Whitepaper

Steer-by-Wire –

Rethinking the steering system to realize improved performance, layout and comfort

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Steer-by-Wire - the next big thing?

Over the last couple of years, Steer-by-Wire (SbW) has become one of the trending topics in the automotive environment. More recently, the progress in the field of automated driving puts focus on the structural setup of steering systems and especially the SbW technology even more. The steering system in a vehicle is the central system to influence the lateral dynamics by manipulating the direction of travel. New requirements have been established with regard to performance, comfort and vehicle concepts in general. Even though the introduction of electric power steering systems (EPS) already contributed to the performance and the comfort of steering on a large scale, the limits of a steering system with a rigid connection between steering wheel and front wheels on the road are still strongly constrained by its system properties. For the development and the design of new vehicle cabin concepts and differently shaped steering control units (e.g., Tesla Yoke), the before mentioned physical connection is the restricting factor again. Thereby the optimal layout and ergonomics of a vehicle cabin as well as the introduction of new control units are countered by the need to position the steering unit in a way, that it is possible to physically connect the steering wheel to the steering gear by a steering column. Depending on the use case considered, the limits of an EPS differ in their significance for the performance and the comfort during the steering operation. In the case of an everyday road traffic situation with a passenger vehicle an EPS system is capable serving the performance and comfort level requirements sufficiently. For personal vehicles, the perceived comfort during steering is one of the key focuses. Moreover, new vehicle functions like e.g., automated driving, also raise demand for a digitally adjustable steering system and a physically variable steering control unit. Commercial vehicles on- or off-highway are often operated for a consecutive long time. In addition to that the force load for the driver is either very monotonous (on-highway) or has high peaks and overall demand (off-highway). This usage profile can easily lead to physical tiredness or overstressing of the driver. In these cases, alternative cabin and steering unit designs, based on the Steer-by-Wire technology can offer solutions to improve operability, especially in the wide range between parking maneuver at low speeds and quality of on-center behavior at higher speeds. Changing the environment from purpose use to track use, the performance requirements change significantly, as e.g., shorter system feedback behavior is needed and steering impulses have to be applied faster. Across all the previously mentioned usage scenarios the superordinate disadvantages caused by the limitations of an electric power steering are suboptimal ergonomics and overall improvable system performance.

Despite the requirements for a steering system in current use cases, the progress in the field of advanced driver-assistance systems and new features like automated driving increase the need for a more powerful and efficient system even more. On the system side response times, system delays and actuation latency become even more important and the desired range, in which parameters as e.g., steering angles can be set, expands. From the functional layout perspective in context of automated driving vehicles, new and drive mode dependent cabin

designs (self-driving/ automated driving) raise demand for a steering unit which is variable in its position or even retractable. Thereby unintentionally driver-performed steering inputs are prevented and a more spacious and convenient automated travel experience can be provided. Steer-by-Wire offers gains in performance, flexibility and usability of a steering system by being highly adjustable to requirements of various use cases and vehicle concepts. The following elaborations out of a strategic top-level perspective, will give a detailed impression of the strategic relevant differences between EPS and SbW, will outline the status quo with regard to the technology, regulation and foreseeable market diffusion and will finally propose our approach of how to deal with the transition from EPS to SbW.

What is Steer-by-Wire?

The terminology Steer-by-Wire already contains the main key indicators of how the system differs from conventional steering setups. In contrast to an electric power steering layout, which is the dominating variant of steering systems in the market today, the information about a steering command in a Steer-by-Wire system is not transported mechanically but digitally. While the turning angle of the steering wheel and the force feedback during steering operation in an EPS equipped car are exchanged between the steering wheel and the wheels on the road physically by the steering column, the steering gear and the electric steering actuator, SbW works differently. The parameters of the steering action performed by the driver at the steering control unit, which does not necessarily have to be a wheel, are captured by sensors first and packed into a data set. Subsequently the collected data is transported by wire towards an electric motor at the axis or towards an individual motor per steerable wheel. These motors transfer the digital input into a physical action again by generating a steering angle at the wheels on the street. Vice versa sensors at the wheels can collect data about the counterforce against the steering action, which then is delivered towards a motor at the steering wheel to create force feedback for the driver.

