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Frontloading in powertrain development involving hybrid (virtual and real) development environments

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ABSTRACT

In order to reduce the powertrain development time in the context of increasing system complexity, hardware-related development steps are being shifted to early phases using virtual development environments (frontloading) and agile working methods are being introduced. However, implementation in industrial practice is often insufficient. The application of virtual development environments is often not well accepted, especially since accurate, validated simulation models are not available until late in the development process and the competences/expertise of experts in the development environments of different degrees of virtualisation are often insufficiently brought in jointly and in an agile approach during their development. This is where the publication steps in, introducing a development approach for the agile development, application and further development of validated simulation models and presenting its application and added value on the basis of two practice-relevant case studies (powertrain design, development of torque coordination). It is shown that how real and virtual development environments can be applied in an interconnected way so that frontloading in the real development process succeeds in an agile way. The resulting outcomes are discussed and summarised.

1. Introduction

To achieve climate-neutral mobility, considering the vehicle life cycle and including regional aspects, different powertrain concepts and systems, some of which are highly complex, will be used in the future [1]. At the same time, the development duration of vehicles is to be significantly reduced. Volkswagen, for example, set the future goal to execute vehicle projects within 40 months instead of the current 54 months. To achieve this, the development process is to be focused on functions and systems instead of components (systems engineering) and agile working methods are to be applied [2]. For this purpose, result-critical development steps must be moved forward into early development phases using virtual development environments (frontloading) [3]. Its successful application has already been demonstrated in the context of projects, such as the virtual application of the powertrain and the complete vehicle [4–6]. However, virtual methods are often not recognized in industrial practice [7]. One reason for this is the delayed availability of validated simulation environments in the development process. Moreover, the confidence in the applicability of the particular simulation models depends on the accuracy of the modeling of the properties under investigation and the quality of the validation data. In many cases, the competencies/expertises of experts from the development environments of different virtualization levels (simulation, test bench, test vehicle) are also insufficiently incorporated in modeling/simulation and validation. Furthermore, there is often a lack of a change of perspective and thus also a lack of associated application of the different development environments [8].

In addition, powertrain development still mainly uses "classic", so-called plan-driven development processes, which are too rigid to react sufficiently to the new dynamic environments [9]. One approach is to transfer agile work with methods from software engineering to powertrain development. Since research in the field of agile powertrain development is currently emerging, case studies are recommended for this purpose [10].

This leads to the question: How can real and virtual development environments be applied in an interconnected way so that frontloading in the real development process succeeds in an agile manner? For this purpose, a development approach for agile development, application and further development of validated simulation models is introduced and its application and added value is presented based on two practice-relevant case studies.

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2. Materials and methods

In this section, the applied development environments and the development approach to their interconnected application are presented.

In practice, development environments with different degrees of virtualization have been established for years. In addition to purely real systems in a real environment (test vehicle for RDE driving), X-in-the-Loop techniques (XiL) are used in which real or virtually realized (sub) systems are integrated into a virtual environment so that their testing, application and further development are possible in a reproducible manner in an early development phase. This approach is particularly used for simulation models (Model-in-the-Loop, MiL), for mechatronic (sub)systems (Hardware-in-the-Loop, HiL), but also for engines (Engine-in-the-Loop, EiL) and the complete vehicle (Vehicle-in-the-Loop, ViL).

The subsystems engine, transmission, driver, vehicle and environment are represented in different degrees of virtualization. While development environments with a high degree of virtualization enable very high reproducibility and flexibility of the test environment in its application, real development environments deliver practical results. At the same time, the development environments are mutually dependent on each other, see Fig. 1.

Thus, on the one hand, the validation of virtualized subsystems can only be carried out on the basis of real systems, and on the other hand, the testing and adaptation of virtually applied parameters must be carried out on the real system. This makes it possible to detect potential effects and interactions that have not yet been adequately represented in the virtual model. This must then be adapted and revalidated. This results in an iterative process applying the development environments of different virtualization levels in an interconnected manner. To investigate how frontloading can succeed, the development environments developed/applied in this study (simulation, engine test bench of a hybrid powertrain, chassis dynamometer) are described below:

Simulation model

A hybrid vehicle with an electric machine and an internal combustion engine is modeled. MATLAB/Simulink® is used to set up the virtual development environment. The modeling process complies to the following guideline, so that the simulation model is as simple as possible but as elaborate as necessary:

