Towards Smart V2X-Connected Powertrains

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***Abstract*—In the context of an increasing electrification and automation of future mobility, the research and development of efficient powertrains requires enhanced test methods. One important aspect is to consider the complex interactions between a smart driving strategy, the traffic flow, the energy demand and emissions of an individual vehicle as well as the corresponding overall values. Until now, the respective development domains traffic flow control, powertrain control, component design and inter-vehicle communication have usually been considered separately. This article presents a methodology that combines these areas and allows developers to obtain deep and highly realistic system insights, taking into account the mutual interactions between the domains. For this purpose, an X-in-the-Loop validation platform is constructed building upon a vehicular networking, a road traffic, and a vehicle simulator, all coupled with two real drive unit component test benches. We further show how this methodology can be used to investigate the effects of a novel predictive powertrain control algorithm taking into account Vehicle-to-Everything (V2X) communication. Focusing on a typical urban reference route, we demonstrate that our algorithm allows for maintaining the performance by using electric motors with reduced specifications.**

***Index Terms*—simulator coupling, test bench coupling, electrification, vehicle automation, predictive powertrain control, V2X communication, HIL simulation, smart powertrains.**

I. Introduction and Motivation

In the coming years, motorized, individual mobility will change drastically. This change will be driven by technological and socio-political trends. Vehicles will be connected, automated, shared, and electrified [1]. Along the way, new communication technologies will enable developers to integrate more information from the vehicle environment into control algorithms. In essence, this is important to continuously increase the level of automation for a safer, more comfortable, and more efficient operation. Research and development of these algorithms requires the combination of various domains of expertise. Furthermore, multiple interdependencies between the drive units, the vehicle, and its environment have to be considered as they influence each other. Ensuring the correctness and performance of the interconnected control algorithms is possible only with complex test scenarios. Since the technology, the legislation, and the infrastructure for fully automated traffic are currently not ready, these types of scenarios are not yet available on real roads. Therefore, communication and traffic simulations are required for an efficient development process. As other traffic participants change their behavior in consequence of the predictive driving of the ego vehicle (e.g. in situation where the ego-vehicle approaches slowly a red traffic light, other vehicles might overtake and cut-in in front of the ego-vehicle) and thus influences the own behavior again, an approach with a co-simulation of traffic flow and vehicle simulation is chosen. For investigations on interdependencies between powertrain components and the vehicle, hardware tests are possible but require large investments in building the prototype vehicle. Hence, simulations of the vehicle including its powertrain are also required. For investigations on thermal behavior and emissions of powertrain components, models with a sufficiently high level of detail are mostly not available or require an extensive amount of validation effort. Therefore, physical component tests are also required at some point of the development process. Until now, the different domains are considered separately.

To establish a strong coupling between vehicular simulations and real-world hardware setups of vehicles, a method known as Hardware-in-the-Loop (HiL)-simulation is needed. However, existing cross-domain approaches touch only some of the relevant domains: For traffic and communication simulation, bidirectional coupling [2] is common practice. HiL and traffic simulations have been coupled even before [3]. More recently, it was possible to connect simulated and physical vehicular communication components [4], [5]. In previous work, we showed a concept to combine traffic and communication simulation with a HiL system [6]. Powertrain component testing that uses HiL setups has already been demonstrated for combustion engines [7] and electric motors [8]. Our previous research included the coupling of powertrain components on separate test benches [9]. To the best of our knowledge, existing HiL setups for vehicular networks have never been used to holistically investigate a combination of all these domains. We therefore developed an X-in-the-Loop validation platform that combines traffic, communication, and vehicle simulation with actual powertrain components.

