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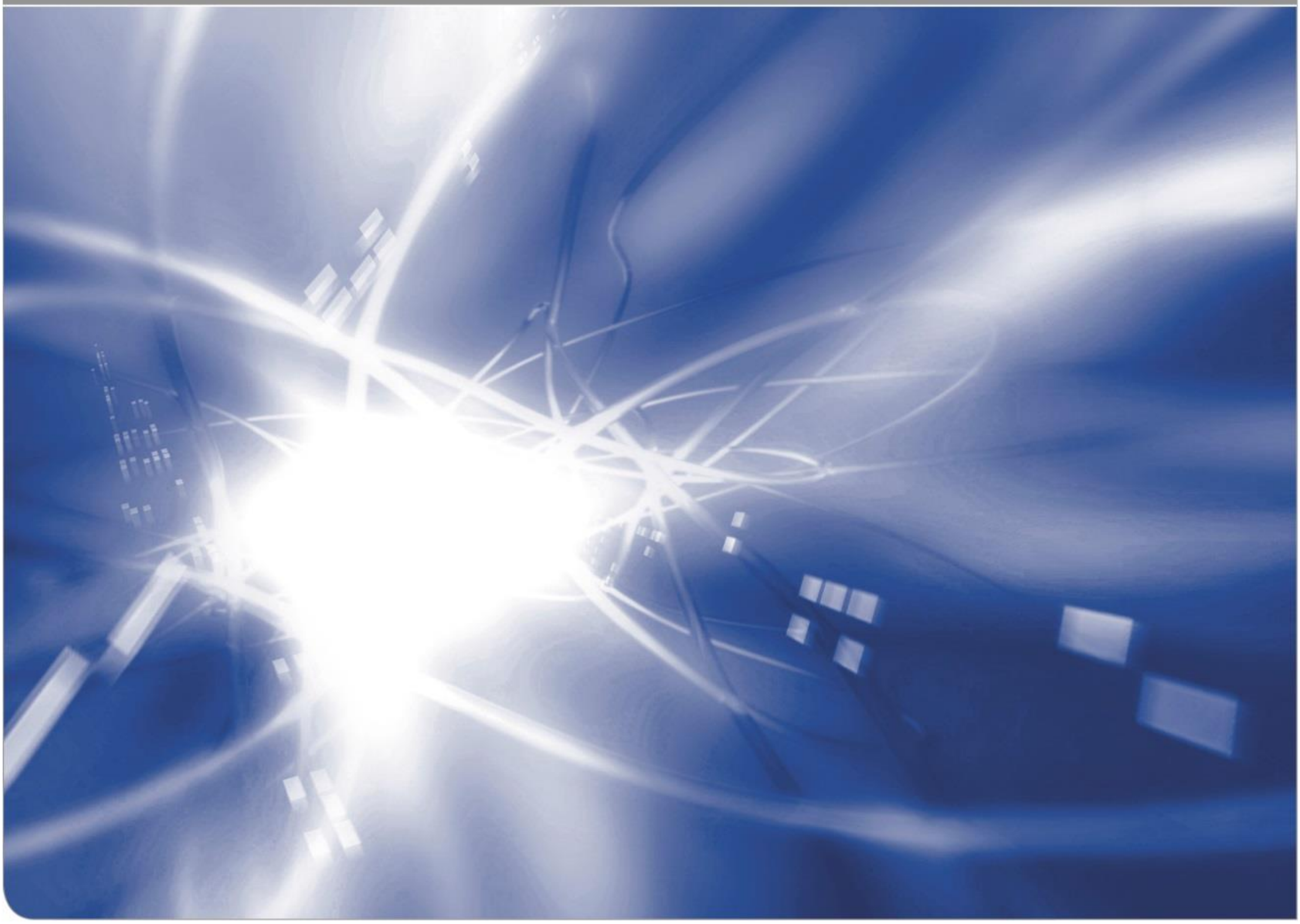

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# ANALYSIS OF THE VARIATION OF PHYSICAL ELEMENTS AND THEIR EFFECTS ON PROPERTIES AND FUNCTIONS USING THE EXAMPLE OF DIFFERENT GENERATIONS OF THE SYSTEM "ROLL STABILIZATION"

*Albert Albers, Tobias Hirschter, Joshua Fahl, Simon Rapp, Kevin Rehn, Steffen Haag*

## 1. INTRODUCTION AND MOTIVATION

Back in 2015, Schaeffler and Continental, for example, succeeded in developing an electromechanical roll stabilization system to series production maturity. In this automotive product development example, mechatronic active roll stabilization represents an innovation that resolves the "classical" conflict of objectives between the properties of vehicle dynamics (especially lateral dynamics) and ride comfort at the overall vehicle level [1]. The principle of passive roll stabilization, in which a stabilizer compensates for suspension differences during cornering by means of a torsional movement, is initially transferred to active roll stabilization. In addition, however, new principles such as mechatronic amplification of the torsional moment and decoupling of the forces acting during road-induced chassis movements are integrated to improve both the driving dynamics and ride comfort of a vehicle. In the overall vehicle, active roll stabilization enables higher maximum cornering speeds due to increased tire contact areas induced by reduced roll, while improving the ride comfort characteristic (especially in the case of road-induced excitations). Early planning of such innovations in new product generations and understanding their development requires a comprehensive analysis of the alternative solution principles, the effects in the overall system and the benefit fulfillment. A core task of development is therefore the transfer of the desired behavior of a product, described by target properties, via functions to the technical solution. The success factor of a holistic system understanding, and the consideration of all stakeholders is crucial for the success of a product development process.

## 2. STATE OF RESEARCH

### 2.1 Model of PGE – Product Generation Engineering

The Model of PGE – Product Generation Engineering by ALBERS [2] describes product development on the basis of the fundamental assumption of a targeted use *of reference system elements* (RSE) as a foundation for the development of a new product. Starting from the so-called *reference system* [3], the RSE can be systematically transferred into a new development project by the three variation types of *principle, attribute and carry-over variation* [4]. Experience shows that in practice companies always try to create a new product generation with a new development share that is as low as possible - but sufficiently large to ensure market attractiveness and competitive differentiation [5]. This strategy is reasonable from both cost and risk perspectives. However, it is important in innovation management to combine this strategy with a comprehensive market-environment analysis to avoid any surprise from competitors (horizontal and vertical). In a *generic reference product model* (cf. Figure 1), ALBERS ET AL. [6] structure technical products according to the three system views *properties, functions* and *physical elements* along different system levels (supersystem(s), complete system, subsystem(s)).

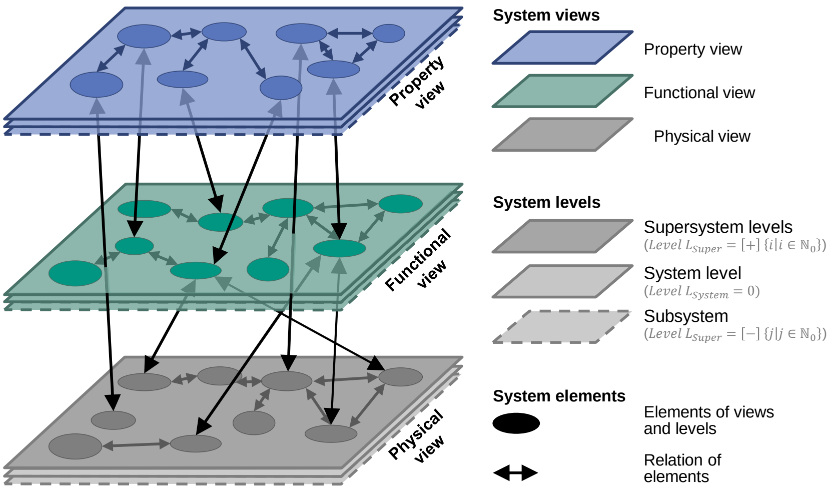



*Figure 1: Basic reference product model in the model of PGE by Albers et al. [6, p. 360]*

## 2.2 Properties, Functions and Physical Elements of Technical Systems

In order to consider relevant stakeholders (especially customers and users) in the development of technical systems, numerous approaches in the literature describe a *property-based requirements definition* [7]. This approach allows the product developer, for example in the automotive industry, to focus on *customer and user needs* at an early stage [8]. In light of this, SCHUBERT [9] defines *properties* as objectively assessable design elements that represent the *nature of a product* and can be influenced by the product developer to satisfy needs. EHRLENSPIEL AND MEERKAMM [5, P. 30] describe as a property *everything that can be determined of an object by observations, measurement results, generally accepted statements, etc.* The *property view on a system* likewise makes a description of the behavior possible from among other things customer, user and/or provider view in a defined context. The product developer can specify the desired, solution-open *target (product) behavior* (*"What"* should the system accomplish?) via properties. In addition to this, this view can be used to characterize the resulting, solution-specific *actual (product) behavior* that results from the realization via elements of the functional and/or physical view.

FELDHUSEN AND GROTE [10] understand a *function* generically accordingly as the *general and intentional relationship between input and output of a system with the goal of accomplishing a task*. EHRLENSPIEL [11] understands a function as a *property change* between an input and output state. Following on from this, a function can be formulated as a combination of a noun (denotes the turnover product) and verb (denotes the property change that occurs). Thus, in the *functional view of a system*, the desired or resulting behavior of the system to accomplish a *purpose* (task, action, or activity) is specified without consideration of the interacting physical solution elements being used [7]. According to ROPOHL [12], the functional view of a system in systems theory describes the *interaction of the system with its defined environment* through *input and output variables* and the *possible states*.

The *physical view on a system* describes the *physical elements* (electronic and mechanical components) of a data processing or mechatronic system (cf. e.g., ISERMANN [13]), consisting of the two complements hardware (tangible) and software (intangible, e.g. programs and data) (cf. e.g., VDI-FACHBEREICH PRODUKTENTWICKLUNG UND MECHATRONIK [14]). This view is used to specify the technical solution (*"How"* should the desired behavior and purpose of the system be realized?) via mechatronic scopes.

### 2.2.1 *Characteristics-Properties Modelling (CPM) and Property-Driven-Development (PDD)*

In the CPM approach of WEBER AND WERNER [15], *characteristics* ($C_i$) and *properties* ($P_j$) of a system are systematically related to each other. For this purpose, additional elements are taken into account. WEBER distinguishes hereby two basic operations. In the *analysis* ($R_j$), the resulting properties (behavior) of the product are determined or predicted based on existing characteristics. This can be done physically, but also virtually. In *synthesis* ($R_j^{-1}$), the required characteristics (or combinations of characteristics) are determined on the basis of required properties (target properties). WEBER AND WERNER [15] see in this activity the core of the product development, since on basis of the requirements of the customers and/or the market (represented by the target properties) the characteristics of the solutions are specified. The results of the analysis as more "unambiguous" than those of the synthesis, since in the synthesis there are often conflicts of objectives in the relation with further properties. The analysis of characteristic-property relations in technical systems, which are still in the development, models are necessary, on the basis of which one can predict the properties already in the development (cf. Figure 2).

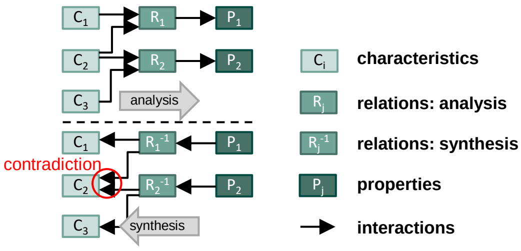



*Figure 2: Analysis and synthesis and emerging conflict of objectives in WEBER's CPM approach [16]*

Furthermore, the basic CPM approach can be extended to characteristic-property relations by considering external conditions. According to WEBER [16], the relations can only be meaningfully evaluated in the context of certain external conditions ($EC_j$). For example, the relations are perceived differently by the observer (customer, user and provider) during the analysis. In addition, different boundary conditions (e.g., temperature influence) have an influence on the analysis results (e.g., electrical range). Thus, it can be formalized that a realized technical system (product) "adheres" to certain properties ($P_j$) under consideration of external conditions ($EC_j$).

The number of synthesized and analyzed properties or characteristics and considered systems in the development process quickly exceeds the number that can be handled manually by a product developer, which is why computational assistance is necessary. In addition, however, the procedures can be summarized in a simplified process model, the *PDD – Property-Driven Development* (see Figure 3). In PDD, the process is represented as a sequence of synthesis, analysis and evaluation steps. The aim of PDD is to achieve the defined target properties in the process in the best possible way by means of the analysis-synthesis sequence. During evaluation, the aim is to achieve the smallest possible deviation between the target and actual properties. The control loop is run through as often as required, with further characteristics being defined or varied for each run, and at the same time the behavior of the system under consideration becoming more precise as a result of the analysis of these characteristics.

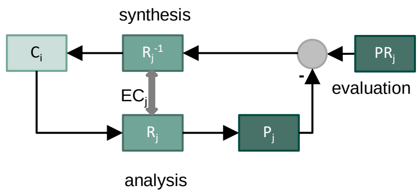



*Figure 3 Process model: PDD – Property-Driven Development by WEBER [17]*

### *2.2.2 Contact, Channel and Connector Approach (C&C²-A)*

The *Contact, Channel and Connector Approach* (C&C²-A) is a meta-model by ALBERS AND MATTHIESEN [17], which with 20 years of application experience enables the modeling of embodiment-function relationships (GFZ) in product development [18]. The *"thinking tool"* considers the *"pair character"* of the functionally relevant system components and includes the system environment [19]. According to ALBERS [20][1], the objects generated in a development process must be described in relation to the intended functions in order to keep the objectives transparent. Therefore, the C&C² approach aims at supporting product developers in identifying function-relevant parameters and thinking in a system context [21]. According to ALBERS AND MATTHIESEN [17], core elements for the representation of C&C² are *working surface pairs* (WSP), *channel and support structures* (CSS) and *connectors* (C).

- **Working surface pairs** (WSP) are surface elements that are formed when two arbitrarily shaped surfaces of a solids or generalized interfaces of liquids, gases, or fields come into contact and are involved in the exchange of material, energy, and/or information [22].
- **Channel and support structures** (CSS) are volume elements that describe volumes of solids, liquids, gases, or field-permeated spaces that connect exactly two WSP and enable conduction [channel] of substance, energy, and/or information in between [22].
- **Connectors** (C) are representative surface elements with a linked model of the relevant abstraction of the system environment that integrate properties relevant to the description of the considered function outside the current design domain into the system consideration [22].

The C&C² approach postulates three fundamental hypotheses, which represent the set of rules for model building. Accordingly, a *function needs interaction*[2] (basic hypothesis 1) and *minimum elements* (basic hypothesis 2). Furthermore, C&C² model building has a *fractal character* (basic hypothesis 3). [17]

## 2.3 Roll Stabilization System in Vehicle Development

In addition to the suspension and damper system, the *stabilization system* of a vehicle is the third fundamental component that determines the essential driving properties. Roll stabilization is usually achieved by elastic torsion bars that connect the wheel carrier to the axle and thus limit the lateral inclination of the vehicle when cornering. In the product development and tuning of a vehicle, the wheel load distribution (during dynamic cornering) and consequently the self-steering behavior can be influenced by the characteristic of the stabilizer bar hardness at the front and rear axle of the vehicle. In contrast, driving over bumps on one side of the road, for example, has a direct effect on the suspension behavior via the stabilizer system, since forces

[1] cf. 4th central hypothesis by ALBERS [20, p. 5].
[2] cf. 5th central hypothesis by ALBERS [20, p. 6].

are also transmitted to the opposite side. The design of the elastic torsion bars is therefore aimed at achieving a compromise between the lowest possible lateral tilt (for high driving dynamics) and high-quality suspension behavior (for high ride comfort). *Active roll stabilization systems* (generation of active forces on stabilizers by actuators) can resolve this customer-relevant conflict of objectives and almost completely compensate for lateral tilt, depending on the technical solution principle. Likewise, the self-steering behavior can be actively influenced. as the roll stabilization system has evolved over several generations, it is very well suited to analyze the variation of physical elements and their effects on properties and functions. [23]

## 3. RESEARCH PROFILE

### 3.1 Research Objective and Questions

For the reasons outlined in section 2.3, the alternative reference system elements (RSE) of the roll stabilization system are very well suited for a retrospective investigation across different system levels. The model of PGE (cf. Section 2.1), the CPM/PDD approach (cf. Section 2.2.1) and the C&C² approach (cf. Section 2.2.2) were used to deepen the understanding of the variation of system elements from different views (properties, functions, physical elements). In particular, the aim of the research project is to understand the dependencies of the variation types in the different views, to derive requirements for a generic variation operator and to apply the system understanding to functions and properties.