Simple

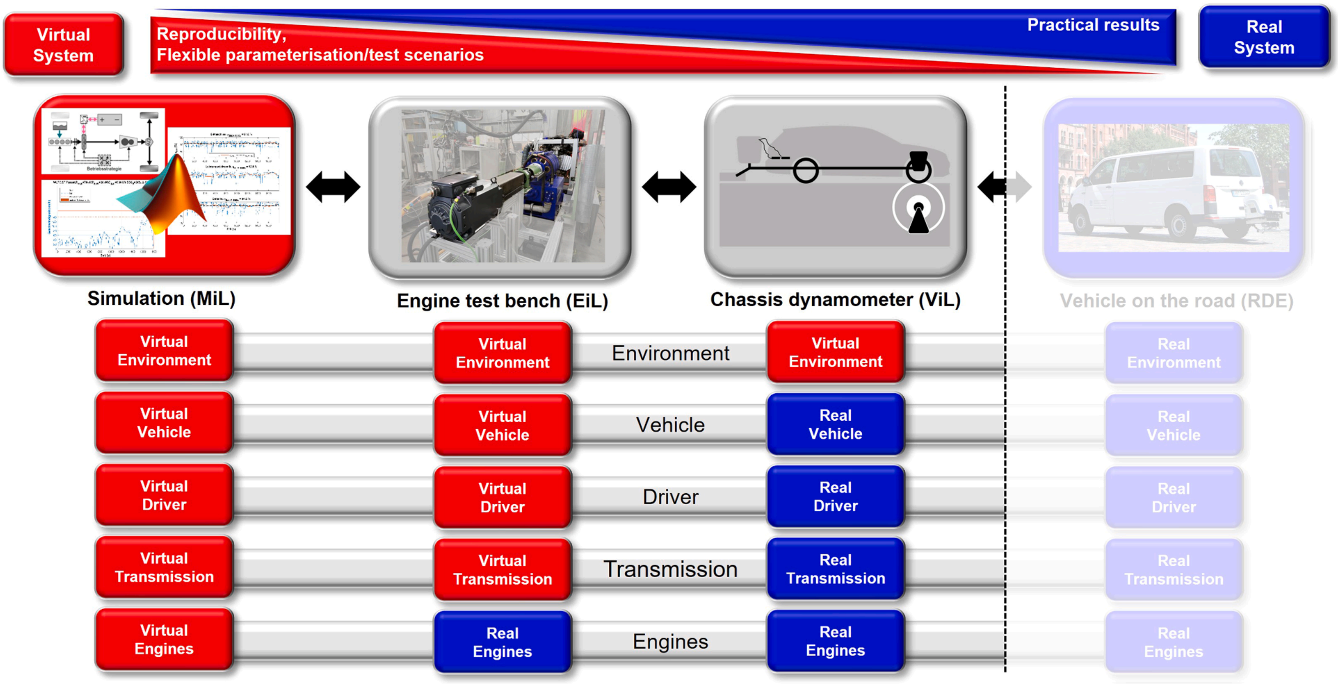
- Use existing validated models.
- If no models exist, create black-box models using experimental data as a map (linear interpolation between the data points and no extrapolation).
- Model main influences on the energy demand of the vehicle:
  - Driving resistances (air, rolling, climbing resistance)
  - Vehicle inertia (translational and rotational)
  - Powertrain efficiencies (motors, inverter, battery, and transmission)

Elaborate

- Starting from the simple approach, properties that have been insufficiently mapped are modeled step by step by replacing the black-box models with gray- and/or white-box models.
- Existing interactions and those to be investigated must be modeled (In the case of black-box models, this requirement means that the interactions must also be represented as a black-box model. This is usually not necessary for gray- or white-box models).

Therefore, a longitudinal dynamics model approach is selected for the modeling: Influences from lateral/vertical dynamics are not considered, since their influence on CO_2 emissions is small relative to longitudinal dynamics. In addition, a backward model approach is chosen for the vehicle model, in which the input variables are the speed of the vehicle and the inclination angle of the road. The propulsive torque that must be available at the wheels can be determined from the most important characteristics of the vehicle as well as the drive train, see Fig. 2.

In the process, the energy management strategy was determined using measurement data from a midsize plug-in hybrid electric serial vehicle. After verification and validation, which were performed using the same measurement data, the simulation model or parts of it can be used for system architecture studies, parameter studies and concept studies. In particular, the calculated engine torque and speed are used to



	Simulation (MiL)	Engine test bench (EiL)	Chassis dynamometer (ViL)	Vehicle on the road (RDE)
Environment	Virtual Environment	Virtual Environment	Virtual Environment	Real Environment
Vehicle	Virtual Vehicle	Virtual Vehicle	Real Vehicle	Real Vehicle
Driver	Virtual Driver	Virtual Driver	Real Driver	Real Driver
Transmission	Virtual Transmission	Virtual Transmission	Real Transmission	Real Transmission
Engines	Virtual Engines	Real Engines	Real Engines	Real Engines

Fig. 1. Virtualization in powertrain development.

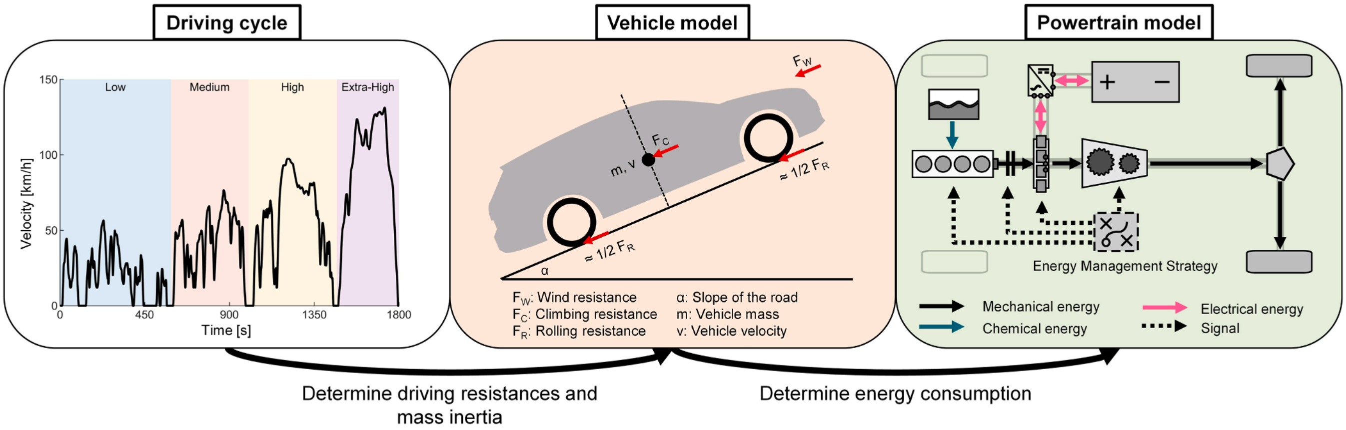


Fig. 2. Schematic structure of the kinematic simulation approach.

