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A Method for Quantification of Powertrain Electrification Impacts on Driving Dynamics

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Summary

The paper discusses a novel simulation-based study quantifying the impacts of driving dynamics in electrification of conventional powertrains to hybrid powertrains. On that account, Fourier Amplitude Sensitivity Test (FAST) is used to facilitate sensitivity analysis. Design-of-Experiment and artificial neural network methods are employed for approximation of solution space to ensure computational efficient application of FAST. To demonstrate this method an exemplary simulation-based study is conducted to evaluate electrification impacts in a driving dynamic challenging investigation scenario.

Keywords: case-study, parallel HEV, powertrain, simulation, vehicle performance

1 Introduction

Electrification of conventional powertrains towards hybrid powertrains opens up new degrees of freedom to influence longitudinal and lateral driving dynamics. Such influences can result from selection of the powertrain topology, sizing of its components and their vehicle integration. A hybrid powertrain topology defines the driven axles and wheels as well as the positioning of the electrical machine in a conventional powertrain. Consequently, there is a connection between the topology and the driving dynamics because various functionalities are feasible in dependency on the topology. Exemplary functionalities are all-wheel-drive or torque vectoring. Sizing of powertrain components determines component specific variables, for instance power and torque of an electrical machine or maximum energy content of a battery. Further, sizing can imply interactions with correlating component masses. Thus, sizing specifies the fundamental performance of a powertrain. Positioning of powertrain components into a vehicle characterizes integration. It is able to effect vehicle's centre of gravity, consequently wheel load distribution and traction capability while accelerating or cornering, respectively.

These degrees of freedom can be utilized to improve driving dynamics through appropriate system design. Due to various combinations of powertrain topologies and component sizings, the system design of a hybrid powertrain results in a wide and complex solution space. Its correlations between design variables and evaluation criteria are often uncertain.

In this paper, a novel simulation-based method is presented for quantification of these correlations utilizing Fourier Amplitude Sensitivity Test (FAST). It identifies the sensitivity of each system design variable towards an evaluation criterion. The generated results are extended by local sensitivity analyses. These reveal correlation curves between each single design variable and an evaluation criterion for a limited section of design space. To ensure computational efficient application of FAST and the local sensitivity analyses, compensatory models of the solution space are built by utilizing Design-of-Experiment and artificial neural network methods. An explanation of the proposed method is given in Chapter 2. To demonstrate this method an exemplary simulation-based study is conducted. Its objective is to quantify powertrain electrification impacts on the required time to accomplish a challenging driving profile. Baseline of this study is a conventional front wheel driven vehicle. Its electrification design space includes various hybrid powertrain topologies and sizing variables of electrical machine and battery. Chapter 3 presents the corresponding experimental set-up in detail and in Chapter 4 the study's outcomes are illustrated and discussed. A conclusion as well as an outlook is given in Chapter 5.

2 Quantification method

The proposed method elucidates the impact of design variables of powertrain electrification on driving dynamic related evaluation criteria. On top level, this method consists of two segments. Firstly, computational efficient models of the solution space are generated. Secondly, based on these models sensitivity analysis is performed to identify variable specific impacts. These analyses imply global sensitivity analyses using FAST and local sensitivity curves to support the findings generated by FAST. An insight of these approaches is explained in the following two subchapters.

2.1 Solution space approximation

In this method, a solution space consists of a defined hybrid powertrain topology, various sizing variables and evaluations of its combinations in a defined investigation scenario. To generate a compensatory and computational efficient model of such a solution space, a three-step approach in the style of [1-3] is applied as shown in Figure 1.