In order to showcase the effectiveness of the methodology, we investigated the potential impact of predictive powertrain control algorithms that use the information provided by the networked environment. Existing research shows that predictive, automated longitudinal control of vehicles can yield significant energy saving potentials [10]. Also, real-time optimization of energy management in hybrid vehicles can further increase the fuel economy based on predictive information [11]. We therefore developed a set of real-time capable predictive

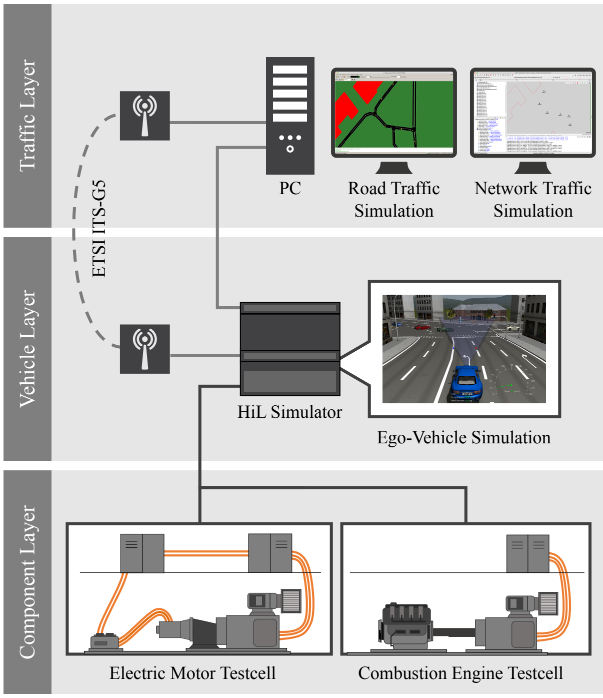


Figure 1. System overview of the developed platform.

control algorithms that utilize the information provided via Vehicle-to-Everything (V2X) communication to demonstrate the application of the proposed methodology. These algorithms include a prediction model for the upcoming traffic situation, an automated velocity controller, and an optimized energy management strategy.

The contributions of this paper can be summarized as follows:

- We present a holistic methodology combining communication, traffic, and vehicle simulation with real drive units.
- Using this methodology, we show that predictive control algorithms utilizing networked environment data can lead to a right-sizing of powertrain components.

II. System Design

In this article we present a comprehensive methodology that combines simulations and hardware tests (for the first time) into a distributed X-in-the-Loop research and development platform for automated and electrified vehicles. The methodology is centered around the *ego-vehicle*, a specific vehicle under investigation. As shown in Figure 1, the methodology consists of three layers, each covering a different aspect of the ego-vehicle and its surroundings.

- Using the open-source-framework for network simulations Veins [2] on a Linux PC, the traffic layer models the greater environment of the ego-vehicle. It simulates the behavior of all other vehicles in the scenario and the V2X communication. Position and status data for vehicles close to the ego-vehicle are provided to the vehicle layer. V2X messages that can be received by the ego-vehicle are transmitted as real, standard-compliant signals via an over-the-air interface.
- In the vehicle layer, this information is decoded and dSPACE Automotive Simulation Models (ASM) are used to model the vehicle dynamics, the close environment, and the powertrain components. The vehicle layer is executed on a HiL simulator, to enable the integration of components of special interest as real hardware at component test benches in closed loop. This is also the point where predictive algorithms for controlling the vehicle can be evaluated.
- In contrast to the traffic and vehicle layer, the component layer employs a real Internal Combustion Engine (ICE) and a real Electric Machine (EM) with its power electronics in separate test cells. The simulated rotational component speed is sent to the dynamometer of the test benches for component speed control. Both components can then apply torque requests received by the HiL simulator (e.g., calculated from the predictive algorithms) as these are passed on to the respective control units. The actual measured torques are fed back to the HiL simulator.

In order to be able to implement the approach described above, a number of challenges must be mastered. For example, real-time capability is a fundamental prerequisite to run the three different simulations including complex optimization algorithms on two machines in combination with two test benches. Moreover, to guarantee valid results, coupled simulators must have equivalent models of both offline data, such as road networks, and runtime data, such as the position, orientation, or speed of vehicles, to guarantee valid results. Last but not least, standard-compliant V2X communication has to be implemented before it is available on real roads. Our solution to these challenges is described in the following.

