generic model for fast and medium-speed ship engines. This should be possible in real time and offer sufficient precision for embedding in the maneuver simulation. At the same time, a control strategy is to be devised for the entire hybrid powertrain, which avoids inefficient operating modes and malfunctions. Another new feature is the approach of developing different sets of controller settings for different maneuver situations (for example, acceleration or emergency stop), which can be used by the ship automation system depending on the identified situation.

5 SUMMARY AND OUTLOOK

Hybrid powertrains are an important element of the transition towards climate-neutral mobility – for road vehicles, but also for work machinery and shipping applications. In order to gain the full benefit of these, further research is needed regarding their operating strategy and development methods in particular. By making the derived knowledge available via the FVV pre-competitive platform, Industrial Collective Research is making a key contribution towards keeping even small and medium-sized enterprises competitive during the transformation.

The "ICE2025+" project financed with FVV funds has proven that the combination of hybridization and synthetic fuels has the potential to achieve very high levels of efficiency in combustion engine powertrains [3]. The follow-up project "ICE2030" has already begun and it aims to identify further potential for increasing efficiency, including through operation with a high oxygen excess [4]. The results of this will be reported in this magazine.

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