The overall research objective of the paper is operationalized by the following research questions:

- How can the *information of variation* among *alternative reference system elements (RSE) of the roll stabilization system* from the *property and function viewpoint* be modeled and activities derived in the model of PGE?
- How can the *phenomena of variation of properties and functions be generalized* in the model of PGE?
- What *contribution* can the *generalization of the findings* of the *relationships between properties, functions and physical elements* make in application?

### 3.2 Design Research Methodology and Research Procedure

The procedure in the research project was planned systematically in order to build up a comprehensible chain of reasoning and to generate robust results. The foundation for this is provided by the *Design Research Methodology* (DRM) by BLESSING AND CHAKRABARTI [24]. Therefore, in the *Descriptive Study I* (DS-I), the variation of system elements on different system levels was analyzed first (cf. chapter 4). A generalization of the findings on types of variation of functions and properties as well as the interrelationships of the phenomena in the views is performed in the *Prescriptive Study* (PS). In addition, both property and function understanding are defined to support the product developer, especially in purposeful variation in the Early Phase in the model of PGE (cf. Chapter 5). Finally, in the *Descriptive Study II* (DS-II), the generalized findings on the phenomena of variation of properties and functions are demonstrated. The specific procedure shown in Figure 4 was implemented in this research project.

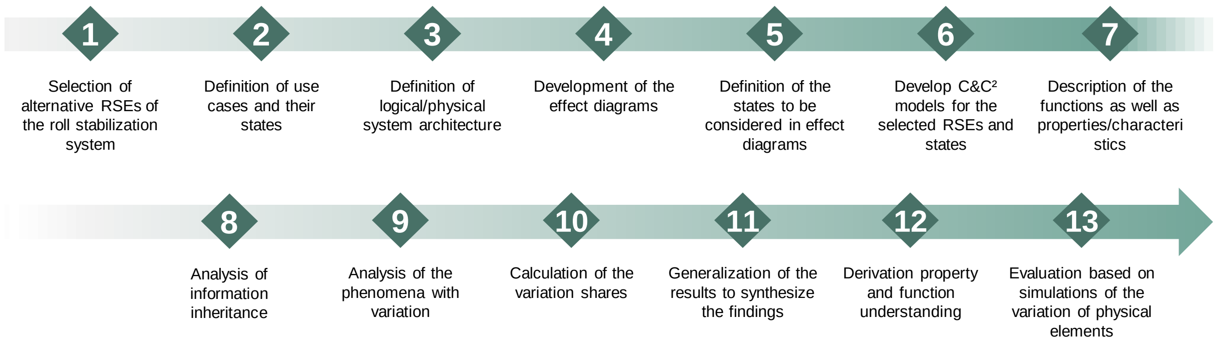



*Figure 4: Research Procedure*

In a first step, three alternative RSEs of the roll stabilization system were selected [1] and use cases (dynamic sequence of multiple states) respectively their (static) states were defined [2]. To enable comparability of the results, a logical as well as physical system structure or architecture were subsequently defined [3], in which the three alternative RSEs were located. Following this, the effect diagrams were developed on the first three system levels of the vehicle [4] and the states to be considered were defined in these same effect diagrams [5]. Subsequently, C&C² models were developed for the selected RSEs and associated states [6]. Based on the C&C² models and the effect diagrams, functions as well as the properties and their characteristics were described [7]. Subsequently, the inheritance of the information across the system levels was analyzed [8], and finally, the phenomena of variation were investigated from the function and property viewpoints [9]. Next, for this purpose, the variation proportions of the three alternative RSEs were calculated and compared [10]. In a further step, prescriptive generalization of the results was performed to synthesize findings [11]. Furthermore, a consistent understanding of properties and functions was derived and defined [12]. Finally, the evaluation of the prescriptive content was performed using simulations of the variation of physical elements [13].

## 4. ANALYSIS OF THE VARIATION OF PHYSICAL ELEMENTS AND THEIR EFFECTS ON PROPERTIES AND FUNCTIONS (DS-I)

### 4.1 Selection of Alternative Reference System Elements (RSE) of the Roll Stabilization System

In a first step, the physical solution alternatives of the roll stabilization system in vehicles currently available on the market were analyzed. Three main variants were identified, which were subsequently selected as the three alternative RSE of the roll stabilization system in the subject of this study (see Figure 5).

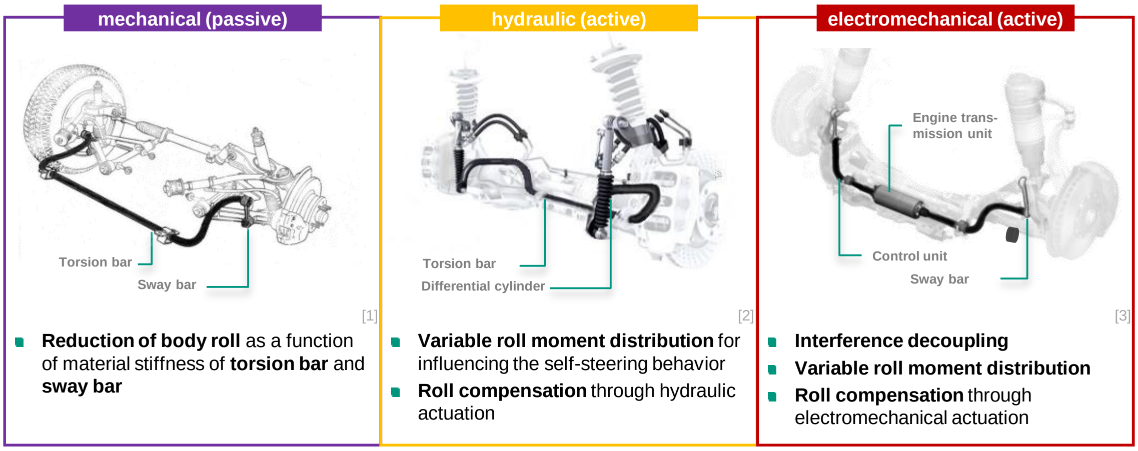



*Figure 5: Overview of the alternative reference system elements (RSE) considered for passive, hydraulical active and electromechanical active roll stabilization*[3]

The original roll stabilization system of mechanical **passive roll stabilization** (hereafter referred to as PRS) is used today in some basic product variants of the Porsche 718, 911, Macan and Cayenne, for example, and is implemented by an elastic torsion bar spring that is connected to the *wheel carriers* of an axle via *sway bars* (see Figure 5, left). This allows *passive limitation or reduction of the driver-induced roll of the vehicle when cornering*. In the case of *one-sided road excitations*, however, this variant of the RSE is followed by so-called *roll copying*. As a result of the compression of suspension springs to the vehicle body, a roll moment is generated, which causes torsion of the stabilizer system (torsion bar spring and sway bar) and thus a moment in the same direction.

In relation to the PRS, the **hydraulic active roll stabilization system** (hARS) replaces the sway bar in the Porsche 911, for example, with *actively adjustable differential cylinders* (see Figure 5, center). The differential cylinder therefore connects the respective wheel carrier with the torsion bar spring. The preload of the torsion bar spring can be influenced by *electronically controlled pressure regulation of the hydraulic oil in the differential cylinder*. By individually controlling the hydraulic actuators depending on the driving situation, the *self-steering behavior* can be positively influenced. The additional support of the roll damping leads to an *active reduction of the road-induced roll tendency* (roll copying) and thus ultimately to an increase in vehicle stability.

The third alternative solution, **electromechanical active roll stabilization** (hereinafter referred to as eARS), is currently used in the Porsche Taycan, for example (see Figure 5, right). The basic design consists of an *electromechanical actuator* (brushless DC motor and three-stage planetary gear) located between the *two split halves of the torsion bar spring*. Like the PRS, the torsion bar spring halves are connected to the respective wheel carriers of an axle via a pendulum support. The *electromechanical actuation and control* of the roll stabilization system enables *almost complete active compensation of the roll tendency* thanks to the high actuation dynamics (approx. -30% reaction time compared with hARS). In addition to the hARS, the eARS can *absorb or decouple disturbing influences* on roll damping and thus *virtually completely prevent roll copying*. A further technical advantage is that the full power of the eARS is permanently available. The hydraulic pump of the hARS, on the other hand, is usually operated via the vehicle's internal combustion engine and thus has disadvantages at low engine speeds. The greater flexibility from the point of view of system integration and freedom from maintenance of the eARS may therefore mean lower system costs than the comparable hydraulic system and may also promote lower energy consumption due to the *power-on-demand principle*.

[3] Image source: Dr. Ing. h.c. F. Porsche AG

## 4.2 Definition of the Relevant Use Cases and their States

The relevant *dynamic use cases* in which the roll stabilization system significantly influences the overall vehicle behavior were examined subsequently (cf. Figure 6). For the four *"extreme cases"* in the application, the relevant *static states*[4] *of the system* were defined depending on the context.

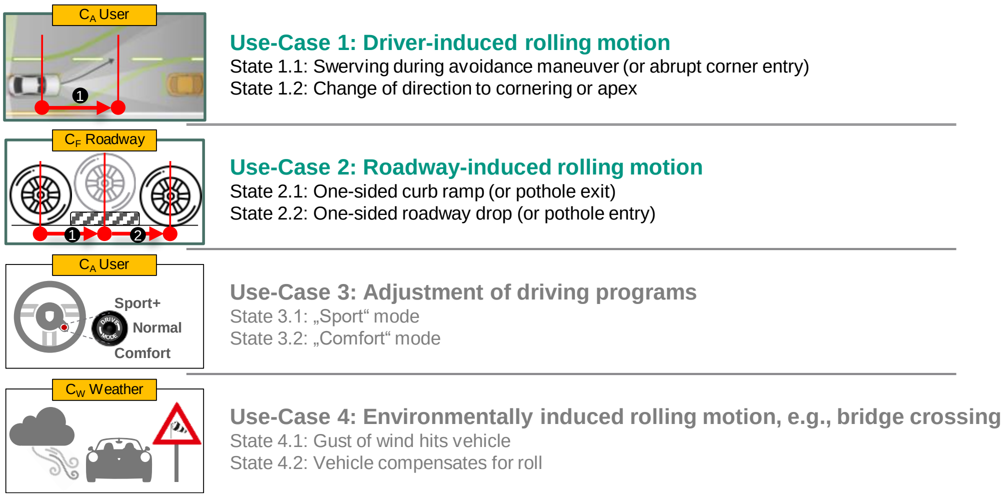



*Figure 6: Overview of the considered use cases and their relevant states*

From the total of *four relevant use cases* for the roll stabilization system, the *driver-induced roll motion* (via connector user $C_A$) and the *road-induced roll motion* (via connector road $C_F$) were selected for further consideration. A representative example of the driver-induced roll motion of the vehicle is, for example, the *swerving during an evasive maneuver* or an *abrupt initiation of cornering* (state 1.1). By applying force to the vehicle body in the form of lateral acceleration, a rolling moment is induced by the centrifugal force (acting on the vehicle's center of gravity) and hits the wheel guidance system (spring, damper, control arm, etc.), the wheel carrier, the wheel, and finally the road [26]. The load change reaction (state 1.2) is not considered further since it corresponds to a reversal of the steering direction by the driver and has the identical effect[5]. A *one-sided road unevenness* – e.g., curb rise/impact hole exit (state 2.1) or road dip/impact hole entry (state 2.2) – characterizes a *road-induced rolling motion*. In this case, a force is applied to the wheel in the form of normal force changes due to asymmetrical road unevenness. The unilateral road impulse via wheel, wheel carrier and wheel guidance system finally induces a rolling moment in the body system [26]. In vehicles today, the control of active roll stabilization systems can often be influenced by adjusting the driving program (via Connector user $C_A$) [26]. In a *"Sport" mode*, for example, the prioritization is usually on high, dynamic driving characteristics of the overall vehicle behavior, while in *"Comfort" mode* it is more on driving comfort. Since in this case no comparison can be made with passive roll stabilization (no influence possible via driving program), *Use Case 3 is neglected*. A rolling motion of the vehicle can be equally induced by the environment (connector weather $C_W$) or aerodynamic forces with a component in the y-direction of the vehicle, e.g., when crossing a

[4] Following THAU [25, p. 82], a *state* describes an arbitrarily long period of time in which an unchanged number of functions act, which always starts anew when a working surface pair (WSP) or a channel and support structure (CSS) or a corresponding function is added or removed, or when the properties of the embodiment function elements change to an extent relevant to the function.

[5] In accordance with ZINGEL [27, p. 145], the *effect* refers to a natural scientific law for determining the relationship between inputs and outputs in working surface pair (WSP) and channel and support structure (CSS), taking into account their relevant characteristics and properties.

bridge in windy conditions. The greatest influencing factor here is the lateral vehicle base area, which is hit by a gust of wind, for example. As the three roll stabilization systems are not currently used in a product variant in which all other influencing factors could be kept the same, no direct comparison is possible here. *Use case 4 is also not considered further*.

### 4.3 Determination of the Logical and Physical System Architecture

Product developers are responsible for adopting or varying the *logical reference structures of the system levels* or for sensibly restructuring a new product (in the sense of a $G_1$ in the PGE model, cf. ALBERS *ET AL*. [28]) into system levels. The result of a development task or product can coincidentally be a subsystem of another product (e.g., of the same domain) [29]. The transmission is the product of a supplier (here: automotive supplier) and at the same time a subsystem of a vehicle of an OEM of the domain automotive industry [29]. From the automotive OEM's point of view, the vehicle thus forms a *monolithic system of subsystems* (cf. ALBERS *ET AL*. [30]), a context-dependent system of the associated supersystem. Nevertheless, e.g., vehicles, smartphone apps, and the transportation infrastructures can form a supersystem that works seamlessly together to jointly satisfy customer and user needs. Here, all individual (autonomous) systems together form the *System of Systems* (SoS) of seamless mobility [31]. Consequently, the outlined supersystem level can be characterized as SoS in this example. Depending on the observer (e.g., domain, organization, or product developer), the hierarchical structure can differ into system level and super- and subsystem level(s). Within a domain, it can be beneficial to standardize a *global view* for an industry, value chain, etc. An example of this is the *labeling system for rail vehicles* (cf. DIN DEUTSCHES INSTITUT FÜR NORMUNG E. V. [32]), in which a uniform hierarchization of the system levels within the domain was adopted (cf. Figure 7, left). The advantages of this standardization can be seen in more efficient subcontracting of subsystem developments to service providers, domain-related standardization of tests/validation and/or releases. In addition, a differentiated view can take place within the organizational structures of a provider. In this case, a hierarchy of system levels can be defined on an organization-global or provider-specific basis. However, problem-solving teams in specialist departments of the supplier or individual product developers can specifically relate their level of the “system of interest” and, for example, convert an absolute scale relative to it (cf. Figure 7, center). Similarly, a supplier who develops only a subsystem for the provider, or another provider who supplies part of a supersystem, can orient itself to the defined system levels via a relative scale (cf. Figure 7, right).