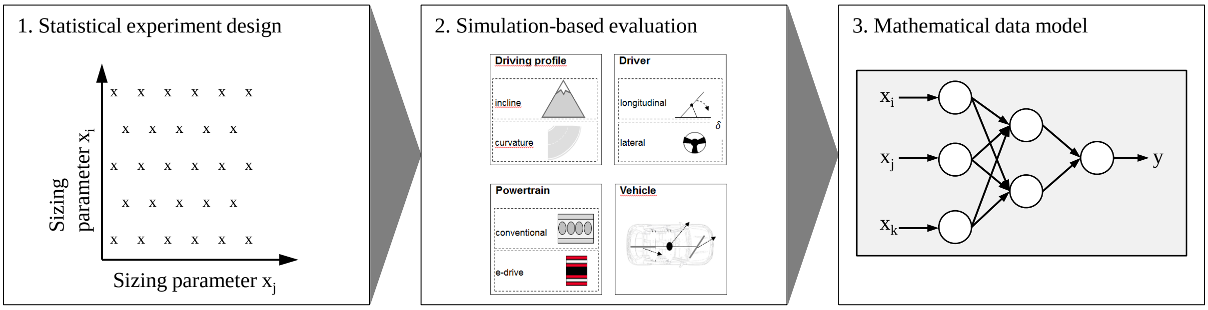

Figure 1: method for solution space approximation

Firstly, the sizing variables' design space is discretized by using statistical experiment design for every hybrid powertrain topology individually. Accordingly, every experiment presents a system design consisting of a specific hybrid powertrain topology and determined values for each sizing variable. Secondly, these system designs are evaluated with a quasi-steady-state simulation model, which includes physical compensatory models for powertrain and vehicle as well as a control strategy optimization algorithm. The applied optimization algorithm is a further development of [1]. Its objective is to minimize the required time for a given track by application of an electric drive in consideration of its electrical energy content and thermal boundary conditions. Based on the simulation outcome, mathematical data models of the solution space model are generated for each hybrid powertrain topology. These models are generated using artificial neural network and they enable faster evaluation of new system designs compared to the physical simulation model.

2.2 Sensitivity analysis

The sensitivity analysis is divided into a global and local part. The global part of the sensitivity analysis identifies main impacts on an evaluation criterion for each sizing variable. This identification is performed with application of FAST. The local part of the sensitivity analysis allow for conclusions on the results generated by FAST. For that, it presents correlation curves between each sizing variable and an evaluation criterion in a local scope around the optimal design. Following sections explain the essential steps of the FAST algorithm and demonstrate it exemplarily on a basic Equation.

According to [2], FAST is appropriate to generate accurate and significant correlations with little computational effort. Its approach can be characterized as in Figure 2 consisting of four steps: transformation, model stimulation, frequency analysis and sensitivity calculation [3].

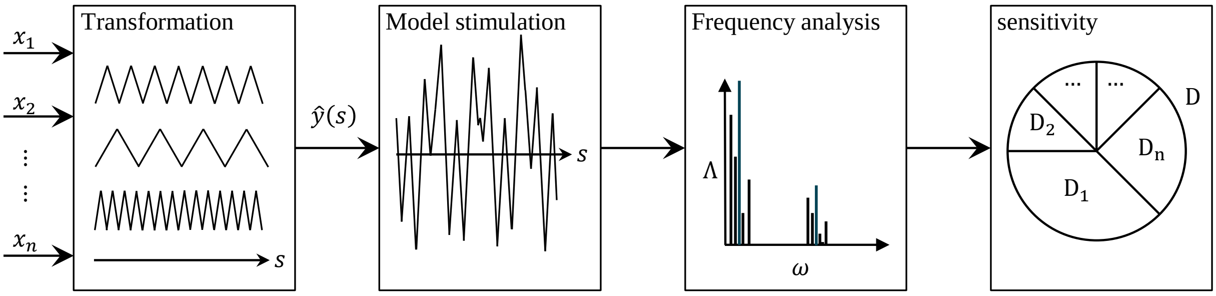

Figure 2: Fourier Amplitude Sensitivity Test

Starting point is a transformation of a multidimensional problem with various design variables into a one dimensional problem, which is represented by a function of a single variable s. For that, each design variable x_i is assigned to a frequency ω_i and represented by a compensatory function of s and ω_i as well as a transformation function G_j (cf. Equation (1)) Output of the transformation is the in Equation (2) presented function $\hat{y}(s)$, which combines all compensatory functions.

$$\hat{x_j} = G_j\left[\sin(\omega_j \cdot s)\right], \qquad -\infty \leq s \leq \infty \tag{1}$$

$$\hat{y}(s) = f\left(x_j(s)\right) \tag{2}$$

Secondly, this function $\hat{y}(s)$ is stimulated. This leads to an oscillation, which indicates correlations between a design variable and an evaluation criterion. In the third step, a frequency analysis is performed to quantify these correlations, which are determined by their frequency specific amplitudes $\Lambda(\omega_i)$. Comparative calculations of these amplitudes reveal the specific impact of each design variable in the last step. According to Equation (4), a main impact results from the sum of frequency specific amplitudes $\Lambda_{k\omega_j}$ in relation to the sum of all amplitudes Λ_k.

$$\text{main impact} = \frac{\sum_{k=1}^{+\infty} \Lambda_{k\omega_j}}{\sum_{k=1}^{+\infty} \Lambda_k} \tag{3}$$

In conclusion, this main impact characterizes the strength of correlation between a design variable and an evaluation criterion. For this method, the applied FAST algorithm is based on the algorithm developed by [4].