predict fuel consumption and CO_2 emission, respectively, based on the sequence of steady-state operating points [11–13].This involves a combined consideration of the CO_2 emissions generated by the internal combustion engine and those generated during electricity production [14]. For this purpose, the variable $CO_{2\text{-VKM-BAT}}$ is introduced, with which it is possible to make a more general statement about the efficiency of the hybrid vehicle under investigation.

To analyze the energy efficiency of the modeled powertrain, the efficiencies of the frequency inverter, electric machine and combustion engine are modeled as experimental black-box models based on efficiency maps. The battery is modeled on the basis of an equivalent circuit modeling method. For this approach, empirical data of internal resistance and open circuit voltage of a common Li-Ion cell are used. The operation strategy is rule-based and includes typical operation functions of a hybrid vehicle [15]. It is modeled on the basis of decision logics determined in preliminary tests on a hybrid vehicle in a state machine using Stateflow®. The assumptions and specifications made, simplify the modeling and simulation effort [16] and do not require elaborate physical modeling of the subsystems in the first step.

Multiple verification and validation of the simulation model is performed using the DoE method [17], which enables parameter study for simulation verification and can reduce the number of WLTP runs on the chassis dynamometer.

Engine test bench

The engine test bench of a hybrid powertrain or hybrid test bench was developed and implemented at University of Applied Sciences Hamburg. It consists of a 20 kW asynchronous machine (ASM), which can be operated in 4 quadrant mode with a 30 kW battery emulator and a frequency inverter, whose adjustable speed range was limited to 0 - 6000 rpm. A 90 kW four-cylinder gasoline engine with 1.4 l displacement and turbocharging is used as the internal combustion engine, see Fig. 3.

Both engines are coupled via a removable cardan shaft and an eddy current brake, which operates as a passive dynamometer. The internal combustion engine measurement variables are recorded using a measurement system from ETAS. In addition, all measured variables relevant to hybrid operation are processed using a MicroLabBox from dSPACE. This system is also used to control the torque of the asynchronous machine and the driver's desired torque of the combustion engine and its allocation into the torque components of the combustion engine and the asynchronous machine.

Separate or coupled operation of both engines is possible on the test bench. Using dSPACE's ControlDesk development environment in conjunction with MATLAB/Simulink®, operating functions such as boosting, load point reduction, and load point increase [18] can be integrated and executed automatically in defined cycles. Recuperation or general towing operation is not possible, due to the passive dynamometer. This enables reproducible maneuver-based test drives on the test bench, where the systems surrounding the engine (in particular the environment, driver and vehicle) are simulated (Engine-in-the-Loop, EiL). This enables investigations and predictions of the fuel consumption and emission behavior of a real engine, the validation and further development of simulation models, and also the function development.

Chassis dynamometer

With the chassis dynamometer at HAW Hamburg real vehicles can be reproducibly tested in an idealized environment by specifying time-varying driving resistances that are applied to the driven axle (Vehicle-in-the-Loop, ViL).

For this purpose, the driving resistances such as air resistance, rolling resistance, climbing resistance and translatory acceleration of the vehicle are modeled depending on the vehicle data in the simulation environment and generated by a DC motor on a roller, see Fig. 4.

The chassis dynamometer makes it possible to run reproducible driving profiles. The study uses real drivers who generate non-reproducible factors, such as varying acceleration behavior. These can lead to changes in shift timings and thus to variations of the energy effort.

Development approach

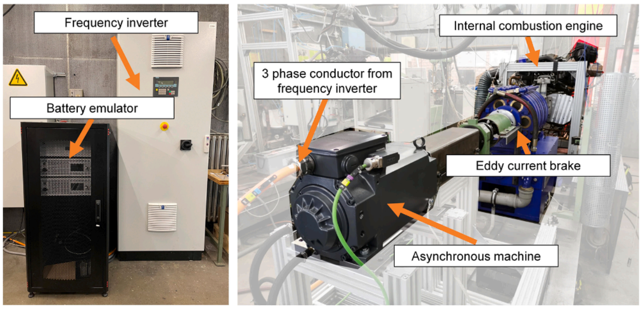


Fig. 3. Engine test bench of the hybrid powertrain.

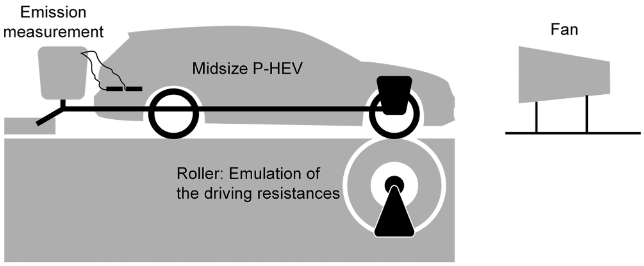


Fig. 4. System architecture chassis dynamometer.