A. Road Traffic & Network Traffic Simulation

The traffic layer provides an interactive environment of connected traffic for the ego-vehicle, using two established simulators: SUMO [12] and Veins [2].

SUMO simulates an entire city with individual vehicles and infrastructure, such as traffic lights. The simulation takes place in fixed-length steps, during which vehicles can move along their route (adhering to traffic rules), traffic lights can switch and so forth. Between these steps, the simulation state can be queried, e.g., for vehicles, traffic lights, or aggregate statistics such as traffic density, via the integrated network interface TraCI.

Veins simulates V2X communication based on vehicle positions obtained from SUMO. In the context of this work, a simple beaconing system based on ETSI ITS G5 Cooperative Awareness Messages (CAMs) was run: Every vehicle periodically broadcasts CAMs containing its current status (e.g., position and speed). Close-by vehicles receiving CAMs such as the ego-vehicle can then optimize their driving behavior based on that information, which may not be available via the vehicle's own sensors. Veins contains the models that decide which vehicles can successfully receive which message, depending on the distance and presence of obstacles (such as buildings) between sender and the receiver. It also takes care of modelling lower layer communication protocols such as medium access and message encoding.

B. Ego-Vehicle Simulation & Environment

ASM is used to simulate the ego-vehicle and the nearby environment. It is a tool suite for detailed real-time simulation of combustion engines, electrical components, vehicle dynamics, and the traffic environment. The traffic environment consists of a simulation of multiple fellow vehicles to represent the traffic around the ego-vehicle and various sensor models that enable the ego-vehicle to detect other vehicles, traffic signs, and obstacles. The related model libraries are based on open MATLAB/Simulink models. The flexible, modular model structure allows modeling of multiple hybrid electric powertrain configurations. For this investigation a parallel hybrid electric drivetrain topology with the EM connected to the gearbox output shaft (P3) is chosen. In addition, it enables the predictive algorithms to be easily integrated as a device under test and the interfaces for signal exchange with the test bench automation systems required for test bench coupling to be implemented.

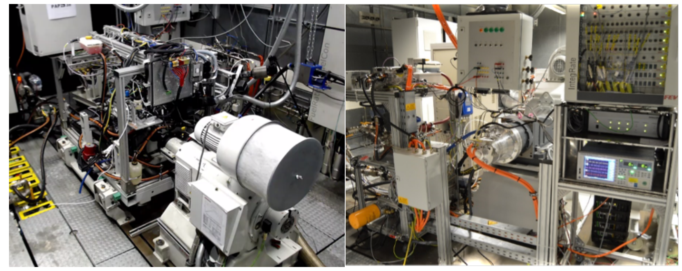
In addition to the vehicle movement at simulation time, the offline data of the environmental simulation, i.e., the road network in ASM and SUMO have to be synchronized. Both tools must represent the environment in a suitable way. While both ASM and SUMO support the conversion of OpenStreetMap (OSM) data, we developed a dedicated SUMO to ASM road network converter to ensure the models are as similar as possible.

C. Simulator Coupling

The connection between traffic layer and vehicle layer has to couple simulators stemming from different disciplines. These simulators follow different maxims, e.g. for their model of road networks, simulation of vehicle interaction, and real-time compliance. To solve this issue, we introduced the Ego-Vehicle Interface (EVI) [6].

The EVI manages the progression of the coupled simulation and exchanges data between the simulators. It also controls which vehicles are synchronized to ASM, using a floating hierarchy of four concentric Regions of Interest (ROIs): (1) the ego-vehicle itself, (2) the fellow vehicles synchronized to ASM, (3) the communicating vehicles synchronized to Veins, and (4) the entire scenario in SUMO.

The synchronization itself is organized in cycles of 100 ms. ASM starts each cycle by sending the current state (position, speed, orientation, etc.) of the ego-vehicle to the EVI. The EVI immediately responds with the pre-computed state of the fellow-vehicles for ASM, the state of traffic lights and surrounding traffic for the HiL simulator in the vehicle layer. ASM internally maps the fellow states received from the EVI to the fellow vehicles, ensuring consistent vehicle identities, and transforming the coordinates to its own representation. The EVI also sends the current traffic state in the ROI for V2X to Veins. Afterwards, the EVI updates the ego-vehicle in SUMO and triggers the pre-computation of traffic for the next cycle. The results are stored in the EVI for the next cycle.