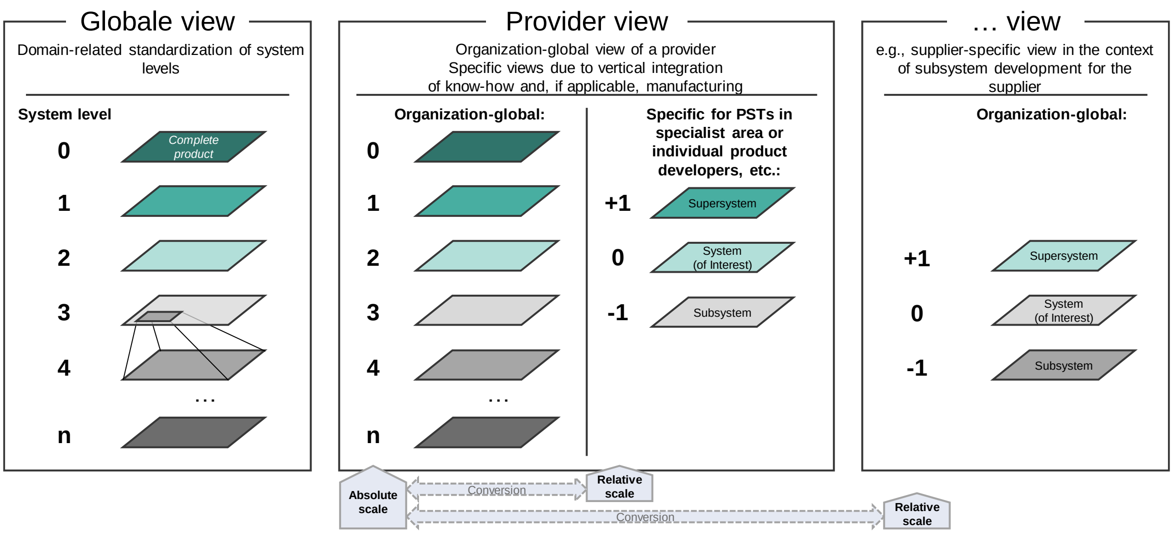



*Figure 7: Understanding of system levels in the model of PGE*

For the purpose of comparability of observations and analysis results, a *(solution-open) logical system architecture* for the vehicle system in the study was defined below. This logical system architecture was derived from observations in the automotive industry and aims, on the one hand, not to anticipate any technical solutions in the description of the systems and, on the other hand, to serve as a *"reference system architecture"* over several generations. The relevant section for the study is shown in Figure 8.

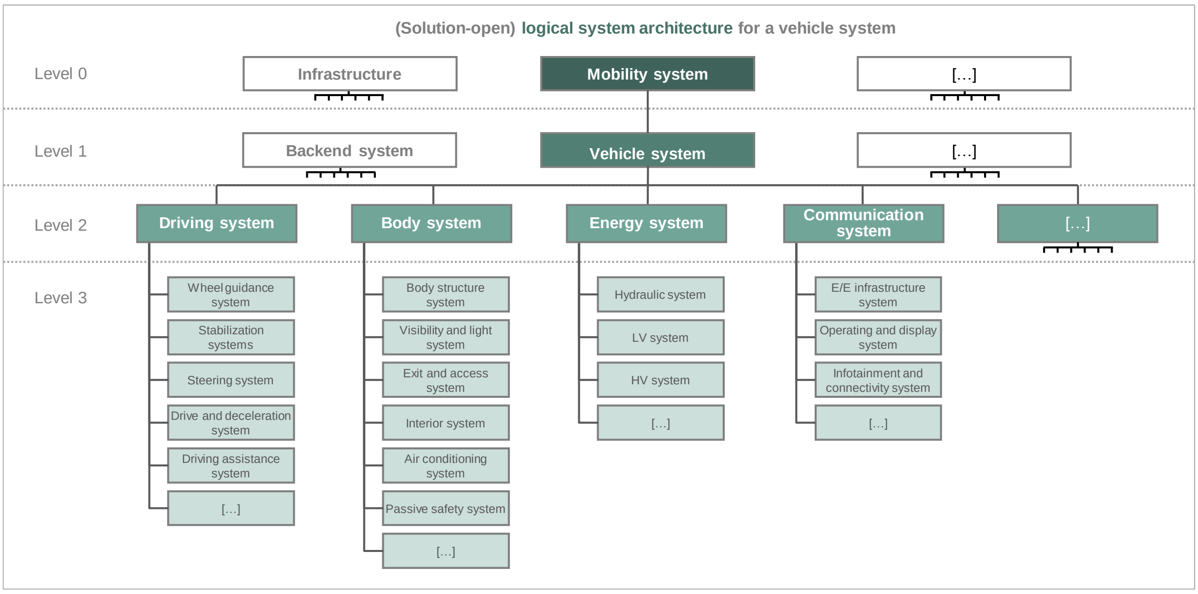



*Figure 8: Excerpt of the used (solution-open) logical system architecture for a vehicle system in the study*

In reality, the *vehicle system* is itself part of a supersystem, which can be described as a mobility system, for example. In combination with the infrastructure, this can be characterized as a *system-of-systems* (cf. e.g., ALBERS *ET AL*. [30]). In the defined, logical system architecture, the vehicle system is initially subdivided at *level 2* into the four systems: *driving system*, *body system*, *energy system and communication system*. The *stabilization system*, which is the focus of this study, is illustrated at *level 3* as a *subsystem of the driving system*. Other level 3 subsystems that are connected to the stabilization system via interfaces and interactions are also shown as examples in Figure 8.

Following the definition of the logical system architecture, a *(solution-specific) physical system architecture* was derived on three further subsystem levels in order to locate the *three alternative RSEs of roll stabilization and their constituent subsystems*, which are the focus of this study (see Figure 9).

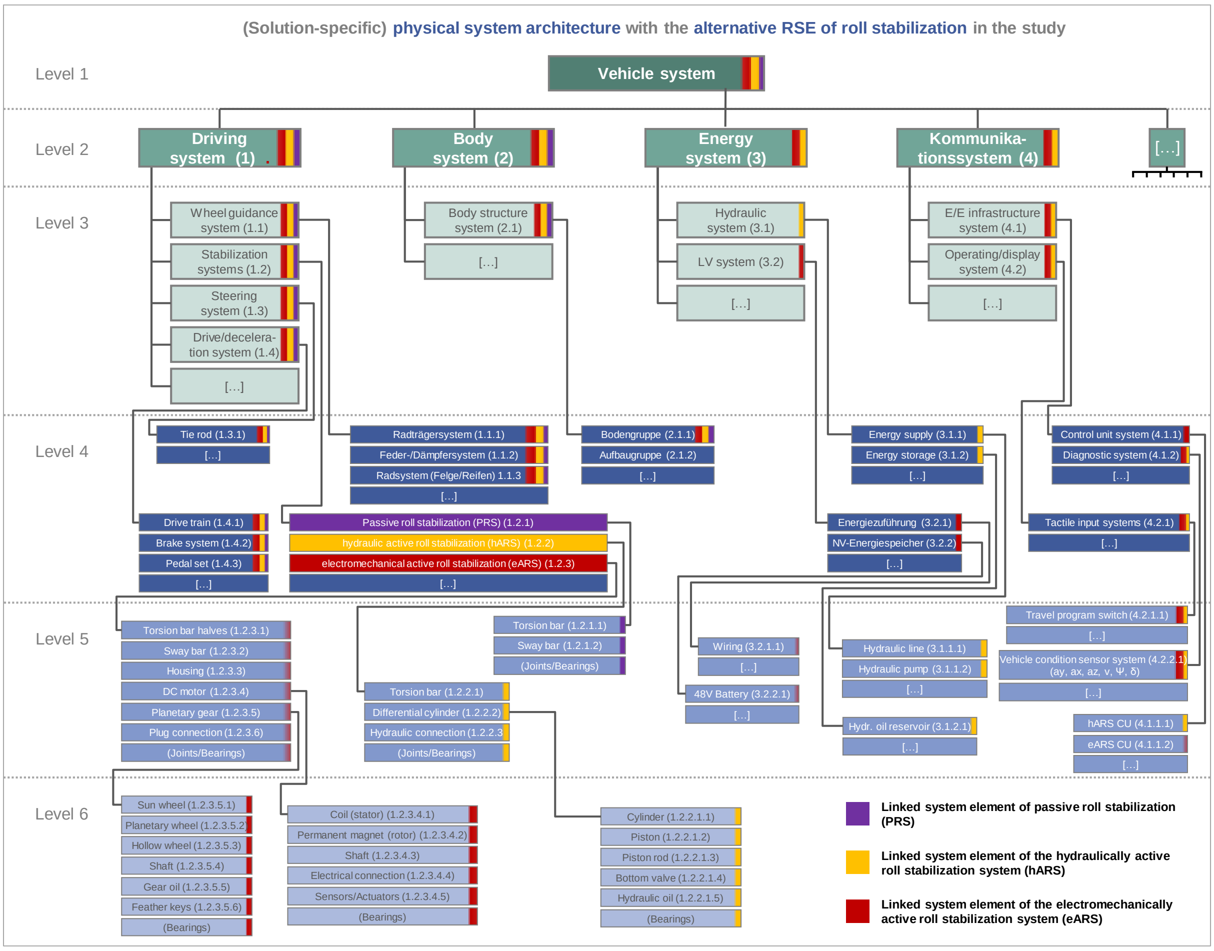



*Figure 9: Excerpt of the used (solution-specific) physical system architecture for levels 4,5 and 6 in the study*

The *system elements are assigned to the three alternative RSEs* of the roll stabilization system (PRS, hARS, eARS) and are *highlighted with different colors* in Figure 9. Generally, only one alternative solution of the roll stabilization system can be implemented in a vehicle at any one time. Theoretically, different variants could be used on the front and rear axles, but in practice this is virtually impossible due to the effort involved, costs, complexity, etc. Accordingly, only the variants marked in color are shown. Consequently, only the system elements linked by color coding are necessary and all others – at least from the point of view of one variant of the roll stabilization system – are superfluous. In the example considered, only the roll stabilization of the steered front axle is dealt with in a simplified manner. The effects of the physical elements of the three alternative roll stabilization systems have also been marked in the logical system architecture for reasons of clarity.

## 4.4 Development of the Effect Diagrams of System Levels 1, 2 and 3

With the aim of showing the concrete interrelationships of the use cases in the logical system structure, a *system level effect diagram* was elaborated for each of the levels 1, 2, and 3 (see Figure 10, Figure 11 und Figure 12).

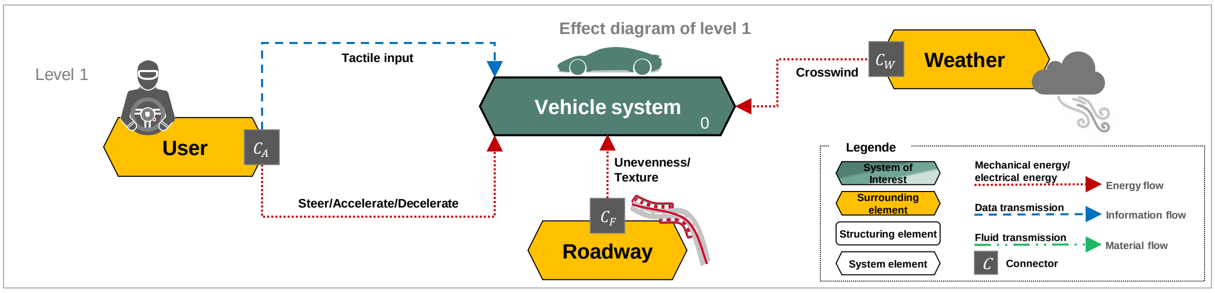



*Figure 10: Effect diagram of level 1: Vehicle System*

The *vehicle system in level 1* is affected by three *environmental elements*: *the user*, *the road surface and the weather* (see Figure 10). The *crosswind* acts in the form of an energy flow via the connector $C_W$ (use case 4), and the *unevenness and condition of the road surface* flows into the vehicle system as an energy flow via the connector $C_F$ (use case 1). The user can influence the vehicle system via *steering*, *acceleration and deceleration* (energy flow in Use-Case 2) on the one hand, and via an information flow through *tactile inputs* (data transmission in Use-Case 3 – only possible with hARS/eARS) through the Connector $C_A$ on the other.

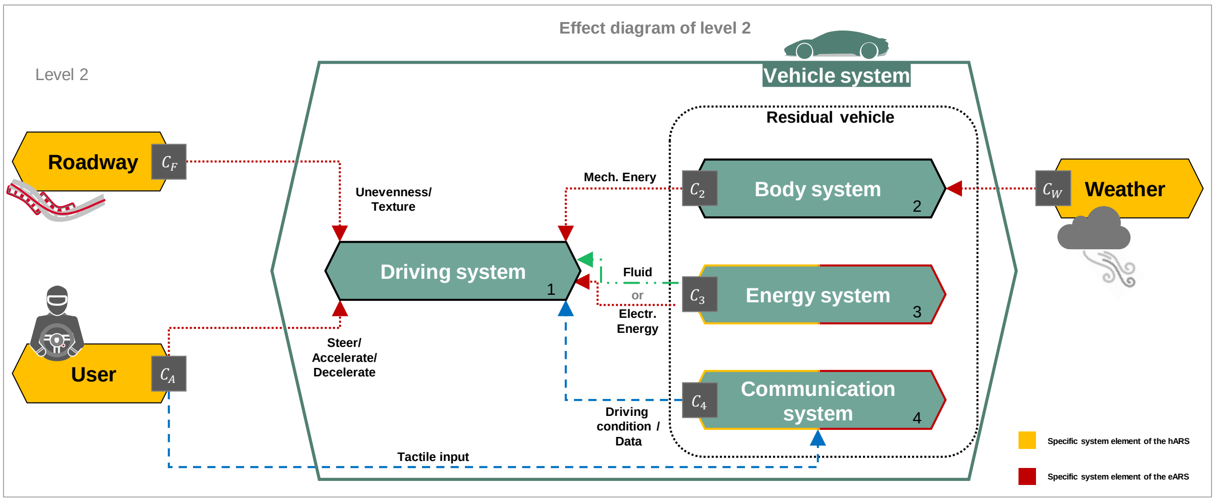



*Figure 11: Effect diagram of level 2: Driving System*

At the more concrete *level 2* (cf. Figure 11), it is evident that the *weather* has a direct effect on the *body system* via $C_W$ and that the *road* has an effect on the *driving system* via $C_F$. The *user* influences the driving system via $C_A$ by driving commands (acceleration, deceleration, steering) on the one hand and the vehicle's *communication system* via tactile inputs on the other hand for the two alternative RSE of the hARS and eARS. Within the vehicle system, *mechanical energy* flows from the body system (via $C_2$) and *fluid* (hARS) or *electrical energy* (eARS) flows from the energy system (via $C_3$) to the driving system. The communication system sends *information*, e.g., on driving status or selected driving program (only for hARS/eARS), to the driving system via the connector $C_4$ as required by the user's input. Since the focus is on the driving system and the interactions with the road and the user, the three system elements body, energy and communication system are grouped under the *"rest of the vehicle"* in the effect diagram.