An exemplary demonstration of FAST is given for Equation (4), in which the evaluation criterion y is a function of the design variables x_1, x_2 and x_3.

$$y = \frac{1}{2}x_1 + 2x_2 \cdot x_3 \tag{4}$$

The results in Figure 2 show the global sensitivity analysis's outcome as main impacts of each design variable. It presents that variables x_2 and x_3 have greater impact on y compared to x_1. Main reasons for that are different coefficients in Equation (4) as well as the multiplication of x_2 and x_3.

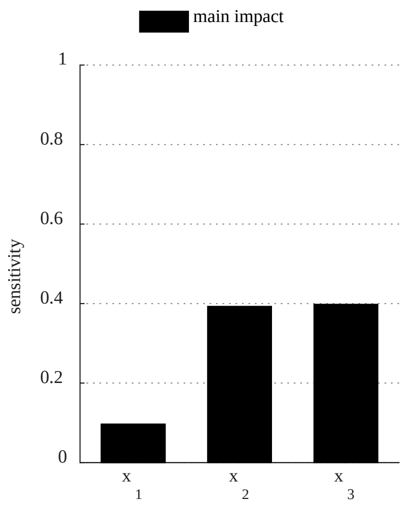

Figure 3: Result of FAST for Equation (1)

3 Experimental set-up

Objective of the proposed study is to investigate the impact of certain sizing variables on the required time to accomplish a defined driving profile. Additional investigation aspect is its dependency on various hybrid powertrain topologies. Following experimental set-up defines the investigation scenario as well as the design space of sizing variables and powertrain topologies.

Investigation scenario is a challenging driving profile, which is derived from the Nürburgring race circuit [5]. Accordingly, required lap time characterizes the evaluation criterion. Furthermore, the achieved lap times shall be reproducible. Thus, the battery's state of charge as well as the thermal state of an electric drive have to be almost equal at the beginning and the end of the given track.

Baseline of this study is a conventional front-wheel-drive vehicle. Its electrification design space includes three different hybrid powertrain topologies and sizing variables in terms of electrical machine and battery. Figure 4 shows the baseline topology as well as its electrification towards three different hybrid powertrain topologies.

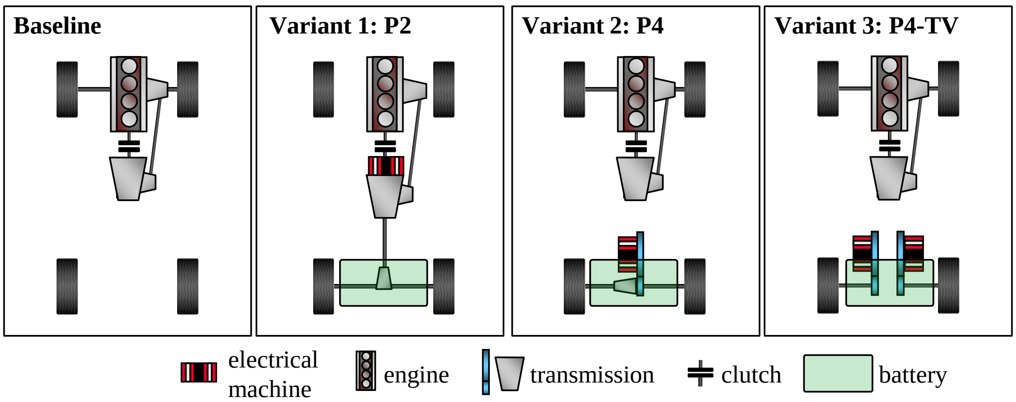

Figure 4: Design space of hybrid powertrain topologies

In Variant 1, the baseline powertrain is extended by an electrical machine, which is integrated between clutch and transmission. This configuration enables a boost functionality meaning an addition of engine and electrical machine torque. Mounting of an electrical machine together with an additional transmission at the rear axle characterizes Variant 2. In addition to the boost functionality, this topology is capable of all-wheel-drive. Variant 3 extends Variant 2 by installation of single-wheel-drive at the rear axle. This allows free torque distribution between left and right rear wheel. This so-called torque vectoring functionality (TV) enables, for instance, improvement of cornering regarding driving stability and velocity. According to [6], these introduced hybrid powertrain topologies are labeled as P2, P4 and P4-TV. These labels are used in the further work. For all these variants, a battery is integrated above the rear axle.

All these topology variants are equipped with the same engine, which is specified to a maximum power of 185 kW and a maximum torque of 400 Nm. A 7-speed gearbox connects this engine to the differential of the front axle. The sizing variables' design space is summarized in Table1. It includes sizing variables, which effect dimensioning of electrical machine and battery.