(a) ICE Test Cell (b) EM Test Cell

Figure 2. Test bench setup at the Center for Mobile Propulsion at RWTH Aachen University.

V2X data, such as CAMs, between Veins and ASM are exchanged over a separate, physical channel, compliant to the IEEE 802.11p standard. Building upon the LAN Radio extension [4], the simulated network interface of the ego-vehicle within Veins is connected to a physical sender module. To do so, we extended the LAN Radio system to allow transmission of standard compliant ETSI ITS-G5 CAMs. All CAMs received by the ego-vehicle are forwarded to this sender module and emitted as wireless signals in the real world in real time. A Cohda Wireless MK5 receives these signals and forwards them to the HiL simulator using the dSPACE V2X Blockset.

D. Test Benches & Component Coupling

The main component of the two coupled test benches is the vehicle simulator, which connects the electric drivetrain with the ICE to a virtual hybrid electric vehicle. For this purpose, two control paths were implemented in each test cell.

There is a speed control of the dynamometers as well as a torque control of the respective test object. The ICE is a three-cylinder in-line turbocharged engine with a total displacement of 898 cm^3, a rated power of 66 kW, and a maximum torque of 135 Nm at 2500 rpm. The EM is a permanent magnet synchronous machine with a maximum power of 80 kW. The active parts with the stator hairpin winding were designed for a maximum torque of 160 Nm by a Finite Element Method (FEM) tool chain. The main housing and bearing concept consists of two housing parts and allows for a maximum speed of 15 000 rpm. For open control implementation and connection to the power electronics, a custom printed circuit board was coupled to a rapid control prototype platform. Both test benches are connected to the vehicle simulator using a real-time capable EtherCAT connection that sends component torque requests and simulated speeds from the simulation to the test cell controller and feeds back actual torques from the test benches into the real-time simulation. The final test bench setup is shown in Figure 2. Both test objects are equipped with dedicated measurement equipment to analyze relevant values such as fuel consumption, emissions, and temperatures.

III. Predictive Control Algorithms for Connected Powertrains

All data received by the ego-vehicle is made available to a set of predictive algorithms designed to increase the efficiency

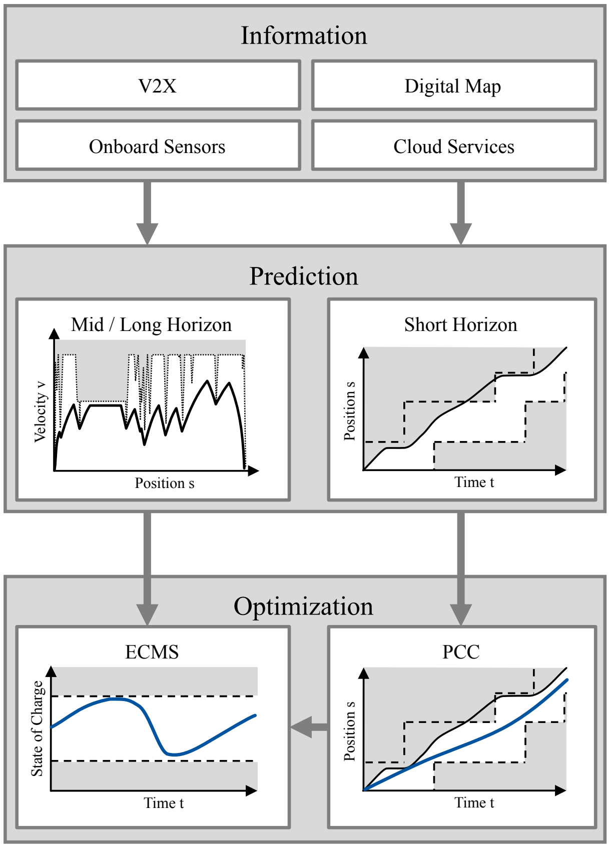


Figure 3. Cascaded three-layer approach to Predictive Cruise Control (PCC) and adaptive Equivalent Consumption Minimization Strategy (ECMS) implemented on the Hardware-in-the-Loop (HiL) simulator.