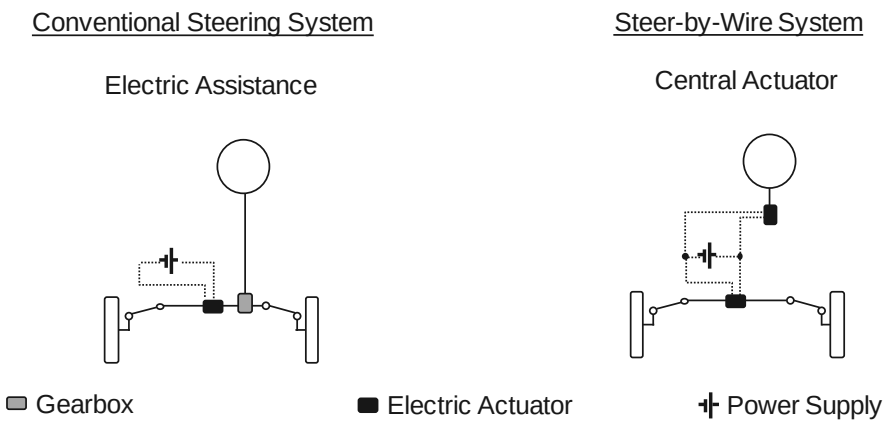

FIGURE 1: BUILT STRUCTURE EPS AND SBW

Since the steering impulse and the feedback is not transferred via an end-to-end mechanical connection within a SbW system but in the shape of a data-driven mechatronic system, it is obvious that there has to be some kind of logical scheme to be able to process this information. This scheme, paired with calculation algorithms is represented by software. A Steer-by-Wire system would not work without a software, because the input and output signal between the interfaces of the steering-wheel-section and the wheel-section are not equal. The interfaces are connected via a translating algorithm, which marks the significance of software as one of the key elements of a Steer-by-Wire system. Furthermore, the software does not only enable the two mechanically unconnected modules of a steering system to communicate with each other but also serves as an access point to digitally influence the steering characteristics or serves as an interface to high-level AD-functions. While a conventional steering system is mainly influenced by e.g., the steering gear ratio, which is not as instantly and highly adjustable to the driving situation or a selected drive mode, a Steer-by-Wire setup offers the opportunity to manipulate the input data and create variable output data during the transportation from one interface (steering wheel) to the other (road wheel actuator). The relation between input and output does no longer has to be necessarily linear. The SbW layout together with a capable software package enables a highly adjustable steering system to change the steering characteristics (performance perspective) or can offer support (comfort perspective) within no time by adapting intentionally (indicated by the driver) or automatically (advanced driver-assisted systems) to the specific conditions. In addition, it is also possible to give cars a unique steering feel which can be dependent on e.g., the vehicle class (SUV or sportscar) or the brand characteristics without having to develop completely new steering systems but only flashing different software on a (mostly) unified physical system. The field-of-action for vehicle developer expands even further as SbW raises the possibility to give a vehicle of a certain type (e.g., SUV) a non-vehicle-typical steering feel (e.g., of a sportscar) for this specific vehicle class.

Current developments in the framework of Steer-by-Wire

Industry activities and drivers

As automated driving is identified as one of the key drivers for the progress in the field of SbW a holistic consideration of the vehicle structure is recommended. When setting up an automated vehicle concept it is necessary to have a vehicle base, that can process digital inputs very efficiently. The vehicle has to be able to transform these inputs into performance outputs in the form of vehicle dynamics. A low latency of a SbW system erases the inertia and slight inaccuracy of a full mechanical system, as can be found in an EPS system, including a lot of mechanical interfaces and connections for power transmission. But a Steer-by-Wire system does not only have a superior performance in contrast to an electronically powered steering system. In the context of automated driving the SbW-solution also offers the chance

to steer a vehicle via a digital input and without the steering wheel turning. The technical decoupling of the wheels on the road and the steering wheel therefore allows automated travels in a more comfortable and more undistracting way. On this basis it is possible to realize the edge case of a fold-away-steering wheel or steering unit with SbW. Having this in mind it becomes obvious that the according configuration of the hand wheel actuator and the road wheel actuator has to be specified as well. This is covered by the integration of relevant Tier 1 suppliers into the product development process as well as through OEM-internal actions.
Considering the cabin layout and the overall packaging in a more general way, a new freedom in designing and positioning of steering units is created by the implementation of Steer-by-Wire. In theory the steering control unit can be placed anywhere in the entire cockpit, as no physical connection to the wheels or the steering gear is needed. Even though this is a huge advantage for interior designers of vehicle concepts, the benefit is even higher for the ergonomics in commercial and utility vehicles. The position of the steering unit as well as the type of steering control unit (wheel, joystick, etc.) can be set and chosen in the optimal way to prioritize the ergonomics. Thereby best visibility during operation, less effects of making the operator tired and efficient movement radius while steering can be guaranteed.
The main attribute to prevent the last two effects mentioned (tiredness, movement), is the software defined character of a Steer-by-Wire system. Depending on the requirements of different use cases, either comfort, performance, or a good compromise of both can be focused on regarding the interaction with the steering system. The implementation of highly customizable steering modes is possible. A steering algorithm, designed for heavy duty vehicles e.g., can scale down the feedback forces on of the wheels on rough terrain, so that the operator of the vehicle experiences a smooth and even steering feel, without perceiving any loss in controllability of the system.