Table1: Design space of sizing variables

Sizable variables		Constant variables	
$P_{\mathrm{EM,max}}$	$20-250\ \mathrm{kW}$	$M_{\mathrm{EM,max}}$	$350\ \mathrm{Nm}$
$P_{\mathrm{EM,c}}$	$(20-80\ \%)\cdot P_{\mathrm{EM,max}}$	$M_{\mathrm{EM,c}}$	$200\ \mathrm{Nm}$
E_{max}	$0.2-20\ \mathrm{kWh}$	$n_{\mathrm{EM,P2,max}}$	$n_{\mathrm{VM,max}}$ = 6500 rpm
m_{Bat}	$f(P_{\mathrm{EM,N}}, E)$	$n_{\mathrm{EM,P4,max}}$	$15000\ \mathrm{rpm}$
m_{EM}	$f(P_{\mathrm{EM,N}}, M_{\mathrm{EM,N}})$	t_{max}	$10\ \mathrm{s}$

Sizable variables of the electrical machine are the maximum and continuous power ($P_{\mathrm{EM,max}}$, $P_{\mathrm{EM,c}}$). The design space of the maximum power ranges from 20 to 250 kW. The continuous power is defined as a function of the maximum and is sizable from 20 to 80 % of the maximum power. The possible overload time t_{max} of the power is set to 10 s. A value of 350 Nm is defined for the maximum torque $M_{\mathrm{EM,max}}$ and a value of 200 Nm for the continuous torque $M_{\mathrm{EM,c}}$. Regarding the P4-TV-topology, these electrical machine values correspond to the sum of two single electrical machines. The maximum speed of the electrical machine is limited to the maximum speed of the engine in terms of the P2-topology ($n_{\mathrm{EM,P2,max}} = n_{\mathrm{VM,max}}$ =6500 rpm). In terms of the P4- and P4-TV-topology, a value of 15000 rpm is selected for the maximum speed of the electrical machine and additionally performance optimal gear ratios for the electric drive transmission. Regarding battery, the maximum energy content E_{max} is sizable in a range from 0.2 to 20 kWh.

For the masses of the components battery (m_{Bat}) and electrical machine (m_{EM}) basic functions are postulated in Equation (5) and (6).

$$m_{\mathrm{Bat}} = \max\left(P_{\mathrm{EM,c}} \cdot k_{\mathrm{Bat,P_{EM,c}}}, E \cdot k_{\mathrm{Bat,E}}\right) \tag{5}$$

$$m_{\mathrm{EM}} = \max\left(P_{\mathrm{EM,c}} \cdot k_{\mathrm{EM,P_{EM,c}}}, M_{\mathrm{EM,c}} \cdot k_{\mathrm{EM,M_{EM,c}}}\right) \tag{6}$$

Due to these functions, the electrical machine and battery mass result from sizing of continuous power, continuous torque, energy content and coefficients $k_{\mathrm{BAT/EM}}$. For the application in this study, the coefficients are derived from a specific Li-ion battery [7] and electrical machine design [8], respectively.

$$k_{\mathrm{Bat,P_{EM,c}}} = \frac{2\ \mathrm{kG}}{3\ \mathrm{kW}} \qquad k_{\mathrm{Bat,E}} = \frac{25\ \mathrm{kg}}{2\ \mathrm{kWh}}$$

$$k_{\mathrm{EM,P_{EM,c}}} = \frac{4\ \mathrm{kG}}{3\ \mathrm{kW}} \qquad k_{\mathrm{EM,M_{EM,c}}} = \frac{1\ \mathrm{kg}}{3\ \mathrm{kWh}}$$

4 Study's outcome and discussion

Outcomes of the performed study are the lap time sensitivity of the variable's maximum power, continuous power and energy content in dependency on the hybrid powertrain topology. Firstly, the resulting main impacts are presented, which are created by FAST. Secondly, the conducted local sensitivity analyses are discussed to reveal the lap time impact of each sizing variable individually and consequently to derive an understanding of the results generated by FAST.

Figure 5 demonstrates the outcomes of the global sensitivity analysis by application of FAST. It shows the sizing variables' specific impacts for the three selected hybrid powertrain topologies: P2, P4 and P4-TV.