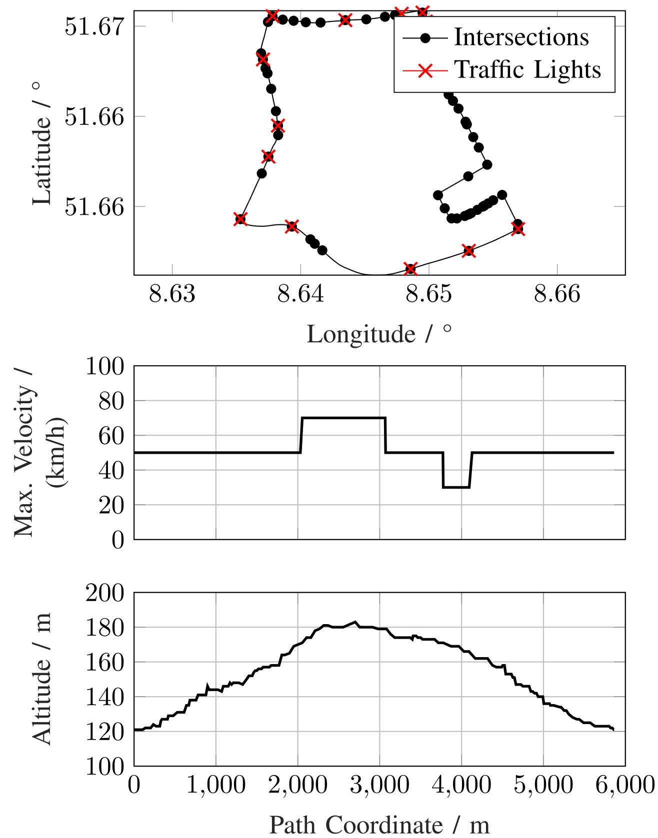


Figure 4. Ego-vehicle route including velocity limitation and altitude profile along the path coordinate.

of the hybrid electric powertrain. They are integrated as a device under test on the HiL simulator.

To meet the demanding real-time requirements despite the complex dependencies, a cascaded 3-layer approach (illustrated in Figure 3) is chosen: First, the information about actual traffic states gained from V2X, cloud, and sensor data is condensed and predicted into the future. The discrete Gipps-model [13] is used to predict the behavior of preceding vehicles dependent on the upcoming traffic light schedule retrieved from the cloud, while artificial neural networks are used to predict the behavior of crossing vehicles at intersections. The constructed solution space is then forwarded to the Predictive Cruise Control (PCC) algorithm, which uses a quadratic programming solver to minimize acceleration maneuvers over a receding prediction horizon of up to 30 s [14]. This algorithm outputs a desired acceleration to the vehicle control model, while it also provides the expected velocity profile to the predictive hybrid operation strategy. An adaptive Equivalent Consumption Minimization Strategy (ECMS) is used to optimize the torque split for the hybrid electric powertrain, considering component efficiencies, battery state of charge, and the predicted velocity profile.