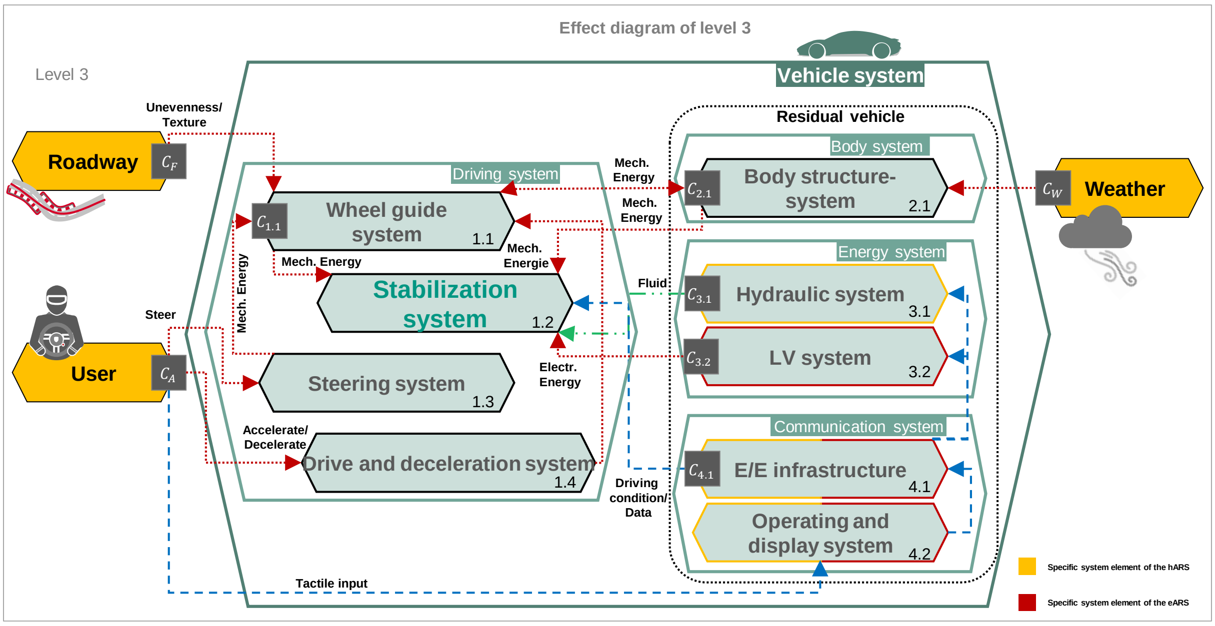



*Figure 12: Effect diagram of level 3: Stabilization System*

The detailed *effect diagram on level 3* (cf. Figure 12) shows that the roadway has a direct and unrestricted effect on the *wheel guidance system* in the driving system. The energy flow from the user, on the other hand, is divided between the *steering system* (steering) and the *drive and deceleration system* (acceleration and deceleration). Both steering and drive/deceleration systems subsequently transfer mechanical energy to the wheel guidance system. The concretization of the three elements in the *"rest of the vehicle"* indicates that the weather experienced by the *body structure system* is transmitted via mechanical energy to the wheel guidance system on the one hand and to the stabilization system on the other. At the same time, the wheel guidance system transfers mechanical energy back to the body structure system in the case of road excitation. In the case of the hARS, the stabilization system is also supplied with a fluid (hydraulic oil) from the *hydraulic system*. The eARS, on the other hand, is supplied with electrical energy from the *low-voltage system*. In the case of the hARS and eARS, the *control and display system* takes tactile inputs (e.g. driving program selection) from the user, forwards this information to the *electrical/electronic architecture*, which in turn sends information to the stabilization system.

## 4.5 Development of C&C² Models, Function and Property Structures for the Selected RSE and States

The three alternative RSE of the roll stabilization system are analyzed at level 4 in the next step using the *C&C² approach* (cf. Section 2.2.2). The C&C² approach is particularly suitable because functions are qualitatively related to functionally relevant *working surface pairs* (WSP) and *channel and support structures* (CSS) [33]. In the study, the WSP and CSS of the passive and the two active roll stabilization systems were determined and *characterized in their respective system embodiment* (cf. Figure 13, Figure 16 und Figure 19).

The design-related determination of the functionally relevant effect locations, principles and movements is assigned in a *function structure* as an example in order to show the change across the variants of the RSE of the roll stabilization system (cf. Figure 14, Figure 17 und Figure 20). In addition, the effects on the behavior in the overall system as well as the subsystem levels were each shown using a *property structure* (cf. Figure 15, Figure 18 und Figure 21). The *capture of the system environment and boundaries*, consequently the connection with further *interacting subsystems* on level 4, is an essential step in the procedure. Using the *connectors* of the alternative roll stabilization systems, *system interfaces and interactions* for *traceability of information inheritance* were captured and their influence on the RSE under consideration was *specified*. The roll stabilization systems are connected by couplings of the torsion bar spring (halves) to the *vehicle floor* (connection points in the body structure system) and by a *joint/coupling* of the sway bar and the differential cylinder to the wheel carrier. In the example considered, the connection points to the wheel carrier as well as the body structure system and the connection to the hydraulic (hydraulic connection of the hARS) or the electrical (wiring of the eARS) energy supply system and communication system (hARS/eARS) represent the *system boundaries* of the three alternative RSE. The aforementioned, physical system interfaces, as well as their characteristics, are essential to the functional performance of the system. The *required information and interrelationships* were *discursively and investigatively* collected based on *literature review* and *expert interviews* during the participatory observation. Interactions of the roll stabilization system both with other interacting systems and in the overall system were *partially simulated, subjectively evaluated by experts, or predicted*.

### 4.5.1 Passive Roll Stabilization (PRS): C&C² Analysis, Function and Property Structure at System Level 4

The *results of the C&C² analysis* of the *mechanical passive roll stabilization* (PRS) at level 4 are shown in Figure 13. The PRS is composed of the *torsion bar spring* ($CSS_{1.2.1.1}$) and two *sway bars* ($CSS_{1.2.1.2}$). The joints/couplings at the connections are neglected for simplification in this study. Within the PRS, there is one *WSP each between the torsion bar spring and the sway brackets on the right and left* ($WSP_{1.2.1.1\,-\,1.2.1.2}$). At the *system boundary*, the PRS is connected on the one hand to the floor assembly in the body structure system via the torsion bar in *Connector* $C_{2.1.1}$ and to the wheel carriers on the right and left via the sway bars in *Connector* $C_{1.1.1}$. The information from the interacting systems, which flows into the connectors of the PRS, for example in the form of mechanical energy, is also shown in Figure 13.

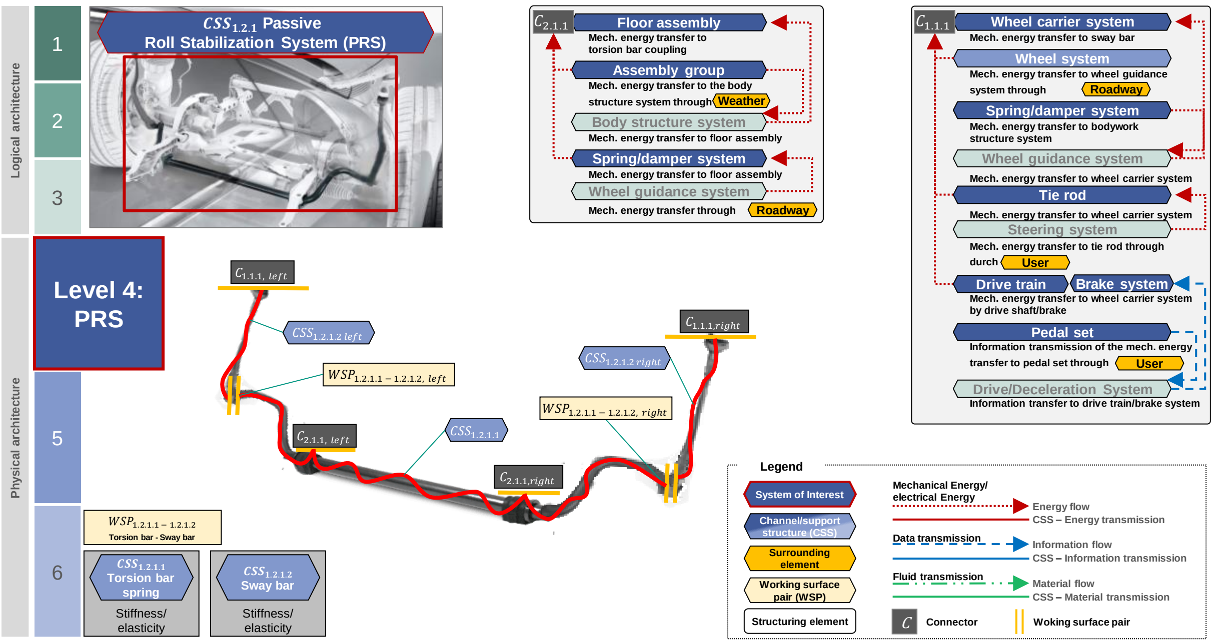


*Figure 13: C&C² model on level 4: Passive Roll stabilization (PRS)*[6]

[6] Image source: Dr. Ing. h.c. F. Porsche AG

The *main function* to be performed by the passive roll stabilization system in the overall vehicle is the *passive reduction of driver-induced roll caused by a steering impulse* (see Figure 14). For this purpose, the main function was subdivided into further subfunctions in order to assign the involved and function-realizing CSS and WSP to the functional structure of the PRS. For example, to passively reduce driver-induced roll, *spring differences of the wheels for dynamic and load-dependent wheel load distribution in the overall vehicle* are compensated by the *torsion of the torsion bar spring* ($CSS_{1.2.1.1}$) at the level of the *technical functions*. To enable the *torsional movement of the torsion bar spring around the y-axis*, it is supported on the one hand via couplings ($C_{2.1.1}$), as described, and transmits the force via the $WSP_{1.2.1.1-1.2.1.2}$ into the sway bar or absorbs forces coming from the wheel carrier or $C_{1.1.1}$.

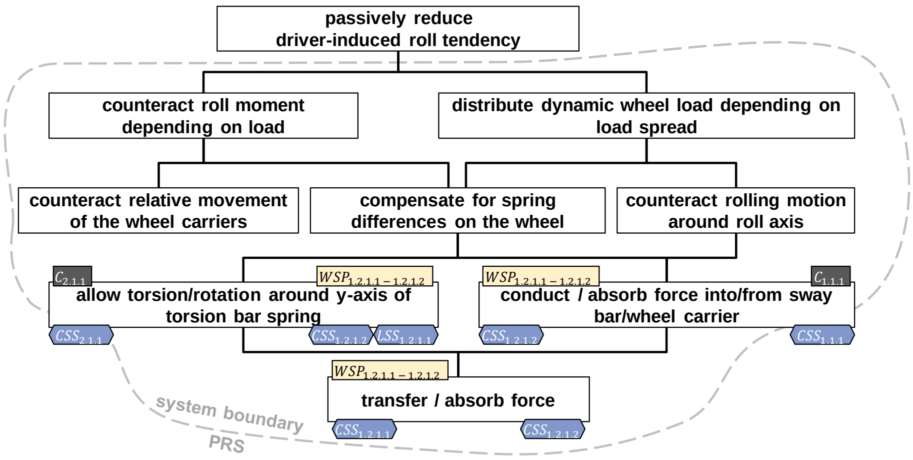



*Figure 14: Function structure of the passive roll stabilization system (PRS)*

In the following, the *resulting properties of the system and overall vehicle* (see Figure 15) were analyzed on the basis of the *function structure of the PRS*. It was initially determined that only the *constituent attributes of the characteristics of a desired/intended property* (in this case, roll angle and roll acceleration) can be *influenced* during product development. In the example of the PRS, the maximum torsion angle of the torsion bar spring can be directly influenced within the system limits via its *material or geometric dimensions*. *Stiffening the torsion bar spring* reduces the roll angle, for example, and thus *increases* the *lateral dynamic properties of the vehicle*. Such a stiffened torsion bar spring leads to faster or more direct force transmission into the body when excited by road unevenness, for example, and thus *promotes undesirable roll copying*. In this case, the user perceives a *deterioration in ride comfort*. The variation of the characteristic values of the properties of the roll stabilization system, but likewise of the overall system, can consequently be determined and described. The use of mechanical PRS therefore presents the product developer with an *unresolvable conflict of objectives between ride comfort and driving dynamics*.

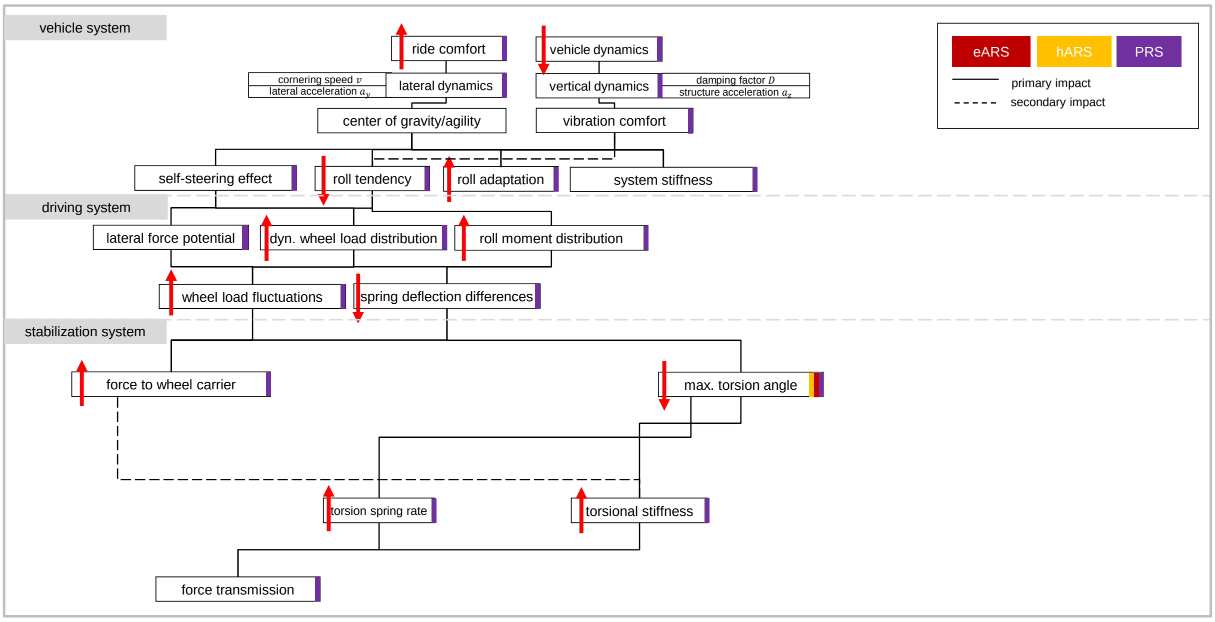


*Figure 15: Property structure of the passive roll stabilization system (PRS)*

### 4.5.2 *Hydraulical Active Roll Stabilization (hARS): C&C² Analysis, Function and Property Structure at System Level 4*

Figure 16 shows the *results of the C&C² analysis* of the *hydraulic active roll stabilization* (hARS). The hARS *"replaces"* the sway bars of the PRS with *differential cylinders* ($CSS_{1.2.2.2}$) and is also supplemented by a *hydraulic connection* ($CSS_{1.2.2.3}$). The torsion bar spring ($CSS_{1.2.2.1}$) remains identical. Therefore, for the hARS, there is one *WSP each between the torsion bar spring and the differential cylinders on the right and left* ($WSP_{1.2.2.1-1.2.2.2}$). Analogous to the PRS, at the *system boundary* there are the couplings of the torsion bar to the floor assembly in the body structure system via *connector* $C_{2.1.1}$. The differential cylinders are also connected to the wheel carriers via joints/couplings in *Connector* $C_{1.1.1}$. In addition, compared to the PRS, there is an additional $WSP_{1.2.2.2-1.2.2.3}$ between the differential cylinder and the hydraulic connection. *Connector* $C_{3.1.1}$ is used to connect to the energy supply system, through which the *fluid transfer* (hydraulic oil) from the *hydraulic system* takes place. The detailed connections and information inheritance with the interacting systems via the connectors of the hARS are shown in Figure 16.