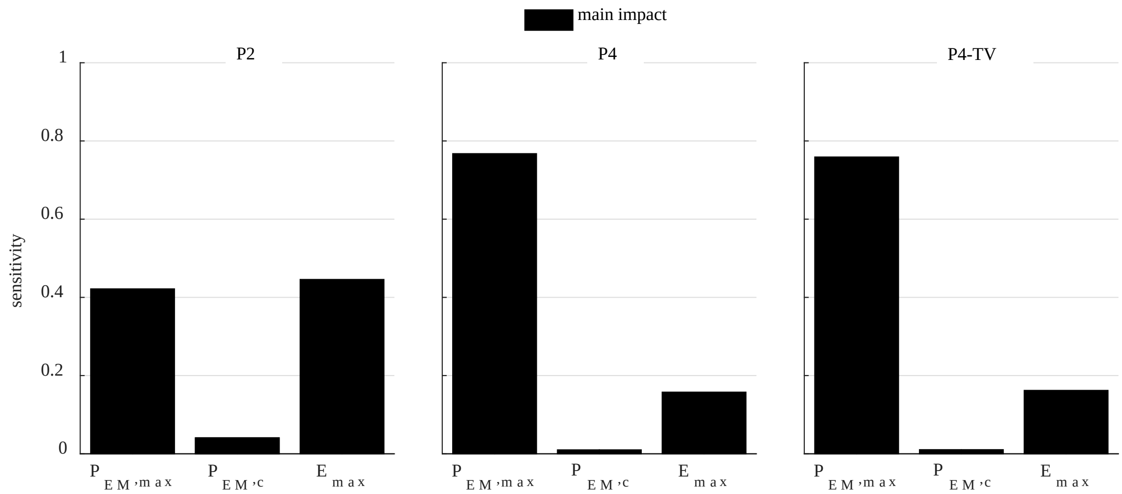

Figure 5: Sizing variable specific main impacts in dependency on hybrid powertrain topology (FAST)

The left diagram contains the FAST analysis for the P2-topology. Its maximum power $P_{\mathrm{EM,max}}$ and its energy content E_{max} reveal the largest main impacts on the lap time with values above 0.4. The impact of the continuous power $P_{\mathrm{EM,c}}$ is with a value of 0.04 comparatively small. For the P4- and P4-TV-topology, the FAST outcomes are shown in the middle and right diagram. As can be seen from these diagrams the outcomes unveil similar main impacts for both topologies. Their maximum power $P_{\mathrm{EM,max}}$ has the largest influence on the lap time, the energy content E_{max} the second largest and the continuous power $P_{\mathrm{EM,c}}$ the smallest. From the comparison of the FAST's outcomes across topologies it can be seen that the maximum power $P_{\mathrm{EM,max}}$ has an about 0.35 higher impact on the lap time for the P4- and P4-TV-variant than for the P2-variant. The energy content E_{max} influences the lap time most for the P2-topology. In relation to that, the main impacts of the energy content E_{max} are less than half for the P4- and P4-TV-topology. In all three hybrid powertrain topologies, the continuous power $P_{\mathrm{EM,c}}$ has a relatively small impact.

Figure 6 shows the local sensitivity analyses. Every column shows the variation of one single sizing variable. In this scope, other sizing variables are fixed to their identified optimum. The first row reveals the impacts on lap time in ratio to the lap time of the baseline configuration. Negative values imply a lap time improvement. In the second row, vehicle mass modifications are illustrated. Due to different optimal values for the design variables, the mass curves are slightly varying. Different line styles indicate the powertrain topologies.