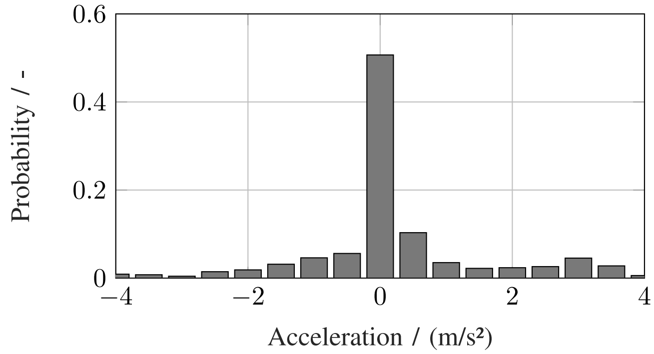
A. Test Setup

In order to demonstrate the capabilities of both the described methodology and the described algorithm, we defined a test course through the city of Paderborn (Germany) for the ego-vehicle. The route has an overall length of 5.9 km and has a maximum altitude difference of 75 m. The course leads through residential areas with a speed limit of 30 km/h, inner-city arterials (50 km/h), and a short segment of an extra-urban road with a speed limit of 70 km/h. A total of 14 intersections along the track are equipped with traffic light signals, for which the traffic light schedule is made available to the predictive algorithms by means of a virtual cloud interface. A validated traffic scenario, which reflects a typical morning traffic at 10:00 a.m. on a weekday in Paderborn, is initialized in SUMO.

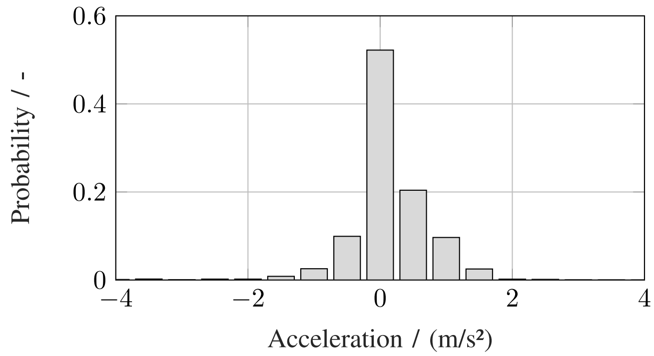
B. Exemplary Results

The test course is driven twice with the reference vehicle. The first run is conducted with a state-of-the-art and traffic light-aware Adaptive Cruise Control (ACC), the second run with the previously described Predictive Cruise Control (PCC) instead.

Comparing the accelerations of both runs in the histogram of Figure 5, we can see a lower probability for high decelerations and accelerations for the vehicle with PCC. Reduced decelerations mean that less kinetic energy is converted into heat by mechanical breaking. Even an electrified vehicle with energy recuperation capabilities faces energy conversion losses and therefore benefits from avoiding decelerations. Lower accelerations lead to lower torque requests to the drive units. For the ICE, this generally means lower fuel efficiency in a wide operating range. In joint operation with an EM, the ICE



(a) Adaptive Cruise Control (ACC)

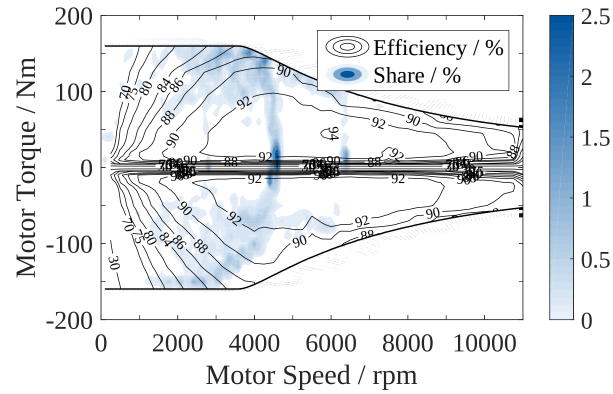


(b) Predictive Cruise Control (PCC)

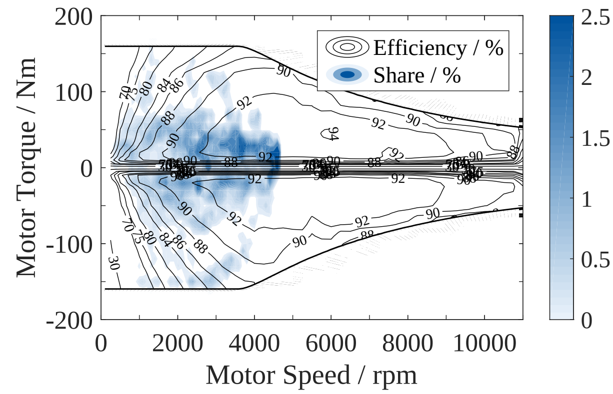
Figure 5. Electric Machine (EM) operation points for the scenario with either Adaptive Cruise Control (ACC) or Predictive Cruise Control (PCC) and adaptive Equivalent Consumption Minimization Strategy (ECMS).

can be operated close to its optimal operation area while the EM covers the difference to the driver torque request.