Agile hybrid (real/virtual) model-based powertrain development is introduced and investigated as a development approach. Here, development is carried out interactively by a self-organized, interdisciplinary team [19].

Within this development approach, two definitions are introduced to describe the origin of validation and parameter data: Primary data and Secondary data. Primary data refer to data that are obtained from the real (sub)system that is to be developed (target system or primary system). They are only available with its prototype. In contrast, secondary data are obtained from an already developed real (sub)system (e.g. serial vehicle or in general secondary system) whose physical properties and measurement data represent those of the target system sufficiently accurately with respect to the properties to be modeled. However, while the qualitative difference between the primary and secondary data is required to be minimal to successfully apply this approach, the quantitative difference can be significant. Therefore, the models based on secondary data should be applied for qualitative investigations. If secondary data are available at the beginning of the development process, this enables model-based development at an early stage of the project.

The following specifications and requirements are made for the development approach:

- Development environments of different virtualization levels are to be used.
- The simulation environment (simulation model in the virtual development environment) must be available as early as possible in the development process. To this end, it should be as simple as possible and as elaborate as necessary in order to represent the properties to be investigated in a model-based manner. For this purpose, all existing validated models are used in the first step and stationary black-box models are created experimentally for non-modeled properties.
- Extensions of the simulation environment take place step by step and modularly. Verification and validation are performed in the same way.
- For validation, secondary data are used first and - as soon as available in the development process - primary data.
- Replacing the secondary data with primary data is done simultaneously for all parameters belonging to a subsystem. This prevents the creation of an unknown subsystem.
- An agile method similar to Scrum [20,21] is used. Here, analogous to software development, small completed parts of the development are carried out iteratively in so-called agile sprints in short periods of time (weeks) and it is checked whether their results can be passed on for further applications. For this purpose, regular short meetings are held to update the interdisciplinary team and to discuss and solve the project progress or current problems [22].

Procedure Development Approach

The process of the development approach is schematically shown in the Fig. 5. It makes use of the processes already known from the V and W models [23,24] as well as its applications [25–27] and extends them by using secondary data and primary data, as well as using agile working methods to further develop the simulation environment. It begins with the development of the simulation model in the virtual development environment. This should be as simple as possible and as elaborate as necessary and should only represent the properties to be investigated. Attention should be paid to stringent and easily modifiable parameterization in order to facilitate model adaptations and to be able to investigate test cases flexibly and automatically. Verification as well as model adaptations and extensions are carried out using the DoE method by evaluating a parameter variation iteratively in an agile sprint (S) within the interdisciplinary team. This can already be done in the simulation environment [17]. During validation, possible model errors and inaccuracies as well as existing and relevant but previously not modeled effects are detected and corrected or integrated at an early stage by comparison with validation data. In particular the dynamics and energy efficiency of subsystems and their interaction when interacting in the overall system on the engine test bench or chassis dynamometer must be considered. As part of the agile sprints, as many iteration steps take place until the simulation model represents the specified properties of the secondary system under investigation sufficiently accurately.

After the development of a functional first version of the simulation model, it can particularly be used in relation to the validated properties for function development. Typical examples are the design of the controller parameters of a torque controller, the development and

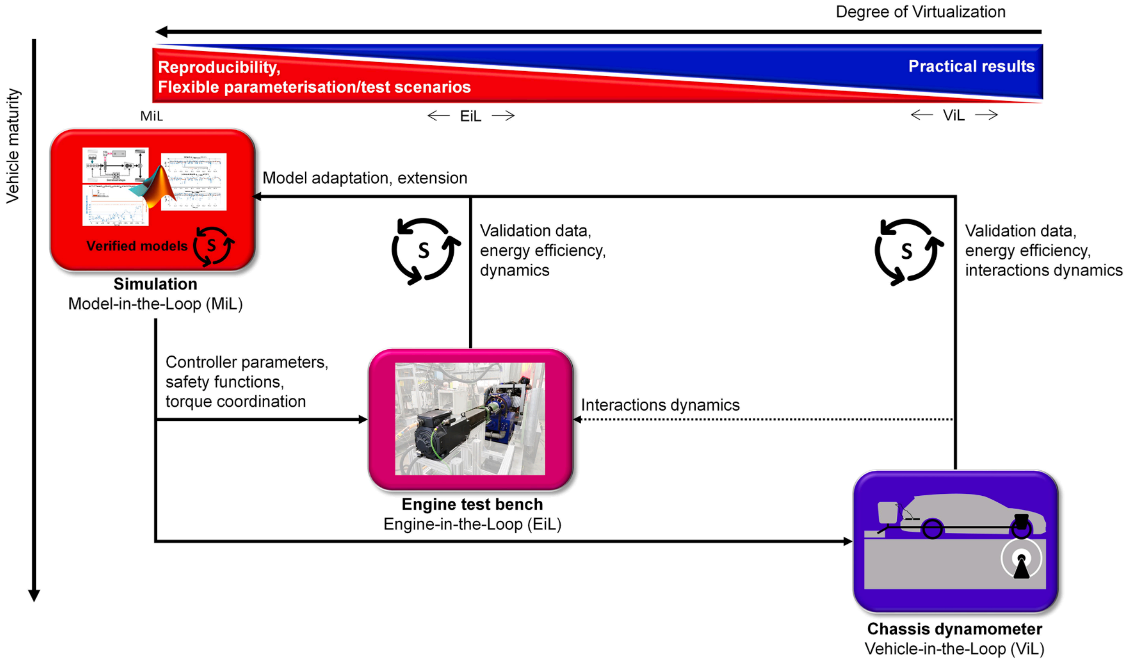


Fig. 5. Development approach: process, interaction in the development environments.

integration of safety functions, and the development and integration of a control concept of the target torques of a hybrid powertrain (torque coordination). In addition, the simulation model can be further developed using primary data, especially if unknown and relevant but previously insufficiently modeled properties or interactions are discovered in the later developed primary system. In this case, validation with the primary data also takes place in agile sprints in an interdisciplinary team using the development environment required in each case.