Analyzing the drivers for a switch from EPS to SbW on a superordinate level, e.g., the production level, the term platform strategy gains relevance. As mentioned before, Steer-by-Wire systems offer the opportunity to be adapted and set up through software. The vehicle producers are able to set up the steering systems for different kind of vehicles on the same technical and physical base, using the same steering unit, the same electric motors and the same sensors, but creating a system that has a completely different steering feel. A high level of standardization in vehicle production and assembly is possible. Efforts of software developers from already inside the automotive industry, but also developers, who were strangers to the industry, are intensified immensely due to the key role in the SbW concept. Different steering variants could to a certain extend be created through different software only. Furthermore, especially in the context of commercial vehicle design, the omission of the long intermediate shaft with universal joints enables a more cost-efficient cabin design with regard to cabin suspension and tilting mechanics for maintenance.

The results are cost savings and variant saving because different vehicle models only must be equipped with different steering algorithms to differentiate and match the type of vehicle.

Regulation

Historically, the legislation for road traffic has been a limiting factor for the transition towards the integration of Steer-by-Wire systems. While this has not been a major problem for pure off-highway vehicles at all, the regulation for on-highway vehicles has changed to the benefit of a SbW integration. In the meantime, a change in the ECE regulation guidelines has been established to clarify, that a continuous mechanical connection between steering wheel and the wheel on the road is no longer necessary but can be substituted by a system fulfilling the same function. Furthermore, the guidelines in ISO26262 express, that a careful check and assessment of the function and safety of a system is sufficient and no specifically designed test procedures for a different variant of a system, e.g., a Steer-by-Wire system, are needed in addition to that. As a result, it can be verified that the regulatory framework is neither a restriction for the integration of a Steer-by-Wire system in off-highway nor in on-highway vehicles anymore.

Since this year, a draft version of the new DIN 70065 “Road vehicles - Requirements for a "Steer-by-Wire (SbW)-system" is available. The provided design guideline especially for the system layout and safety guideline facilitates the approval of the safety concept by a defined process. Especially in the definition of safety goals, error scenarios and transition or degradation concepts valuable information are given.

Technology

The following image (Figure 2) shows the differences in the setup of an EPS and an SbW system and the according flow of information and actuation forces. The main overall difference is the substitution of the steering column by a data stream, in the form of a wired connection.

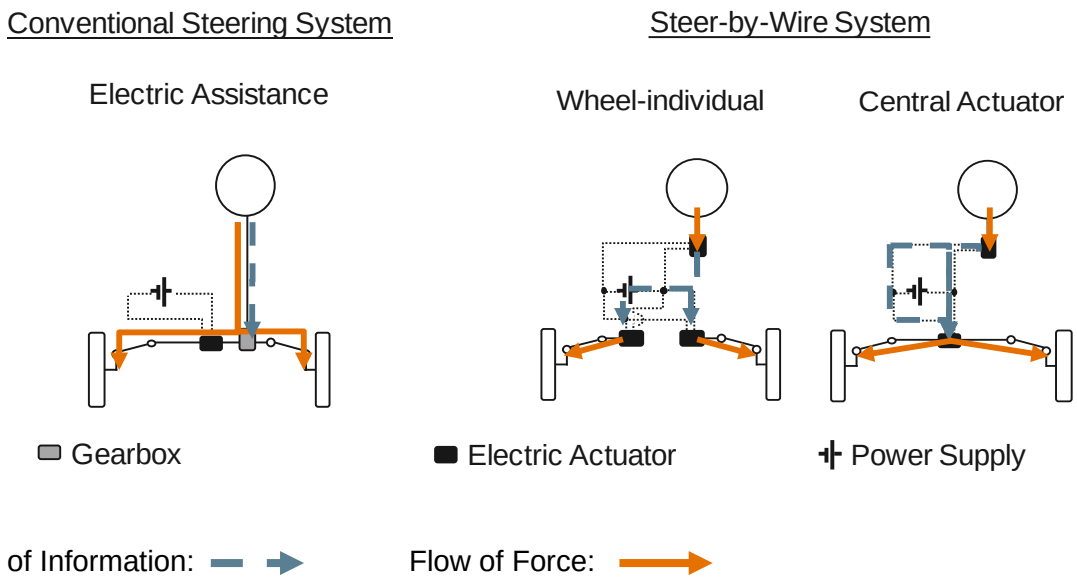

FIGURE 2: CIRCUIT DIAGRAM OF INFORMATION AND FORCE

Even though the main difference in comparison to an EPS system is the same for all Steer-by-Wire solutions, the specific layout can vary. The road wheel actuator motor can either be placed at the steering gear directly to deliver the steering impulse fixed for both wheels via the gear and the tie rods or each wheel does have its own electric motor and thereby receives its own steering impulse.