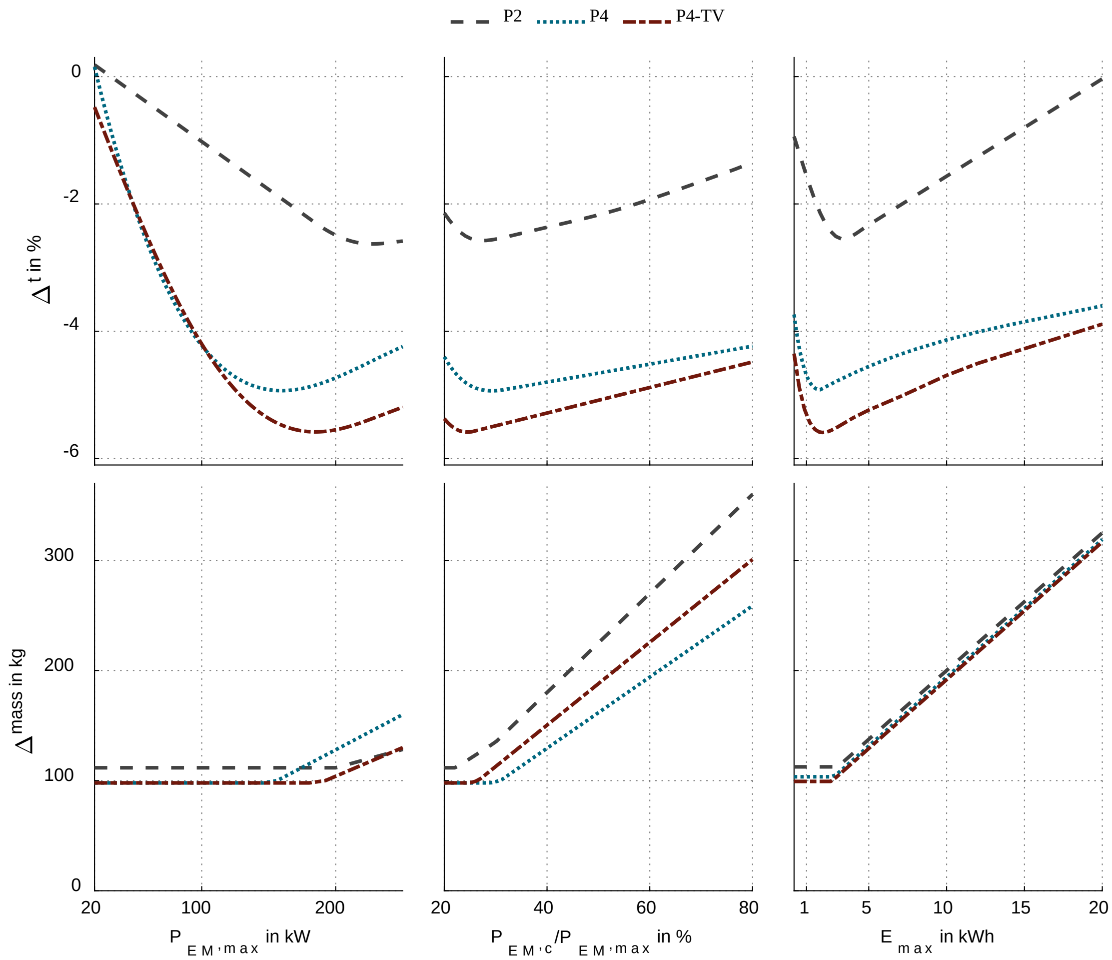

Figure 6: Lap time and mass impacts of each sizing variable around the areas of optimal design for the three defined hybrid powertrain topologies

Maximum power $P_{\mathrm{EM,max}}$

An increase of maximum power $P_{\mathrm{EM,max}}$ results in an enhancement of acceleration and recuperation capability for all three topologies. In terms of recuperation capability, such a power increase enables to regenerate more energy in each single braking and consequently an increase in availability of electric drive. Consequently, these effects lead to lap time improvements. According to the diagrams, this lap time improvement can be seen up to the point of mass increase. This suggests that the lap time improving effects of power sizing are not sufficient to compensate the additional component masses.

Comparison across topologies shows that the FAST's main impacts regarding the maximum power $P_{\mathrm{EM,max}}$ are almost twice as big for the P4- and P4-TV-topology as for the P2-topology. In relation to the local sensitivity analysis, this is connectable to the lap time gradients in the range of 20 to 100 kW. In that range the P4- and P4-TV-designs reveal a gradient twice as big as the gradient of the P2-design. This is because in the P2-topology the engine utilizes most of the traction capability at the front wheels. Due to that the electrical machine can only add torque if the engine is not completely utilizing the available traction at the front wheels. In contrast, the P4- and P4-TV-topologies' electrical machine is able to utilize the entire traction capability of the rear wheels. Further, the P4-TV-variant is capable of utilizing the traction of each rear wheel separately due to torque vectoring functionality. On that account, the P4-TV-topology outperforms the P4-topology for maximum power sizings above 120 kW. This local difference is not represented in the global sensitivity analysis. This implies that this local difference is not to this extent effective in the global solution space.

Continuous power $P_{\mathrm{EM,c}}$

All three topologies reveal an optimal continuous power $P_{\mathrm{EM,c}}$ around 25 to 30 % of the maximum power $P_{\mathrm{EM,max}}$. Smaller sizings result in functional restrictions and greater sizings in overdimensionings: Overdimensionings characterize mass increase of components without functional benefit. Figure 7 demonstrates the causes for those two effects. It shows the normalized thermal load $T_{\mathrm{el}}/T_{\mathrm{el,limit}}$ of the electrical machine for two different continuous power sizings of the optimal P4-design ($P_{\mathrm{EM,c}}$: 20 % and 30 % $P_{\mathrm{EM,max}}$). This thermal load variable is a compensatory variable in the control strategy optimization. It occurs when a power is applied above the continuous power.