For the successful application of the process, the project team has specialists and interdisciplinary competencies, see Table 1.

In particular, experts from all development environments and later users have to be actively involved in the development process. In addition, a senior expert with many years of development experience with development environments of all virtualization levels should closely accompany the project or provide advice.

3. Application of the development approach

In the following, the development approach is applied in two qualitative case studies to investigate how frontloading succeeds in an agile manner in the real development process.

Powertrain design

When designing a powertrain, the aim is to define the parameters of the various subsystems for a specific vehicle while complying with the statutory CO_2 emission limits [28]. In the example of a powertrain design presented here, a midsize plug-in hybrid electric vehicle (PHEV) is considered. The backward, longitudinal dynamics simulation model used for this purpose is based on secondary data from a serial vehicle. The remaining system parameters are scaled, in particular the fuel consumption and the maximum torque proportional to the ratio of the set power divided by the original power. Based on a grid test plan with parameter variations, the associated tests are carried out automatically in the simulation with Matlab/Simulink using a script.

The analysis and evaluation of the parameter variation is carried out using the DoE method. In the first step, cumulative values are determined for relevant target variables for the individual sections of the WLTP cycle and polynomial models are formed: cumulative, corrected CO_2 emissions ($CO_{2\text{-VKM-BAT}}$), rate of electric driving (rate E) and number of combustion engine starts (start VKM). The models can be used to determine the significances of each parameter on the target variables and interactions. All recorded results from the 1080 test points in this example are then visualized according to the method presented in [17].

Agile working methods are used here primarily for the modeling and simulation as well as analysis and evaluation. The development team is set up for both use cases in such a way that the core competencies of the people can be utilized. Thus, the team is composed of experts in modeling and simulation as well as powertrain physics and their application. They meet at eye level (no hierarchical differences) and are in a constant exchange so that questions and problems can be solved directly. The expertise for analyzing and evaluating the results lies primarily in the DoE method, powertrain physics, data processing, and data management. For a successful exchange between all team members during analysis and evaluation, a comprehensible presentation of the results is essential. For this purpose, an example from the present use case is shown below.

Table 1
Subject-specific and generic competencies.

Professional competences	Interdisciplinary competences
Physics of the powertrain	Teamwork
Measurement technology and signal processing	Willingness to learn
Data processing, analysis and management	Open mindedness
Modeling and simulation	Communication culture
Control engineering	Feedback culture
Methodological competence (DoE, XiL, Scrum)	Failure culture

For this purpose, Fig. 6a shows the parameter space of the influencing variables power of combustion engine (PICE), power of electric machine (PEM), type of electric machine (EM), energy content of battery (EB), start state of charge (Start-SoC), and the section of the considered test cycle (Section WLTP) as well as the target variables.

The significance of the influencing variables on the target variable $CO_{2\text{-VKM-BAT}}$ is shown in Fig. 6b. For a clear presentation, the averaged value of the target variable of a parameter is determined. This figure can be used to illustrate the average trends of individual parameters, which means that an initial statement can already be made about the powertrain design. This figure shows that an EB of 13 kWh and a start-up SoC of 60% are optimal in relation to the target value for the vehicle under investigation.