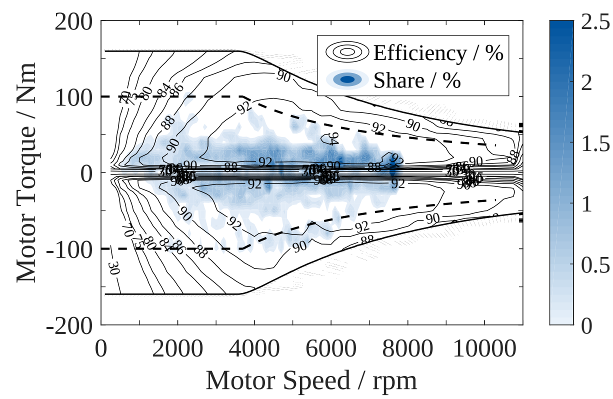
Following this strategy, the operating area of the EM for the run with PCC shrinks compared to the run with ACC. This behavior is illustrated with the energy share diagrams of the EM (without inverter losses) for both scenarios in Figure 6a and Figure 6b. Apparently, with PCC most of the energy conversion does not happen in the maximum efficiency area of the EM map and with lower motor speeds. This behavior can be observed, because the PCC is able to avoid high velocities while keeping the average velocity the same. One of the powertrain design parameters is the reduction gear located between EM and the final drive. To shift the EM operating points towards higher efficiencies, our methodology can be applied to virtually increase the reduction gear ratio without any cost intensive hardware changes. In this case example, this gear ratio was increased by 70%. The resulting energy share diagram is depicted in Figure 6c. Since now the required motor torque as well as the motor power is smaller compared to the run with ACC, a further optimization step could be a reduction of the EM active length. A maximum torque curve of an EM with a reduced active length of 63% is represented by a dashed line in Figure 6c. In this consideration it must be taken into account that the EM efficiencies change also in the event of a length adjustment. However, a smaller machine is easier to install in the vehicle, needs less rare materials, and consequently is less expensive.



(a) Adaptive Cruise Control (ACC)



(b) Predictive Cruise Control (PCC)



(c) Predictive Cruise Control (PCC) with adapted reduction gear

Figure 6. Electric energy share diagrams of the Electric Machine (EM) for either Adaptive Cruise Control (ACC) or Predictive Cruise Control (PCC) (with and without reduction gear ratio adaptation).

IV. Conclusion and Outlook

We demonstrated a holistic methodology for research and development on smart, connected powertrains by combining different development domains. The platform consists of a traffic and vehicular networking simulation, a detailed ego-vehicle simulation implemented on a real-time Hardware-in-the-Loop (HiL) simulator and component test benches for an Internal Combustion Engine (ICE) and an Electric Machine

(EM). This effort was necessary because powertrain design and control, traffic flow, energy demand as well emissions strongly influence each other. To demonstrate the application of the methodology, we implemented predictive control strategies using information provided by the networking simulation via Vehicle-to-Everything (V2X). Selected, exemplary results show that a reduction in vehicle acceleration can be achieved. In consequence, the active operation area of the electric machine is reduced, indicating a possible advantage of re-sizing powertrain components.

In addition to these exemplary results, a wide range of investigations using the proposed methodology is conceivable. An analysis of physical behaviors that can only be modelled with extensive effort, such as the tailpipe emissions of combustion engines or thermal behavior of electric motors, can be easily performed using this holistic X-in-the-Loop platform. Other possible applications can include an analysis of the repercussions the predictively controlled ego-vehicle has on the overall traffic flow in the coupled traffic simulation environment and utilize the developed methodology to lead the way towards smart V2X-connected powertrains.

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