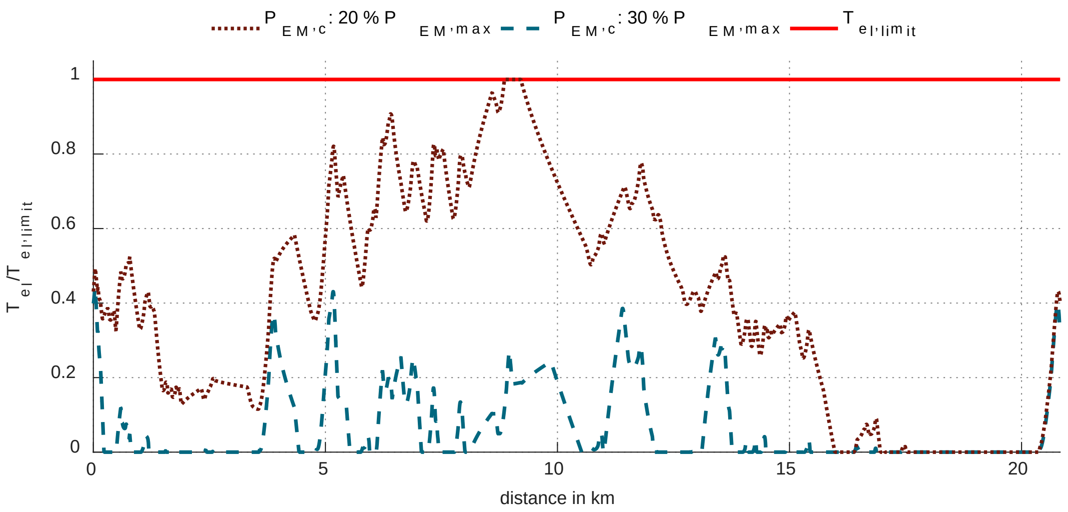

Figure 7: Normalized thermal load over distance for two different continuous power sizings of the optimal P4-design

The diagram illustrates the normalized curves of the thermal load over the distance for two different sizings of the continuous power $P_{\mathrm{EM,c}}$. These curves result from the optimization of the control strategy. For a sizing of continuous power to 20 % of the maximum power, the thermal load requires the entire permissible range. Furthermore, the thermal loads meets its limit at approximately 8 km. Due to these aspects, restriction of the electric drive operation is concluded. An increase in the continuous power to 30% of the maximum power solves this restriction. The associated profile shows no contact points with the thermal limitation. Furthermore, the utilized range of the thermal load decreases. This resulting thermal degree of freedom enables for more frequent and longer operation of the electric drive. Hence, the power throughput rises from 2.8 kWh to 3.3 kWh and exemplarily the lap time improves from -4.5 % to -5 % (cf. Figure 5). A further increase in the continuous power $P_{\mathrm{EM,c}}$ does not lead to any additional enhancement. It just causes growing component masses, which is consequently a reason for lap time decreases.

For all three topologies, the local sensitivity analyses show similar curves at different levels. For higher continuous power sizings, the P2-topology has a slightly higher gradient than the other two topology variants. One reason for that is a higher increase in mass. In relation to the FAST analysis, this difference in gradients correlates with the different main impacts. Thus, the P2-topology presents a slightly larger main impact for continuous power sizing compared to the P4- and P4-TV-topologies.

Energy content E_{max}

Sizing of the maximum possible energy content E_{max} influences the lap time by defining the maximum depth of discharge level as well as its dependence on the battery mass. In the same way as in continuous power sizing, values below its optimum causes functional restrictions and values above effects mass increases without functional benefits. Exemplarily Figure 8 points out this functional restriction. The diagram contains the state of charge (SOC) over the distance for two different energy content sizings of the optimal P4-TV-design (E_{max}: 0.4 and 2 kWh). Initial SOC is set to 60 % for each energy content variation.