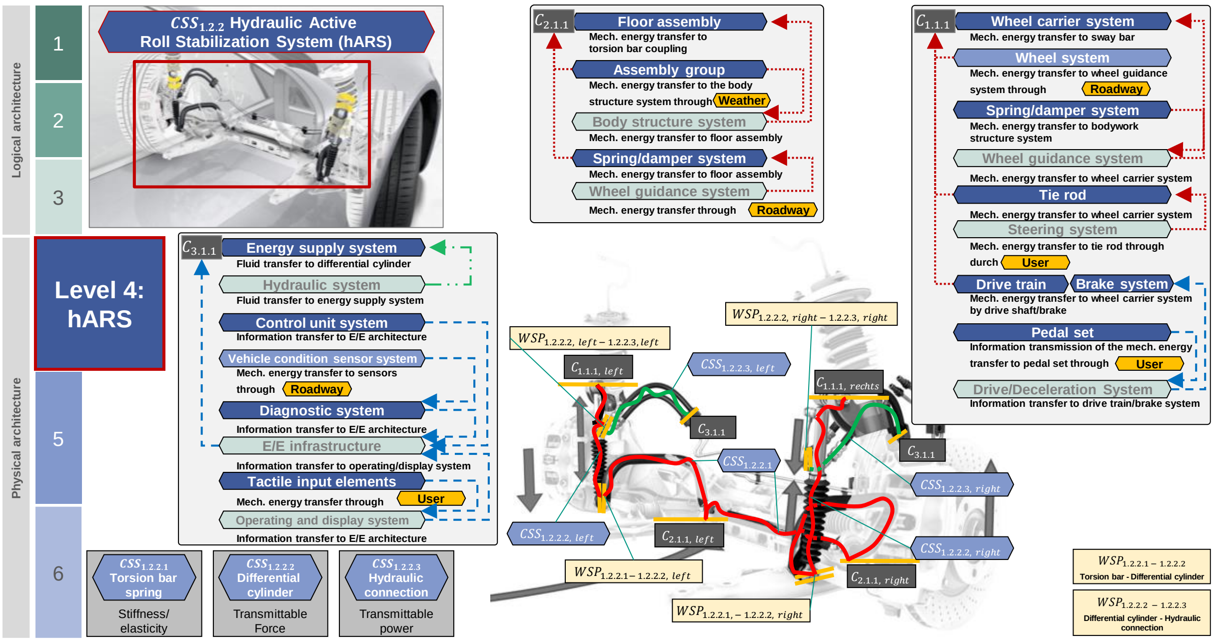



*Figure 16: C&C² model on level 4: Hydraulic Active Roll stabilization (hARS)*[7]

The basic functionality of the PRS at the overall vehicle level *("passively reduce driver-induced body roll")* is initially varied in its attributes, so to speak, in the hARS, i.e., the vehicle roll caused by a steering impulse, for example, can be *"actively"* reduced (see Figure 17). The *rolling moment can be counteracted as required* and the *dynamic wheel loads can be distributed depending on the situation* (both also variations of the functional characteristics compared to PRS). By *controlling the hydraulic pressure* (in $C_{3.1.1}$), a *change in length of the differential cylinder* ($CSS_{1.6.3.4}$) can be enabled via the $WSP_{1.2.2.1\,-\,1.2.2.2}$ in order to *counteract the wheel carrier movement with a torque as needed*. Vehicles equipped with appropriate sensor technology for position detection (e.g., steering angle sensor, longitudinal and lateral acceleration sensors) can intervene almost preventively and actively reduce *driver-induced roll by means of appropriate information transmission and processing*. In addition, the hARS fulfills a second main function of *reducing road-induced roll or roll-copying* (e.g., in the case of one-sided road unevenness). In contrast to the transmission of the one-sided road pulse via the wheel guidance system into the body system - amplified via the torque of the twisted torsion bar spring in the same direction (as with PRS) - the *movement of the wheel carrier can be specifically permitted via a reduction of the hydraulic pressure in the differential cylinder* (in the sense of an *"active softening of the sway bar"* via $WSP_{1.2.2.2\,-\,1.2.2.3}$) and thus support *roll damping in the overall vehicle*.

[7] Image source: Dr. Ing. h.c. F. Porsche AG

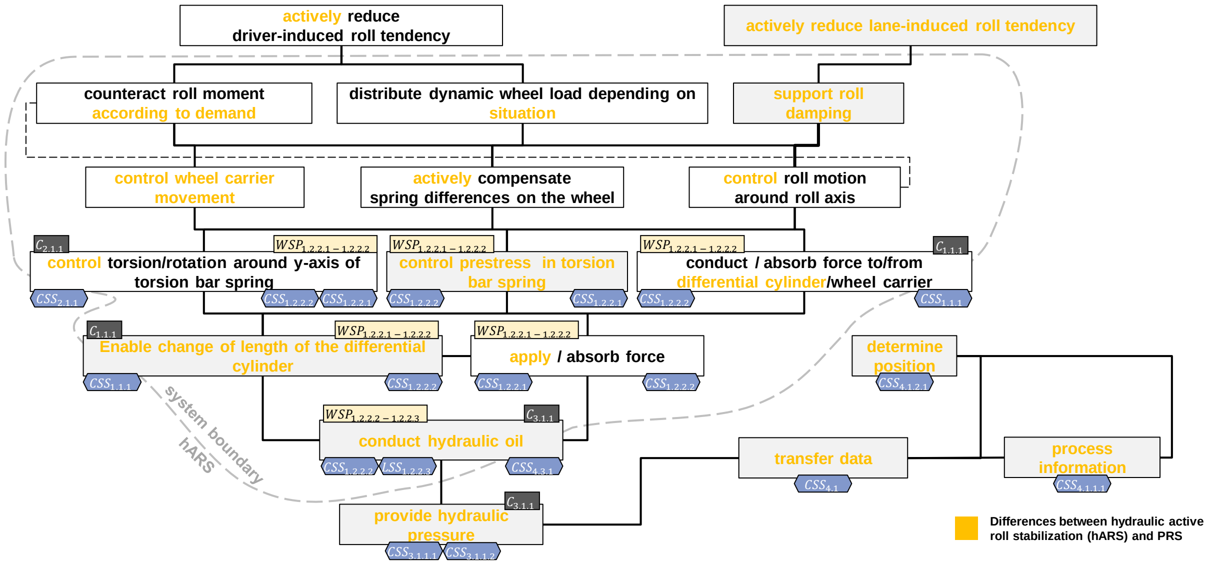



*Figure 17: Function structure of the hydraulic active roll stabilization system (hARS) compared with the PRS*

Building on the functional analysis, the *characteristics that can be influenced and the resulting properties of the hARS and the overall system* were examined (see Figure 18). The *geometric dimensions of the piston rod and cylinder* of the differential cylinder or the *viscosity of the hydraulic oil* are characteristics that the product developer can influence directly by specifying them. This consequently determines properties such as the *transmissible power through the fluid* or *transmissible forces in the differential cylinder*. At overall vehicle level, the hARS ensures both *situation-dependent control of the roll angle* in the case of driver-induced roll and a *reduction in roll copying in the case of road-induced roll*. *Previously conflicting objectives* such as driving dynamics and comfort at the overall vehicle level can therefore be *positively influenced in equal measure* by the hARS.

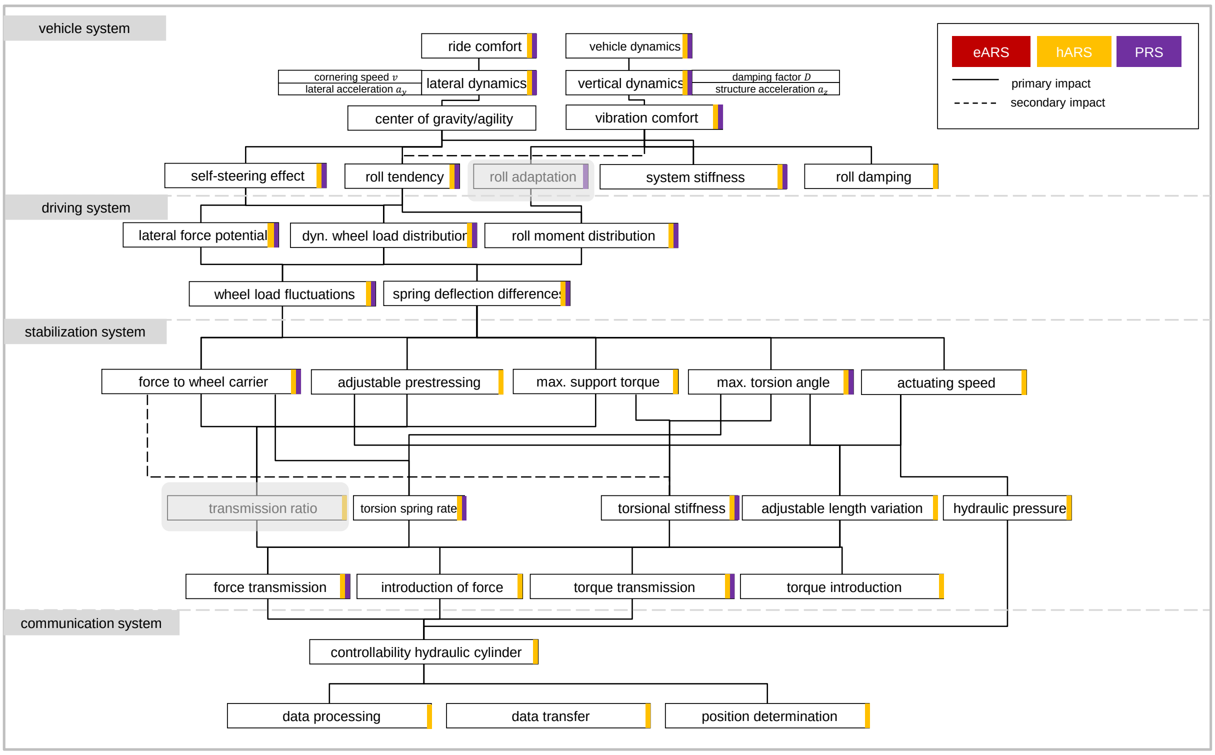



*Figure 18: Property structure of the hydraulic active roll stabilization system (hARS) compared with the PRS*

### 4.5.3 *Electromechanical Active Roll Stabilization (eARS): C&C² Analysis, Function and Property Structure at System Level 4*

Figure 19 shows the *results of the C&C² analysis* of the *electromechanical active roll stabilization* (eARS). The eARS is basically implemented by a motor-gearbox unit integrated between *two torsion bar spring halves* ($CSS_{1.2.3.1}$). The torsion bar spring halves are connected to the *wheel carrier via pendulum supports* ($CSS_{1.2.3.2}$) in the same way as the PRS. The motor-gearbox unit is composed of a *brushless DC motor* ($CSS_{1.2.3.4}$), a *three-stage planetary gearbox* ($CSS_{1.2.3.5}$) and the *enveloping housing* ($CSS_{1.2.3.3}$). In addition to the *WSP between torsion bar spring halves and the pendulum supports on the right and left* ($WSP_{1.2.3.1-1.2.3.2}$), there is the $WSP_{1.2.3.1-1.2.3.3}$ between a torsion bar half and the housing, which in turn is rigidly connected to the DC motor via the $WSP_{1.2.3.3-1.2.3.4}$. The $WSP_{1.2.3.4-1.2.3.5}$ links the motor output to the input of the planetary gearbox unit. Finally, between the planetary gear and the second torsion bar half, there is the $WSP_{1.2.3.1-1.2.3.5}$ in the eARS. The DC motor is also connected to the *electric plug* ($CSS_{1.2.3.6}$) of the eARS via WSP. The torsion bar spring halves are each connected in the form of a coupling via *connector* $C_{2.1.1}$ to the floor assembly in the body structure system and the sway bars in *connector* $C_{1.1.1}$ to the wheel carriers via joints/couplings. The wiring harness of the eARS is connected to the *control unit system* (information transmission) via *connector* $C_{4.1.1}$ and to the *energy supply system* (electrical energy transmission) via *connector* $C_{3.2.1}$. Figure 19 shows the details of the connectors and the interrelationships with the interacting systems and information inheritance of the eARS.

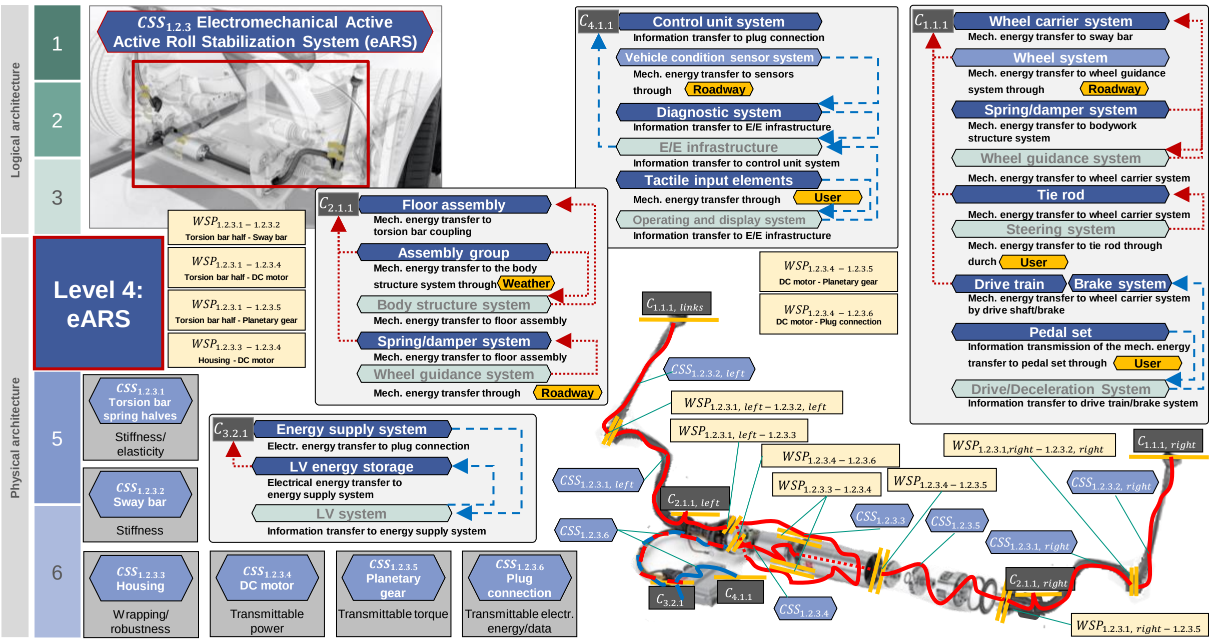



*Figure 19: C&C² model on level 4: Electromechanical Active Roll stabilization (eARS)*[8]

Analogous to the hARS, the eARS fulfills *two main functions in the overall vehicle* (see Figure 20). On the one hand, the *driver-induced roll of the vehicle* can be *actively reduced*, and on the other hand, *road-induced roll* can be *actively influenced*. However, the principle of the second main function of the eARS is varied compared with the hARS in such a way that the *roll tendency* or *roll copying* when driving over uneven road surfaces on one side can *not only be reduced but even compensated for*. Accordingly, the *two torsion bar halves* ($CSS_{1.2.3.1}$), which

[8] Image source: Dr. Ing. h.c. F. Porsche AG

are connected to the engine-gearbox unit, can be *completely decoupled* from each other in the event of a *one-sided disturbing bump* to *allow one-sided deflection* of the wheel carrier and thus *increase ride comfort*. Similarly, the *torsion bar spring halves can be moved or twisted independently of each other* via motor/gearbox and *thus apply or absorb torque* to the $WSP_{1.2.3.1-1.2.3.2}$ to the sway bar as required. In contrast to the hARS, information transmission and processing takes place partly in the roll stabilization system, enabling more compact system integration. The electromechanical active roll stabilization system basically only needs to be supplied with direct current (48V) via the *energy supply system* in $C_{3.2.1}$ and information/data from the *control unit system* (via $C_{4.1.1}$).