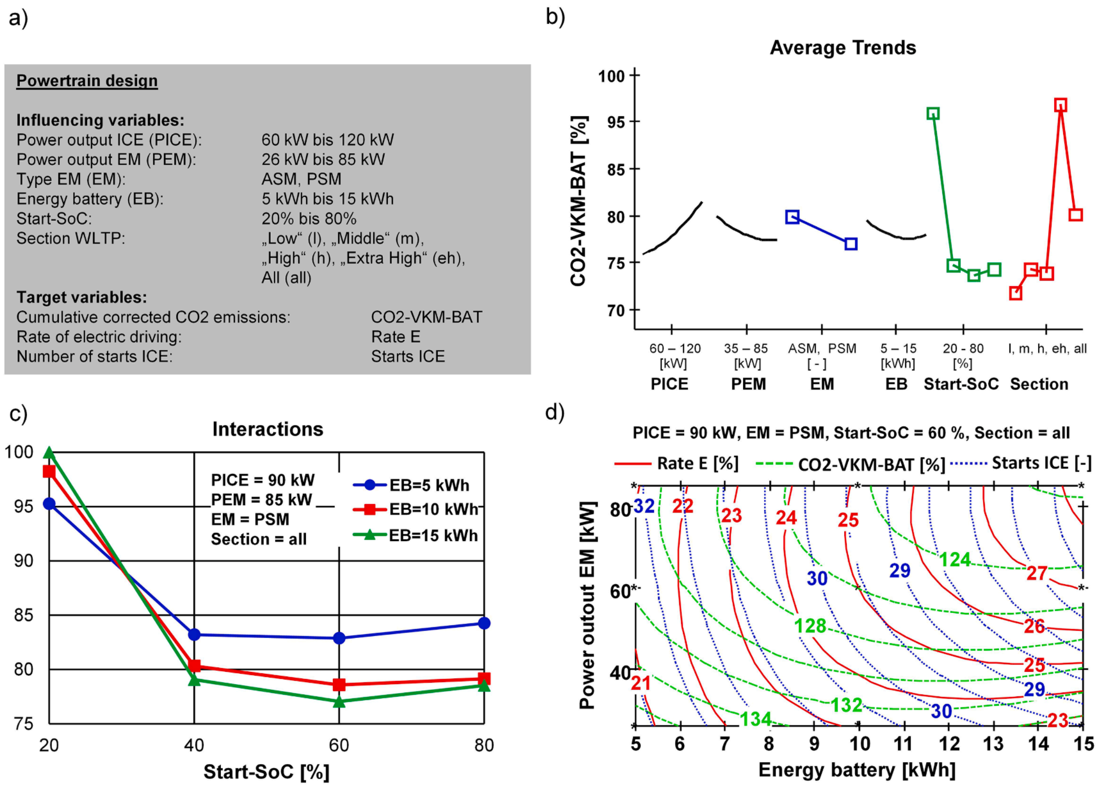
To better analyze the system behavior and sharpen the understanding of the system, the most significant interactions are considered. The interaction between the start SoC and EB shown in Fig. 6c applies to the shown parameter combination. The interaction indicates that the curves are shifted in parallel, on the one hand, and that the gradients of the curves are different, on the other hand. The reason for the increase of the curves at SoC $\leq$ 20% is the energy management strategy, which activates the battery deep discharge protection at SoC $\leq$ 20% and does not allow further discharge. In this case, the vehicle with the largest battery and thus the largest mass produces the highest CO_2 emissions. As soon as the battery has enough starting energy, the largest possible battery is optimal for this parameter combination for the target value.

Fig. 6d shows the contour plot for all target variables in the parameter space PEM and EB for the shown parameter combination PICE = 90 kW, EM = PSM (permanent magnet synchronous motor), Start-SoC = 60% and section = all. For this parameter combination, it is found that the lowest value for $CO_{2\text{-VKM-BAT}}$ is obtained for the largest possible electric machine (PEM = 85 kW) and large battery (EB = 15 kWh). This is due to both the high rate of electric driving (rate E), which reaches its maximum there, and the good utilization of the large battery by a powerful electric machine. The latter is another visible interaction between PEM and EB in terms of $CO_{2\text{-VKM-BAT}}$. At smaller values for PEM, the optimum of the EB also moves to smaller values. This effect is due to the power limitation of the battery, which is set in the battery management. Since the battery also has less power available as its capacity decreases (when considering same cell size and type), the power available to the electric machine decreases. This effect is weakened by the fact that the battery becomes lighter as its capacity decreases. Nonetheless, it is clear from this result that, from an energy point of view, the power of the electric machine and the battery capacity should be matched. This ensures that the weight of the battery is only as large as is sensible for the efficient utilization of the power limit of the battery by the electric machine.

This use case shows the advantage of secondary data, which lies in the early application of the simulation environment enabling early investigations that improve the system understanding. Since the powertrain parameters and consumption data of a serial vehicle were available, it was possible to generate simulation results at an early stage using the modeling methods shown and subsequent verification and validation with the secondary data. Thus, powertrain concepts as well as energy management strategies could be reliably evaluated in relation to each other. In addition, it is shown that secondary data do not need to quantitatively predict the primary systems developed later, they are only intended to analyze trends of their relevant properties.

Torque coordination development

To enable investigations of operating functions such as boosting, load point reduction and load point increase on the engine test bench in the future, a torque coordination is being developed according to the process shown previously. This is the control concept for distributing the driver's desired torque to the individual target torques of the internal combustion engine ($T_{SP,ICE}$) and asynchronous engine ($T_{SP,ASM}$) as well as the distribution of the signals to the control units of the respective engine. The torque coordination is developed/verified in the simulation


a)

Powertrain design

Influencing variables:

Power output ICE (PICE):	60 kW bis 120 kW
Power output EM (PEM):	26 kW bis 85 kW
Type EM (EM):	ASM, PSM
Energy battery (EB):	5 kWh bis 15 kWh
Start-SoC:	20% bis 80%
Section WLTP:	„Low“ (l), „Middle“ (m), „High“ (h), „Extra High“ (eh), All (all)

Target variables:

Cumulative corrected CO2 emissions:	CO2-VKM-BAT
Rate of electric driving:	Rate E
Number of starts ICE:	Starts ICE

Fig. 6. Parameter study powertrain design.

environment and integrated on the engine test bench. The manufacturer’s control of the torque within the control units of the engines (torque structure) remains at the factory settings.

The requirements for torque coordination are established in advance and relate to the functional scope and safety of the function. It is specified that all operating functions of a hybrid powertrain should be included in the functional scope, considering the limited possibilities of a passive load machine: boosting, load point reduction and load point increase. In addition, torque coordination is to be safeguarded against erroneous inputs and undesired setpoint values during operation function switching. The following safety functions are to be integrated:

(A1) The electric machine must not be operated above the speed limit of the combustion engine.

(A2) The electric machine must not be operated in reverse.

(A3) The electric machine requires the same torque setpoint for both motor and regenerative operation, which must be reset when switching between the two modes.