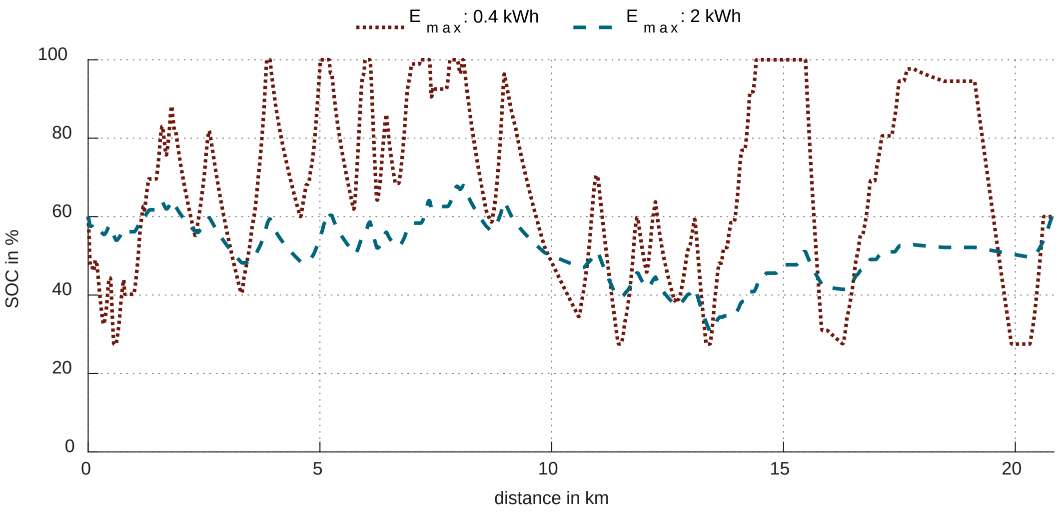

Figure 8: State of charge (SOC) over distance for two different energy content sizings of the optimal P4-TV-design

For the defined investigation scenario Nürburgring, the boundary condition of reproducible lap times is set. Accordingly, just as much electric energy can be applied as it can be recuperated over the track. Therefore, a restriction of recuperation limits the availability of the electric drive and thus the lap time. Such restriction reveal the variant with 0.4 kWh sizing of the energy content E_{max}. This is indicated by several plateaus at 100 % SOC, which represent a fully charged battery. Consequently, no additional energy is recoverable at these track sections. For the variant with 2 kWh sizing a limitation of the energy recovery is not recognizable. Compared to the 0.4 kWh sizing the lap time improves from -5 % to -5.7 % (cf. Figure 5). A further increase in the energy content results exclusively in a growing battery mass and thus in an overdimensioning with decreasing lap times.

Across topologies energy content sizing has the largest main impact for the P2-topology. This is also represented in the local sensitivity analyses, since the P2-variant reveals higher gradients than the P4- and P4-TV-variants. This higher gradient appears towards sizings above 3 kWh, although the mass increase of the battery is approximately equal for all three topologies. A reason for the different gradients results from the interaction of the battery positioning and the powertrain topology. Due to the integration of the battery at the rear axle, a battery mass increase causes a shift of the centre of gravity towards the rear axle. This shift effects a reduction of the traction capability at the front wheels. Hence, this cause-effect relation has a greater influence on the front wheel driven P2-variant than the all-wheel-drive capable P4- and P4-TV-variants.

Sizing variables within each topology

Within the individual topologies, the lap time's curves of the local sensitivity analyses confirm the main impact results of FAST. For that, the local range and the gradients are utilized as indicators of the local sensitivity analyses. Therefor the differences of the minimum and maximum of each lap time curve defines the local range. In terms of P2-topology, the maximum power E_{max} and the energy content E_{max} show the largest local ranges. Furthermore, sizing of the energy content E_{max} reveals greater gradients than the other two sizing variables. In conclusion, these aspects correlate with the main impacts of FAST. Within the P4- and P4-TV-topology, the largest local range and main impact is recognizable for the maximum power $P_{\mathrm{EM,max}}$. Sizing of continuous power $P_{\mathrm{EM,c}}$ and energy content E_{max} display almost equal local ranges. A difference for these two variables appears for sizing towards small values. In that case, the curves of the energy content show higher gradients than the curves of the continuous power. That refers to the larger main impacts of the energy content E_{max} compared to the continuous power $P_{\mathrm{EM,c}}$.

5 Conclusion

Within this paper, a method to quantify variable specific impacts of powertrain electrification on driving dynamics is introduced and exemplarily applied. The exemplary application elucidates the correlations between various electrical machine and battery sizing variables, three different hybrid powertrain topologies and the required lap time for the Nürburgring race circuit. For that, the main impacts, identified by the FAST, are analysed in detail by local sensitivity analyses and additional examinations for defined designs.

In terms of system design of an electrified powertrain, this method supports the identification of design relevance in an early stage of development. In addition to the main impact of design variable, there are interactions between the single design variables. The presented method by application of FAST can be extended to quantify these interactions. This will be addressed in prospective work.

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Stephan Rinderknecht studied aeronautic and aerospace technology at the University of Stuttgart and also made his PhD on delamination of carbon fibre reinforced plastics there in 1994. From 1995 to 2008 he worked as development engineer at the automotive transmission supplier Getrag in various positions, the last eight years as Vice President Research and Development. Since 2009 he is full professor and head of the Institute for Mechatronic Systems in Mechanical Engineering (IMS) at the Technische Universität Darmstadt covering the research fields automotive drives and mechatronic transmissions among others.