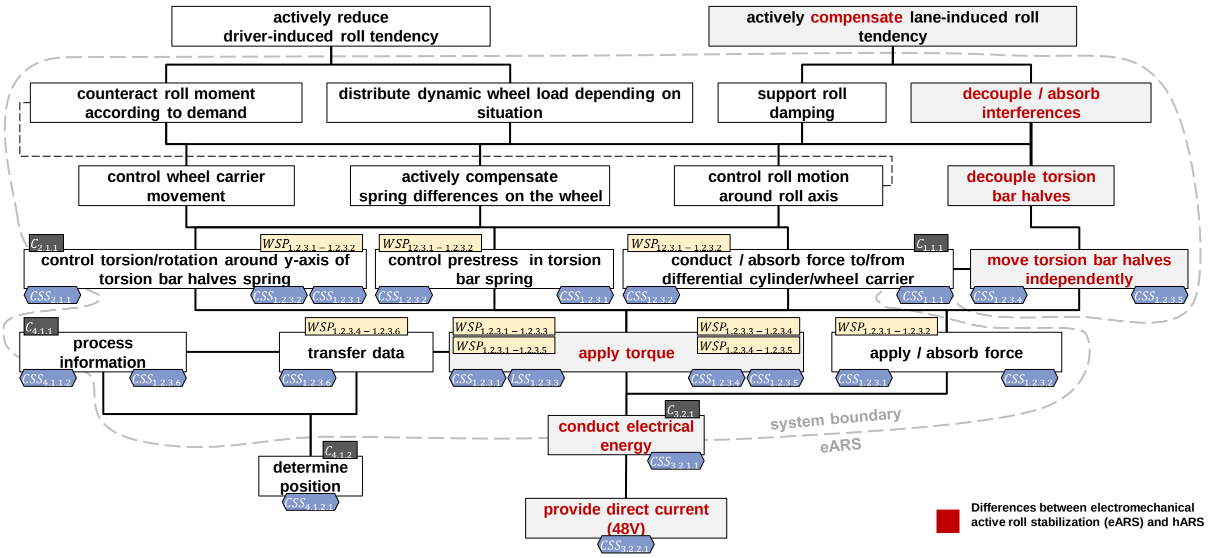



*Figure 20: Function structure of the electromechanical active roll stabilization system (eARS) compared with hARS*

On the basis of the functional structure of the eARS, the *resulting properties of the roll stabilization system and the entire vehicle* were investigated (see Figure 21), as well as the *characteristics that can be influenced by the product developer*. In addition to the properties that can be influenced, such as the frictional torque by defining the feature *"clearance between bearing and torsion bar half"*, the product developer can influence the *properties of the DC motor and planetary gear unit*. The characteristics *number of windings* or *wire diameter* in the DC motor or the *gear graduation* can be defined. At the overall vehicle level, the eARS influences the same properties as the hARS, but the *technical solution positively improves the attributes of the properties*. This can be observed, for example, in *the higher actuating dynamics* due to control times of 0.2 ms in some cases, in which the eARS can provide up to 1200 Nm per wheel [26]. The hARS is technically inferior to the eARS due to, for example, long hydraulic lines and the speed-dependent operation of the hydraulic oil pump via the combustion engine. In addition, the eARS can fully compensate for the tendency to roll by means of interference decoupling and not just reduce it (hARS).

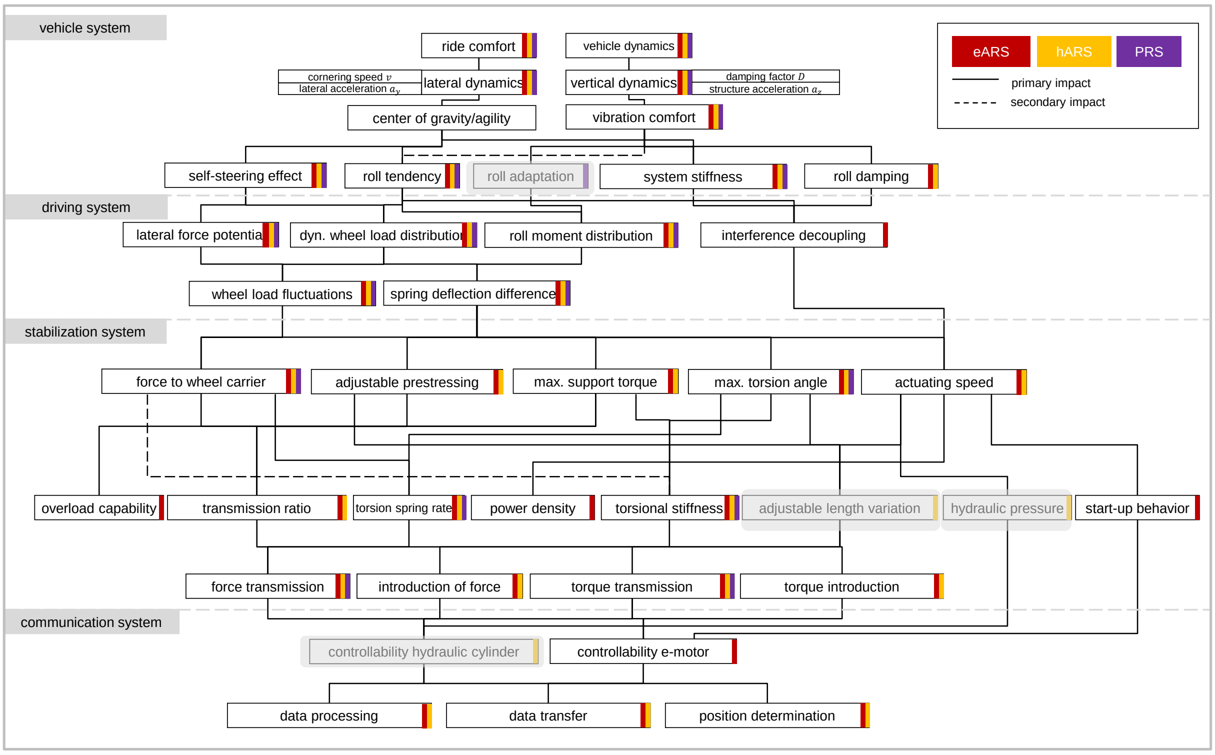



*Figure 21: Property structure of the electromechanical active roll stabilization system (eARS) compared with hARS*

### *4.5.4 Outlook: C&C² Analysis, Function and Property Structure at System Level 5*

In addition, for in-depth analysis, selected subsystems of the hARS and eARS were further investigated using the C&C² approach at system level 5 to observe the phenomena of variation in functions and properties. In the following, the sample *C&C² model of the brushless DC motor at level 5* (see Figure 22) is presented to illustrate *the information inheritance across system levels*.

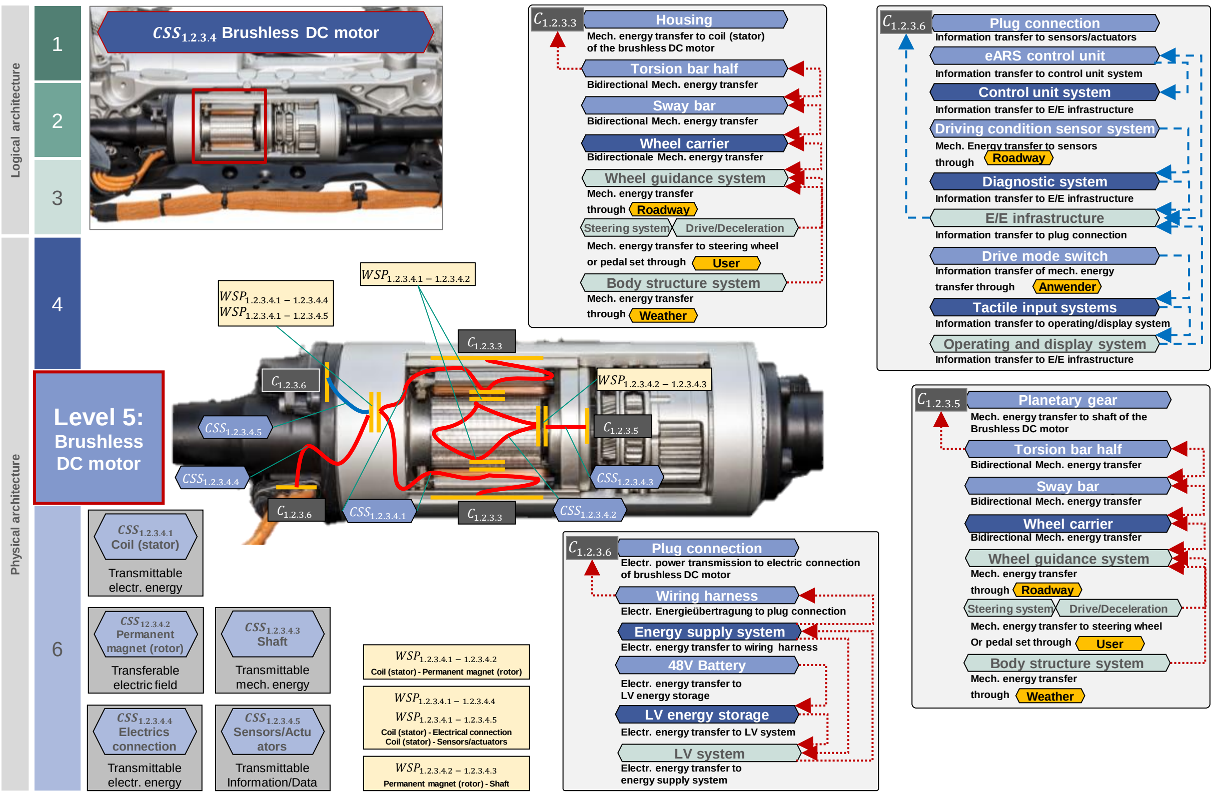



*Figure 22: Selected example of a C&C² model on level 5: eARS brushless DC motor*[9]

The example of the C&C² model of the eARS brushless DC motor shows that the information in the connectors can be used to trace the energy flows from the surrounding elements to the mechanical energy transfer via the housing to the coil (stator) or via the planetary gear to the shaft of the brushless DC motor (cf. Figure 22). This traceability is also ensured in the preceding illustrations of the alternative RSE of the roll stabilization system on level 4 (cf. Figure 13, Figure 16 und Figure 19).

## 4.6 Analysis of the Phenomena of Variation of Selected RSE from Property and Functional Viewpoints

On the basis of the findings of the C&C² analysis at system levels 4 and 5, the phenomena were consequently analyzed from a function and property perspective when the selected RSE of the roll stabilization system were varied.

In order to consider a **carry-over variation (CV)**, in the case study it is assumed that the *mechanical passive roll stabilization system* (cf. Figure 13) is carried over as an RSE into a product generation $G_n$.[10] The *underlying solution principle of the PRS* from the reference system is *carried over internally unchanged in the RSE* (with regard to the number and embodiment of the WSP) and *adaptations* by the product developer may only be made in *accordance with the requirements of system integration and the boundary conditions at the interfaces to other system elements* [34]. Consequently, only a *change in the connectors of the PRS is permissible in the case of a CV*. For example, the material of the wheel support system could be changed, which would affect the mechanical energy transfer between the wheel

[9] Image source: Dr. Ing. h.c. F. Porsche AG

[10] Note: Similarly, the mapping of the RSE of hARS and eARS through carry-over variation into product generation could equally be considered.

support and the sway bar (Connector $C_{1.1.1}$). In the *functional view, no changes can be detected with the carry-over variation*. The reason for this is the constant WSP and CSS, which are necessary for the functional realization of the reduction of roll in the overall vehicle.[11] If we look at the *function structure of the PRS* (cf. Figure 14), the main function *("passively reduce road-induced roll"*) and all other subfunctions remain unchanged and are also transferred from the reference system to the new product generation $G_n$. With the same reasoning, *no changes to the properties within the system limits* can be determined from the *property point of view*. Nevertheless, changes in properties can be identified in the vehicle as a whole, which can be inherited and have an effect up to the connectors of the roll stabilization system.

The next step is to analyze the **embodiment variation (EV)** of an RSE of the roll stabilization system from a functional perspective. In the case study, for example, *the hydraulic active roll stabilization system* is transferred from the reference system to a new product generation $G_n$ and, to this end, the *embodiment of the torsion bar spring is partially varied*. The *underlying solution principle of the hARS is retained* [34]. In the example, the *cross-section of the torsion bar spring and its material were changed*. Many other examples of the EV would be conceivable here. If we look at the *function structure of the hARS* (cf. Figure 17) in the case of the embodiment variation, *neither a change in the main functions* (*"actively reduce driver-induced roll"* and *"reduce roadway-induced roll (roll copying)"*) *nor their subfunctions* can be detected, as in the case of the carry-over variation. Likewise, the *attributes of the material/energy or information flows in input and output variables remains identical* (e.g., *"control torsion/rotation about y-axis of torsion bar"*). Due to the changed cross-section of the torsion bar spring, the *effective range of the function in the torsion bar spring changes*, which in this example *only affects embodiment properties*[12] (permissible torsional moment), *but not the attributes or principle of the function*. Since the *embodiment variation in the model of the PGE does not change the number of existing WSP and CSS of the RSE*, but only their individual embodiment and arrangement (without adding and removing WSP/CSS), *consequently no new functions can be identified*. By the same reasoning, the *embodiment variation does not trigger any principally new properties* within the roll stabilization system. Nevertheless, *changed characteristics* such as the cross-section or material of the torsion bar spring *trigger changes related to the attributes of existing properties*. Contrary to the CV, these changes are not only detectable in the connectors, but also in the inherent WSP and CSS of the roll stabilization system.