Simulation is used for the development and testing of functions and the design of characteristic curves and control parameters. The developed functions are then integrated on the engine test bench, after which validation data can be acquired. The following challenges have arisen during the integration:

(B1) The torque model stored in the control unit of the asynchronous machine deviates from the real measured value, which makes its torque control stationary inaccurate. To solve the problem, an additional measurement of the torque of the ASM is integrated using a measuring shaft. This provides the measured variable for implementing a cascade control of the torque. The PI controller of the outer control loop is set using the frequency characteristic method, and its operation is performed with the MicroLabBox from dSPACE. The inner control loop is operated unchanged with the manufacturer’s control unit.

(B2) The linear simulation model does not fully represent the dynamic behavior of the real system in all operating states. This is due in particular to nonlinear interactions of the asynchronous machine with other system components, so that deviations in the raise time, settling time and the overshoot between the simulation model and the real system occur in the controlled system. However, these are of an acceptable order of magnitude for the application, so that no more in-depth control engineering investigations/adaptations had to be carried out and the simulated control parameters were adopted for the real system.

With the integration of torque coordination on the motor test bench with the solutions to challenges (B1) and (B2), it is possible to set the operating functions boosting, load point reduction and load point increase and to measure the energy flow. In addition, it is possible to preset all target values automatically in a sequence and to record the measurement data during this process. Furthermore, intensive safety tests were carried out in the simulation and on the engine test bench. The torque coordination could be secured within the simulation environment against faulty inputs and undesired set values during changeover processes. The torque structure of the engines cannot be modeled due to a lack of knowledge of the manufacturer-specific control concepts. Therefore, additional tests with the torque structure are performed on the engine test bench. The result of the investigation is that the torque structure of the electric machine is already designed for operation with an internal combustion engine and, in combination with the safety functions A1) to A3) of the torque coordination, cannot trigger any critical cases.

The development of the torque coordination as well as its safety functions has taken three iteration loops, which are depicted in Fig. 8. In the first iteration, the relevant secondary data are collected and examined for their plausibility. Then, the functional structure of the torque coordination and safety functions as well as the black-box motor model are built in the simulation environment and subsequently verified. In the second iteration step, the individual components are virtually integrated into the next higher system level. In this step, the parameters of the functions are adapted to the virtual engine model. Subsequently, it is verified whether the functions also work as expected when considering a dynamic torque behavior. In the final step, the function is integrated on the engine test bench and the function parameters are adapted to the real behavior.

This use case shows that the weighting between real and virtual development environments should be interpreted differently depending on the use case. If the development process shows that the primary system and secondary system are similar, the number for further tests in real test environments can be reduced. In addition, this use case shows that in system development it is important to provide the agile team with a continuously updated overview of all pending tasks including their monitoring. In this way, tasks can be prioritized and the workflow can be maintained. Lastly, the development team has expertise in the areas of function development, measurement technology, control engineering, powertrain physics, and signal and data processing.

Fig. 7.

4. Discussion

The early development and application of a simulation model that is as simple as possible and is expanded stepwise and modular strengthened improves the system understanding for the vehicle to be modeled or the functions to be created. This understanding was further expanded and deepened both in the powertrain design and in the development of torque coordination.

The verification and validation of the simulation model was initially carried out using secondary data and later, as soon as available, using primary data. This enabled qualitative statements to be made about the powertrain at an early stage and a modular extension of the models and functions as well as the integration of test cases to be carried out.

The consequent application of the methods of signal and data analysis – from the plausibility check and conditioning of the measurement signals via feature extraction to the analysis of the system behavior with the help of the DoE method – is the basis for the validation of the results and the gain of knowledge in both case studies. Various topics are linked with it. In particular, its application has significantly reduced the time required for validation and adaptation of the simulation models. The visualization of the system's behavior, which can be easily interpreted, plays an essential role in this context.

By dividing large work packages into smaller subprojects that were worked on in agile sprints (1–4 weeks) in an interdisciplinary team, the development time was significantly reduced. In particular, the frequent short meetings involving all team members relevant to the subprojects led to accelerated development in both use cases. This meant that the simulation model could be verified and validated at an early stage by incorporating the joint expertise from modeling/simulation/powertrain technology as well as data and system analysis. At the same time, confidence in its application was strengthened regarding the jointly defined application area.

During the development of torque coordination, it became apparent that the interconnected application of virtual and real environments in agile sprints with drive engineers, function developers, and measurement and control engineers is a prerequisite for reliable integration of functions on the real system.

Open, clear and appreciative communication as well as flexibility in the team were shown to be particular success factors for agile collaboration. Problems and mistakes were seen as a joint challenge and an opportunity to learn and not as the failure of individuals. Since successes are achieved together, this strengthens the motivation and cooperation of the team members. This positive error culture is an important prerequisite for establishing frontloading.

Moreover, the development environments could be further developed mutually. For example, during the development of the torque control in the virtual development environment, it became apparent that a more precise torque measurement was required in the real development environment. This was then integrated. On the other hand, nonlinear effects occur during the experimental system analysis, which had to be considered in the controller design and its subsequent application in the real system.

In addition to the technical and interdisciplinary competencies described in the development approach, it has been shown that close project support or consulting by a senior expert with many years of experience in powertrain development with development environments of all virtualization levels is an important success factor. With the support of his recommendations, errors can be identified and eliminated at an early stage, systemic effects and interactions can be interpreted, and results can be processed and utilized in a customer-specific manner.

Both qualitative case studies illustrate that and how frontloading can succeed using the development approach introduced and which prerequisites are necessary. This shows that agile working with software development methods can be transferred to powertrain development. In particular, development environments with different levels of virtualization and complexity can be used in conjunction with the corresponding data models. Based on this, more in-depth quantitative investigations related to specific use cases are recommended in further studies.

5. Conclusion

This study presents an agile development approach, and its applicability was demonstrated based on 2 practical use cases. These show how it can be used to link real and virtual development environments so that frontloading in the real development process succeeds in an agile manner. The following findings were obtained from the qualitative case studies:

- The development approach strengthens system understanding and enables frontloading on the basis of simple simulation models that can be extended in a step-by-step modular manner.

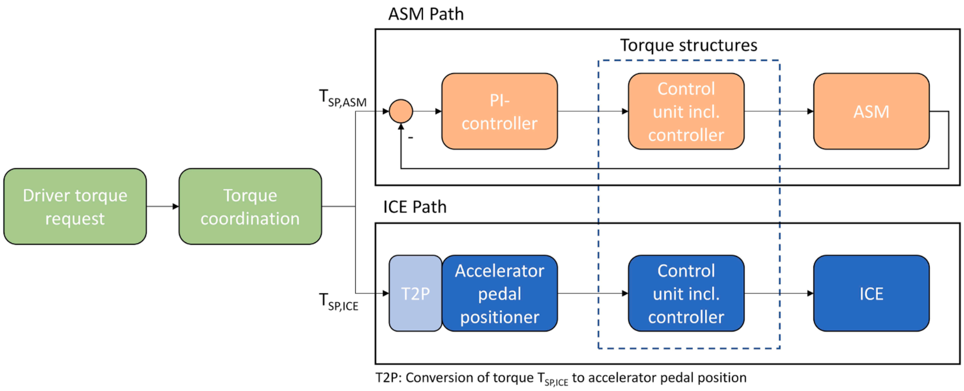


Fig. 7. Schematic structure of torque coordination.

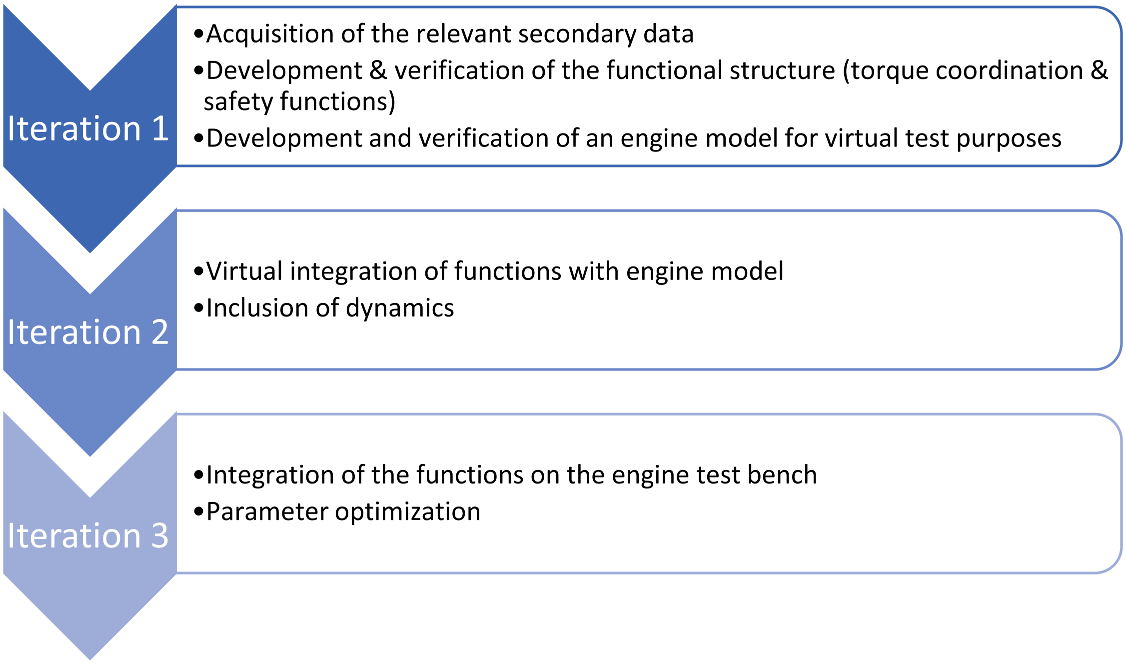


Fig. 8. Iteration loops to development the torque coordination.

- Secondary data enables early development and validation of simulation models and is replaced by primary data as they become available.
- Data analysis, DoE and visualization are the basis for validating results and gaining insights.
- Agile sprints accelerate the development process, increase flexibility and strengthen cooperation in powertrain development.
- The mutual use of the virtual/real development environment takes place depending on the use case.
- Mutual further development of the virtual/real development environment is possible.
- For successful application, professional and interdisciplinary competences and experience are necessary, in particular:
  - Powertrain, measurement and control engineering
  - Modeling, simulation, design of experiments, data analysis and data management, visualization
  - Methodological competence (virtual/real)
  - Mindset, communication, failure culture
- A senior expert with many years of development experience with development environments of all virtualization levels should closely accompany the project or provide consulting support.
- The development approach can also be used for other powertrain configurations than the one investigated.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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