Finally, the **principle variation (PV)** of an RSE is examined with regard to the phenomena from a functional point of view. For this purpose, the case study considers the *variation between a mechanical passive roll stabilization and the electromechanical, active roll stabilization*. In principle variation, a *system is redeveloped by adding and removing inherent elements and links inside a solution principle of the RSE* – this is always accompanied by embodiment variation. Consequently, this results in the *realization of a new solution principle* [34]. If we look at the *function structures of PRS* (cf. Figure 14) and *eARS* (cf. Figure 20), a *fundamentally new, second main function* (*"actively compensate for lane-induced roll tendency (roll copying)"*) can be identified in the comparison. As a consequence, a *number of new sub-functions* such as *"support roll damping"* or *"decouple torsion bar halves"* have been added to the function structure, which contribute to the maxim of the main function. Similarly, these functions are characterized by *new input-output effect relationships*. Interesting implications of principle

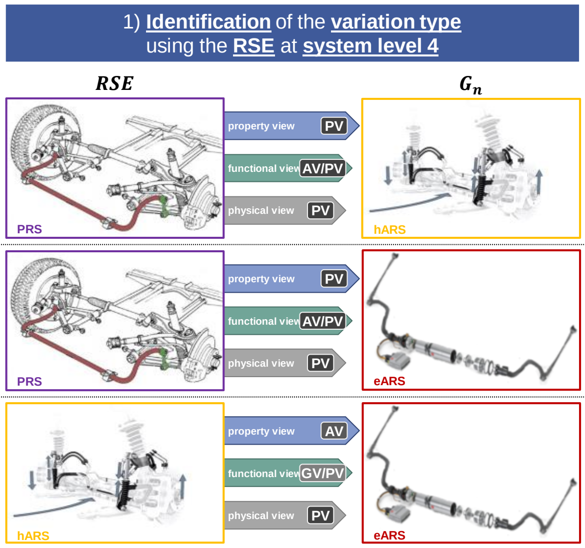
[11] Note: The use of the PRS for a purpose other than vehicle roll stabilization is neglected in this case study.

[12] In accordance with THAU [25, p. 134], *embodiment properties* are the embodiment of an working surface or channel ans support structure, quantify the embodiment-function elements from geometric and material aspects, and determine the effect or functional properties.

variation from PRS to eARS appear in the first main function. The *underlying function principle of PRS* (*"passively reduce driver-induced roll tendency"*) *has not been fully varied*, but *only a variation in attributes of this function occurred*. This is noticeable in the part of the formulation in the adverb *"active"* (or *"passive"* in the case of PRS), which concretizes the verb *"reduce"* (in the sense of basic solution principle of the function) with regard to the expression. From the *property point of view*, the principle variation also leads to *both fundamentally new properties* (e.g., the disturbance decoupling behavior on level 3) and *changes in attributes of existing properties* (e.g., max. twist angle on level 4) in the roll stabilization system due to the new solution principle (or added/removed WSP and CSS).

### 4.7 Calculation of Variation Shares from Property, Functional and Physical Viewpoints

In a final step, the *observable types of variation at level 4* between the three alternative RSE were compared with the *calculated shares of variation from property, function, and physical perspectives*. Since *embodiment variation* (EV) focuses particularly on the presence of material, physical system elements (analysis of principle and embodiment), it cannot be applied to variations from the function and property viewpoints without adaptation. The results in the study suggest that for phenomena of variation of functions and properties comparable to the EV, *only the attributes of the system elements are changing in each case*. For this reason, in the following calculation of variation shares, it is referred to as a generic **attribute variation**[13] **(AV)** of functions and properties [4]. Figure 23 shows the identified variation types of the three alternative RSE of the roll stabilization system on level 4 and the calculated variation shares based on the constituent subsystems on level 5.




2) Calculation of the variation shares using the constituent subsystems at system level 5

| system view / variation type | physical view | functional view | property view |
|---|---|---|---|
| CV | 33% | 14% | 29% |
| EV / AV / AV | 0% | 22% | 29% |
| PV | 67% | 64% | 42% |

| system view / variation type | physical view | functional view | property view |
|---|---|---|---|
| CV | 17% | 11% | 14% |
| EV / AV / AV | 27% | 17% | 29% |
| PV | 66% | 72% | 57% |

| system view / variation type | physical view | functional view | property view |
|---|---|---|---|
| CV | 0% | 59% | 10% |
| EV / AV / AV | 14% | 0% | 38% |
| PV | 86% | 41% | 52% |

*Figure 23: Comparison of variation type of the three alternative reference system elements (RSE) on level 4 and the variation shares of the respective, constituting subsystem elements (level 5) of the roll stabilization system*[14]

The identification of the variation types of the RSE indicates *principle variation* in all combinations of the three variants of the roll stabilization system due to the application of different solution principles at the *macroscopic level 5*. However, if the types of variation of the constituent subsystems are put into relation from a physical point of view, different distributions among the types of variation are obtained. From PRS to hARS, approximately

[13] Note: Attribute variation (AV) in the model of PGE in the system context is formally and generically defined in ALBERS ET AL. [4] and ALBERS ET AL. [35].
[14] Image source: Dr. Ing. h.c. F. Porsche AG

33% can be mapped via CV and 67% via PV at level 5. Between PRS and eARS the share of CV (17%) decreases and 27% is realized via EV. The reason for this is the embodiment variation of the torsion bar, which is split. Between hARS and eARS, 14% are EV and 86% PV, i.e., although both variants represent active roll stabilization systems, the solution principles (hydraulic and electromechanical) are so different that no subsystem can be adopted entirely, and PV represents by far the largest share.

In a subsequent step, the variations of the main functions were compared between the three alternative RSE. Here, the results showed that between the PRS and both hARS and eARS, the first main function (*"reduce driver-induced roll passively/actively"*) is *varied in its attributes* in each case, while the second main function (*"reduce/compensate roadway-induced roll (roll copying)"*) represents a PV in each case compared to the PRS. Between hARS and eARS, the first main function is transferred by CV, but the second main function represents a PV because the roll copying is *"reduced"* in hARS and *"compensated"* in eARS – these represent *two principally different functional principles*. If one compares the subfunctions of the three systems on the basis of the function structures (cf. Figure 14, Figure 17 and Figure 20), the following fractal variation shares of the subfunctions or the attributes of the superordinate main functions emerge. Between PRS and hARS, 14% of the subfunctions are realized by CV, 22% by AV and 64% by PV. The proportions between PRS and eARS are comparable (CV: 11%, AV:17%, PV:72%). Comparing the function structures of hARS and eARS, one can observe 59% CV and 41% PV.

Restricting the analysis of the properties purely to system level 4, a comparison of the PRS with the hARS reveals *properties that either vary in their attributes* (e.g., max. torsion angle) or are *new in principle* (e.g., positioning speed). However, those properties that tend to vary in attributes can also be identified as being carried over on a situation-specific basis. For example, the *max. torsion angle* of both systems can be equally attributed situation-specifically. A pure consideration of the system level 4 without specification of the constituent system levels 5 and 6 as well as the characteristics which can be influenced by the product developer, can therefore lead to deviating results in comparison to a detailed analysis. This is shown by the comparison of the hARS with the PRS. The analysis of system level 4 shows that, for example, the properties *"provable force to wheel support"* or *"max. support torque"* can vary - but there are no fundamentally new properties in this case. The view into the system level 5 shows however that *in principle new properties* (e.g., power density of the DC motor) are *realized by new characteristics* (e.g., number of windings). The calculation of the variation shares on the basis of the constituent subsystems on system level 5 shows that 10% of the properties can be determined as CV, 38% as AV and 52% as PV.

# 5. GENERALIZATION OF ACQUIRED INSIGHTS AND DERIVATION OF AN UNDERSTANDING OF PROPERTIES AND FUCNTIONS (PS)

## 5.1 Generalization of the Findings and Interrelationships of Variation from the Property, Functional and Physical Viewpoints

From the study of the relationship between the variation of physical embodiment and the phenomena of variation of functions and properties, the findings presented in Figure 24 were generalized.

| trigger | | effect | |
|---|---|---|---|
| **variation type (physical view)** | **description based on theC&C² approach** | **functions** | **properties** |
| **carry-over variation (CV)** | ▪ only adaptations to the connector(s) of the physical element possible<br>▪ quantity, layout and embodiment of the channel and support structure (CSS) and working surface pair(s) (WSP) remain unchanged | ▪ due to the unchanged quantity and characteristics/embodiment of the CSS and WSP, the function also remains identical<br>▪ changes to the connector(s) trigger changes in the characteristics of functions at higher levels in the system under consideration | ▪ CV of a physical element does not trigger a change of the properties in the system element under consideration<br>▪ changes to the connector(s) trigger changes in the attributes of properties at higher levels in the system under consideration |
| **embodiment variation (EV)** | ▪ Number of CSS and WSP of the physical element remain unchanged<br>▪ layout and embodiment changes without removing or adding WSP | ▪ due to the constant quantity of CSS and WSP, the EV of a physical element does not trigger any intended/desired changes in the expression of function or principally new functions in the system element | ▪ due to changed characteristics (e.g. material, geometry) in the system element, the EV of a physical element triggers changes in the attributes of properties.<br>▪ however, a EV of a physical element does not trigger any new properties in principle |
| **principle variation (PV)** | ▪ quantity of CSS and WSP is changed<br>▪ PV PV always implies EV<br>▪ new solution principle in the physical element | ▪ due to the changed quantity of CSS and WSP, a PV of a physical element triggers in principle new functions in the system element<br>▪ in addition, identical, modified or principally new functions are possible at higher levels of the system under consideration | ▪ PV of a physical element triggers new property in the considered system element<br>▪ PV of a physical element triggers changes in the attributes of properties at higher levels in the system under consideration |

*Figure 24: Generalization of the findings on the phenomena of variation of properties and functions*

Due to the *constant number and attributes of the embodiment of the WSP and CSS*, it becomes apparent that the **carry-over variation of a physical element** results in a *complete carry-over of the identical functions of the RSE*. Accordingly, *changes in the connectors of the physical element* only *trigger changes in the attributes of functions at higher levels in the overall system*. Similarly, *no new properties in the system element under consideration can be triggered by CV*. *Changes from the property point of view on higher levels* can likewise *only be the consequence of changes in the connector*. The **embodiment variation of a physical element** is characterized by a *constant number of WSP and CSS, whose attributes of embodiment and arrangement*, however, is *changed without altering the underlying solution principle*. Since *no new WSP or CSS are added or removed, no intended/desired changes of the attributes of functions or in principle new functions are realizable in the considered system element by the EV*. The *characteristics* (e.g., material, geometry) *are changed* during the EV of a physical element, therefore a *change in the attributes of properties is also triggered*. *Principally new properties* are *not possible in this case* due to the *carry-over of the solution principle in the EV*. The **principle variation of a physical element** *triggers in principle new functions in the system element* due to the *changed number of WSP and CSS*. Likewise, *identical functions with different attributes or new functions in principle as well as properties at higher levels of the overall system can be realized*.

The *variation operator in the model of PGE* allows to describe the *carry-over, embodiment and principle variation of system elements* from the reference system in relation to the physical embodiment (or WSP & CSS). In order to *describe the variation of different types of reference system elements* (such as functions and properties or building blocks of a construction kit, strategy, etc.), an *unambiguous, generic description* is needed that is *intuitive and applicable in linguistic usage*. ALBERS *ET AL.* [4] therefore introduce the **generic attribute variation (AV) in the model of PGE**, which can be applied to any type of system elements. The study clearly shows that *all views and possible element types of a system strongly interact with each other*. Therefore, the following section derives the *property and function understanding* in KaSPro – Karlsruhe School for Product Engineering resp. the model of PGE.

## 5.2 Derivation of Property Understanding in the KaSPro resp. in the Model of PGE

The analysis of the alternative reference system elements (RSE) of the roll stabilization system validated the distinction between properties and characteristics. Following the understanding according to WEBER [15], properties are defined as follows:

"A **property** in product development is an *element type* of a technical system, on the basis of which the *behavior* can be described from, among other things, the customer's, user's and/or supplier's point of view in a *defined context*. The *attribute* of a property is a quantitatively and/or qualitatively *determinable variable* that *cannot be directly influenced* by the product developer. A *property attribute* is fractally determined by at least one *characteristic* of the same technical system and its attribute."

Analogous to the understanding according to WEBER [15], a property cannot be influenced directly by the product developer - this is done by defining or varying the characteristic attributes. Therefore, the following defines the characteristic term in the context of the property understanding:

"A **characteristic attribute** of a technical system is a *physical variable* that *can be influenced directly* by the product developer and thus partially or completely determines the desired behavior (property attribute) of the technical system."

## 5.3 Derivation of Function Understanding in the KaSPro resp. in the Model of PGE

Furthermore, the analysis proves that a *refinement of the understanding of functions is necessary* in order to *capture the types of variation of "embodiment-less" functions*. Following the understanding according to VDI-FACHBEREICH PRODUKTENTWICKLUNG UND MECHATRONIK [36] and PAHL *ET AL.* [37], **functions are defined in KaSPro resp. in the model of PGE** generically as follows:

"A **function** in product development is a *type of element* of a technical system that can be used to describe an *effect relationship* between a set of (initiating) *input variables* and (resulting) *output variables* as well as the (inherent) *state variables* from a *customer, user, provider and/or product developer perspective* in a *defined context*. The *attributes of a function* result from the *hierarchical arrangement in subfunction(s)* and/or *structural arrangement in main and secondary function(s)*. A *function attribute* is *fractally* determined by at least one subfunction or main function of the same technical system and its attributes."

Another insight is the *differentiation between functions of the overall system*, that can be located in the *solution-open, logical system architecture*, and *technical functions*, that refer to *concrete physical elements or their WSP and CSS*. Likewise, based on the generic understanding of functions in KaSPro, the specific understanding of the **technical function** can be derived and defined following the work of ZINGEL [27], THAU [25] and ALINK [38]:

"A **technical function** in product development is the *function of a physical element* by means of which a *solution-specific effect relationship* between a set of (initiating) *input variables* and (resulting) *output variables* in the form of *material, energy and/or information* as well as the (inherent) *state variables* can be described from a *product developer's point of view*. The *attributes of a technical function* are *fractally* determined by the *working surface pairs* (WSP), *channel and support structures* (CSS) and *connectors* (C) of the physical element."

## 6. EVALUATION AND DISCUSSION OF SIMULATION RESULTS (DS-II)

### 6.1 Carryover variation (CV) from a physical point of view: procedure of furnishing proof using simulations

During the procedure of furnishing proof of carry-over variation (CV) from a physical point of view, the stiffness of the elastomer of the torsion bar spring mounting (Connector $C_{2.1.1}$) was increased by changing the "material" characteristic.
To verify the property attribute in the overall system, the stiffness of the torsion bar spring bearing was varied and compared based on a vehicle dynamics simulation with a consistent reference vehicle. The simulated driving maneuver is based on a sinusoidal sweep, which characterizes a constant steering angle amplitude with increasing steering frequency (0.2 - 4 Hz) at a vehicle speed of 100 km/h. The resulting parameter represents the stiffness of the torsion bar bearing. The resulting parameter represents the roll gradient [°/g]. Conversion into basic units and linear interpolation of the simulation values produces the roll angle versus lateral acceleration diagram shown in Figure 25. Compared with a usual basic application (baseline), the bearing stiffness is halved, and a kinematic connection (infinite stiffness) is added, which confirms the tendency of the property attribute already established. However, in the context of subjective perception, this marginal roll angle change is unresolved.

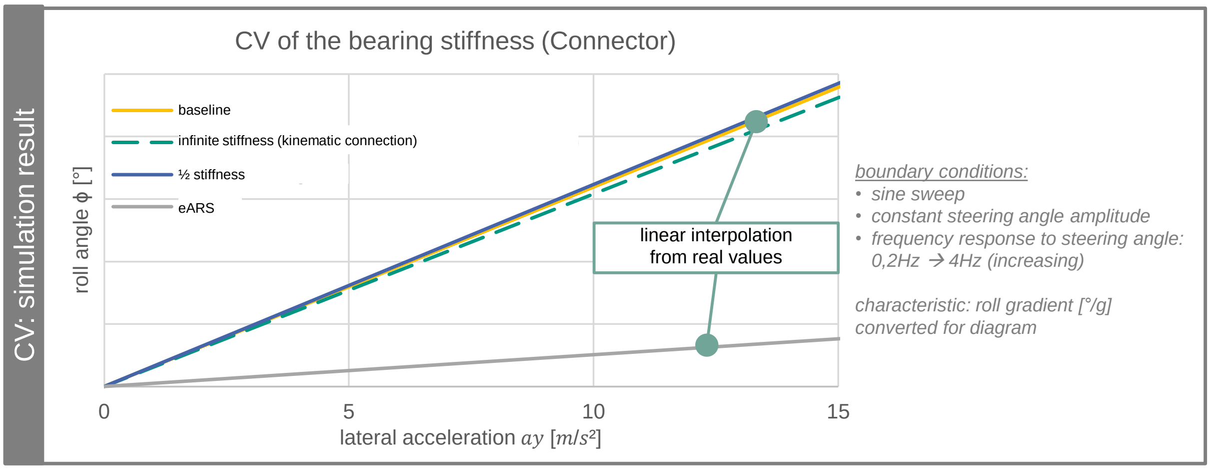



*Figure 25: Simulation result in relation to the effects of a carry-over variation*

Considering the driver-induced roll motion caused by an avoidance maneuver with a single change of direction (use case 1, cf. Figure 6), the simulation shows no changes in the carryover variation across the levels from a functional point of view. Due to the carryover variation, no changes in characteristics within the system boundary of the roll stabilization system can be detected from a property perspective either. Although the bearing (elastomer) represents an active surface of the connector $C_{2.1.1}$, it lies outside the boundary of the roll stabilization system under consideration. This observation can also be justified by the fact that the characteristics of the roll stabilization system can only be influenced by changing the channel and support structure (CSS) and working surface pair (WSP). Following the demonstrated understanding of the analysis in chapter 4, changes in the connectors cause a variation of properties on higher system levels. The specific material selection of the elastomer of the torsion bar bearing, which is located in a metal clamp, leads to an increase in stiffness. This change in the connector therefore neither generates new properties in the roll stabilization system at level 4, nor does it result in a attribute variation of inherent properties. For example, an unchanged torsion angle of the torsion bar spring (in the sense of CV of the property) can be justified by the identical, rotational degree of freedom of the bearing connections. The working surfaces between the connector (elastomer) and the channel and support structure (torsion bar spring) still allow relative motion. Nevertheless, temperature differences and the resulting expansion or contraction could contribute to a change in the property. However, this is neglected according to the defined understanding of the property (cf. Section 5.2) since this variation cannot be influenced by the product developer and is thus based on external boundary conditions. The increased bearing stiffness is followed by a stiffness increase of the considered roll stabilization system of level 3, which is due to a support of the static and dynamic forces in the two bearing points to the floor assembly. This results in lower relative motions between the bearing points and lower energy losses due to decreasing frictional torques. According to this understanding, the wheel load distribution that can be converted and the roll moment distribution that can be provided in the wheel guidance system increases, ultimately resulting in a reduction in driver-induced roll and an increase in the driving dynamics of the overall vehicle.

In summary, it can be stated that a carryover variation of a physical element in the context of the examples considered does not trigger any changes in properties and functions in the system element under consideration. Nevertheless, in the case of changes to the connectors, different manifestations of functions and properties are identified at higher levels, depending on the type of variation.

## 6.2 Embodiment variation (EV) from a physical point of view: procedure of furnishing proof using simulations

To demonstrate the embodiment variation (EV) from a physical point of view, an increase in the diameter (with constant tube thickness) of the torsion bar spring ($CSS_{1.2.1.1}$) of a passive roll stabilization system (PRS) is carried out at level 4.

Due to the linear-proportional relationship between the diameter change and the torsional stiffness, this change in a directly influenceable characteristic results in an increase in the torsional stiffness (property). This relationship between *torsional stiffness* $S_T$ [N*mm²], *shear modulus* $G$ [Pa] and *radius* $r$ [mm] is defined by the following formula:

$$S_T = G * \frac{r^4 * \pi}{2}$$

The radius enters the equation with the fourth power and therefore has a significant influence on the torsional stiffness. The increase in torsional stiffness in turn leads to a reduction in the *passive torsional angle* $\alpha$ [°] based on the inverse-proportional relationship between *torsional moment* $M_T$ [Nm], *bar length* $L$ [mm] and *torsional stiffness* $S_T$ [N*mm²] from the following relationship:

$$\alpha = \frac{M_T * L}{S_T} = \frac{M_T * L}{G * \frac{r^4 * \pi}{2}}$$

As a result of the torsional stiffness increase in the denominator, the reduction of the torsional angle $\alpha$ follows. The direct influence of the torsion bar length can also be derived from the formula. In terms of torsional stiffness, the leg length (lever arm) of the torsion bar spring for connecting the sway bar is thus also an important parameter.

To demonstrate the embodiment variation of the torsion bar spring based on a change in diameter, the roll angle is shown in Figure 26 via the lateral acceleration on the basis of simulation results. The simulated driving maneuver is again based on a sinusoidal sweep and thus represents the behavior of an avoidance maneuver in the first vibration amplitude. On the basis of this, the observed attributes are to be verified. The linear interpolation of the simulation values confirms the reduction of the roll tendency with diameter increase. However, there is no subjective improvement in ride comfort since the increase in torsional stiffness results in an increase in roll copying and an increase in roll acceleration values. Furthermore, during an avoidance maneuver, forced by a steering angle buildup, the vehicle tilt is passively reduced in order to thus achieve a corresponding vehicle stability and agility.

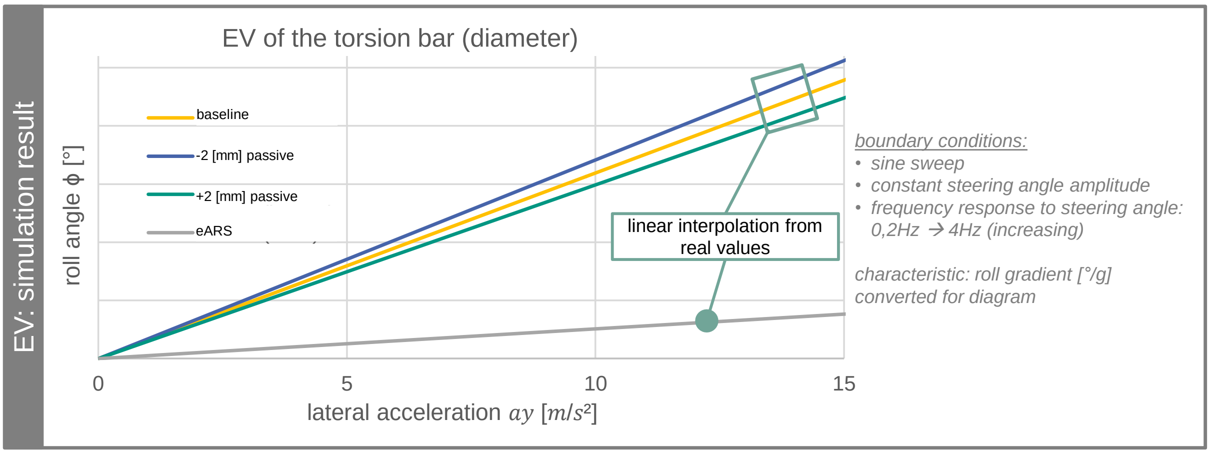


*Figure 26: Simulation result in relation to the effects of an embodiment variation*

In an EV from a physical point of view, the number of WSP and CSS remains unchanged, although a change in individual embodiment and arrangement may occur. Following the generalized findings, it can be stated in this case study that no new functions could be identified in the EV. Furthermore, in the context of the embodiment variation of the torsion bar, neither the attributes of the main functions, nor the sub-functions are varied. During the defined avoidance maneuver (use case 1, cf. Figure 6) and with unchanged lateral acceleration, the reduced torsion angle in the overall system results in a reduction in roll tendency. In addition, the increased torsion bar stiffness causes a system stiffening in the driving system, which is accompanied by an increasing wheel load distribution and rolling moment distribution. In the case of the PRS, this combination of properties has negative effects in the case of road-induced rolling motions due to increased roll copying. Due to the kinematic connection of the roll stabilization in the wheel guidance system, a reduction in roll tendency is also accompanied by a reduction in camber (straightening of the wheel) and thus an increased lateral force transmission potential due to the generated wheel contact area. This in turn results in an increase in cornering speed and lateral acceleration potential. These variations in the properties can be traced back to the variation of a certain characteristic (in this case “diameter” of the torsion bar spring) and its interaction. Accordingly, the increase in torsional stiffness is followed by a reduction in ride comfort, but increased ride dynamics. This can be attributed primarily to the reduced roll tendency and the increased roll copying because of increased roll moments and wheel load distribution. The electromechanical active roll stabilization system (eARS) can compensate for a variation in the “diameter” characteristic of the torsion bar spring as desired, taking into account the maximum actuating dynamics, whereby a low roll angle can be specifically permitted via the control of the eARS.

In the context of the examples considered, it can be summarized that a variation in the embodiment of a physical element triggers attribute variations of properties, due to changed characteristics in the system element. However, new properties are not generated in the course of an EV. Due to the constant number of CSS and WSP, no attribute variations of the functions and no new functions in principle are triggered.

## 6.3 Principle variation (PV) from a physical point of view: procedure of furnishing proof using simulations

In the course of the procedure of furnishing proof of principle variation (PV) from a physical point of view, based on the alternative reference system (RSE) of the PRS, an actuated motor-transmission unit ($CSS_{1.2.3.3}$, $CSS_{1.2.3.4}$ und $CSS_{1.2.3.5}$) between split torsion bar spring halves ($CSS_{1.2.3.1,\ right}$ und $CSS_{1.2.3.1,\ left}$) implemented to realize electromechanical active roll stabilization (eARS).

Figure 27 shows a qualitative comparison of the reduced roll accelerations and angles between PRS and eARS based on simulations. In particular, the active roll stabilization system shows a significant reduction in roll acceleration in the range of the body natural frequency, which benefits the subjective vibration perception of humans in terms of ride comfort. Similarly, the eARS enables demand-based and situation-independent compensation of the roll angle when lateral acceleration values increase.

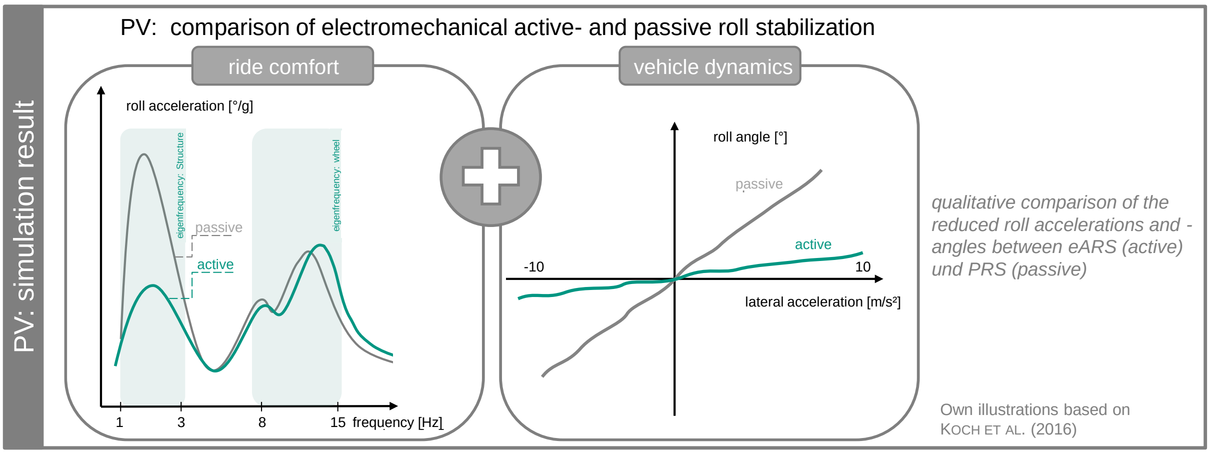



*Figure 27: Simulation result in relation to the effects of a principle variation*

From a functional point of view, the considered principle variation (PV) leads to new functions (in the sense of PV) on level 4 and 5. Furthermore, new subfunctions result, which are or contribute to the realization of the main functions. These observations are due to the changed number and embodiment of the CSS and WSP of the eARS compared to the PRS. Based on the added subsystem elements of the motor-gear unit, new properties (in the sense of PV) are realized within the system boundary. Accordingly, both the road-induced roll tendency and the roll acceleration at the overall vehicle level can be reduced as required by means of an adjustable actuating speed and the adjustable preload & power transmission for a one-sided curb crossing (use case 2, cf. Figure 6). Decisive properties for implementing these actuating dynamics are, for example, the starting behavior and the power density of the electric motor, which in turn are influenced by the number of windings, coil wire diameter or rotor design. The property “road-induced roll tendency” is varied in its attribute in the same way as the properties of the wheel load and roll moment distribution. The advantage of an electromechanical roll stabilization system becomes particularly clear in the context of this Use Case 2. As a result of a one-sided curb ramp, the disturbance pulse provides an inverse behavior of the permanently excited synchronous machine, as a subsystem element of the eARS, in the form of energy recuperation. This recuperation capability is a characteristic property of electric machines and is implemented via the physical elements of the power electronics. Even taking into account the other use cases, the electromechanical active roll stabilization system (eARS) enables the attributes of properties and functions to be changed as required. With regard to the conflict of objectives between driving dynamics and ride comfort considered at the beginning, the simulation results confirm that the eARS can resolve this customer-relevant conflict of objectives as a result of a principle variation and the associated principle and attribute variations of the properties and functions.

In summary, as a result of a principle variation of a physical element, the conflict of objectives between driving dynamics and driving comfort can be reduced or, in the case of an eARS, resolved. Accordingly, new functions in the system element are triggered due to a changed number of CSS and WSP as well as new properties in the considered system element.

## 7. OUTLOOK AND FURTHER RESEARCH

Among the results of the research project are identified relationships between the types of variation of the different system elements: properties, functions and physical elements. For the variation of properties and functions, the previous description, especially embodiment variation (EV), cannot be clearly transferred. Combining the CPM/PDD and the C&C² approaches in the systematic analysis of roll stabilization leads to the conclusion that the model of PGE - Product Generation Engineering in a system understanding requires the addition of attribute variation (AV). In particular, the CPM/PDD approach has strengthened the understanding of the interrelationships between properties and characteristics and their attributes in the product generations studied. The combination of the C&C² and CPM approaches helped in planning characteristics, functions, and physical elements across generations. This allows patterns to be identified in how changeable characteristics affect properties at different system levels. In addition, conclusions can be drawn about how functions are varied. Through the knowledge gathered across generations about cause-effect relationships to customer and user experience, both solution-open (”What behavior should the product exhibit?”) and solution-specific elements (“How will this experience be realized?”) can be planned and linked in the early phase. The findings are synthesized into a consistent understanding of properties and functions in KaSPro - Karlsruhe School for Product Development or in the model of PGE, enabling the transfer of findings in further research to production systems, strategy, business model, etc.

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