Readiness level

From the R&D perspective the Steer-by-Wire technology in general has reached a state of being ready for market. The components, like sensors and electric motors, as well as the underlying steering software along with the included algorithms are developed to an extent that they can secure a safe and well performing experience. The basic technical infrastructure in vehicles being sold today, regarding energy supply, voltage levels, information flow and digital interfaces, facilitates the transfer to and implementation of a SbW system even more. Being equipped with 400 or 800V-systems, digitally interlinked hardware components as well as highly adjustable software and powerful computing units, modern on- and off-highway vehicles are ready for hosting a Steer-by-Wire system. Briefly, the technical readiness of this kind of steering system has already reached a sufficient level to fulfill the different requirements, regarding the speed of the system, the forces the system can cope with and the stability it has to offer for a convenient and performance orientated, but also safe use.

Examples of Steer-by-Wire application

One of the barriers on the way to mass production and high sales volumes seems to be the acceptance and trust of vehicle operators into a steering system without continuous physical connection. On the one hand the progression in automated driving can help to overcome these acceptance issues. The focus during the operation of an automated vehicle sits on the automated driving (AD) function, which makes it irrelevant for the passenger if the steering is realized mechanically or by wire (SbW). On the other hand, vehicle manufacturers have to convince customers to trust in SbW-equipped products independent of the correlation with automated driving functions, as AD is a little further away on the horizon than SbW is. To overcome this challenge prestige projects with great external impact are set up to demonstrate feasibility, performance, and reliability at the same moment. One example for On-Highway application of Steer-by-Wire is the Lexus RZ450e, which will have a SbW-based system called “One Motion Grip” from model year 2025 onwards and will be one of the first series production cars with SbW only. The ”Flex-Steer” called market ready Steer-by-Wire system of Danfoss is a perfect example to show the benefits to usability and operability a switch in steering technology will bring for off-highway applications. Lastly Schaeffler’s Space Drive concept proves the performance capabilities of a Steer-by-Wire system being installed in a race car in GT3-configuration, in combination with other X-by Wire functions.

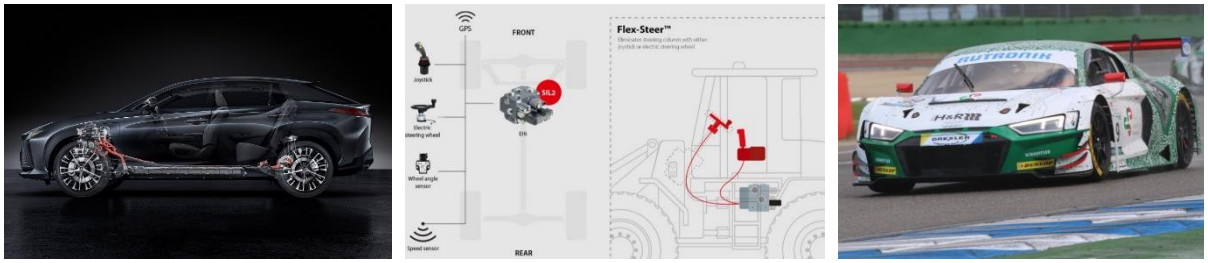

FIGURE 3: LEXUS RZ450E, DANFOSS FLEX STEER, SCHAEFFLER SPACE DRIVE

All three previously depicted examples prove that a Steer-by-Wire system (SbW) can offer the required system characteristics in terms of performance but also freedom for design. This is true for current and foreseeable use cases in different scenarios on- and off-highway. Taking the production perspective into account as well, a Steer-by-Wire system facilitates the standardization, resulting in a more efficient variant handling and management.

Market Assumption

The previously outlined examples and the accompanying proof of performance of Steer-by-Wire systems confirm that the technology is well advanced and close to a volume-market entry. A realistic and customer-oriented perspective on the introduction of the technology to the mass market depicts a more restrained situation. Customers for private vehicles first have to gain trust and confidence into a steering system without a continuous mechanical connection or fallback option, before SbW-equipped vehicles can enter the volume market. Analyzing the timeline of the SbW introduction in the on-highway segment, OEMs were the first players who started working on the topic and tried to do a proof of concept via the premium segment. Right after that, larger system suppliers came onto the field and demonstrated their competences. By establishing an internal patent and certification pool these system suppliers secure their position in the value chain strategically broad. It emerges, that the main support in the SbW progress will come out of the system supplier surrounding. Market entrants, who have to change their core business due to an obsolete component folio or those who are completely new in the field of steering systems (e.g., software companies) probably have to find their position close to the established system suppliers. The high complexity of the new technology and the need for a system-based development of a SbW makes it harder to find a unique market position if a new player only offers isolated components. Independent of the question if SbW is diffused into the passenger vehicle market via specific segments or being a function, the customer can opt for, the efforts of OEMs and larger suppliers illustrate the imminent path into volume production by the end of the decade. (See Figure 4)

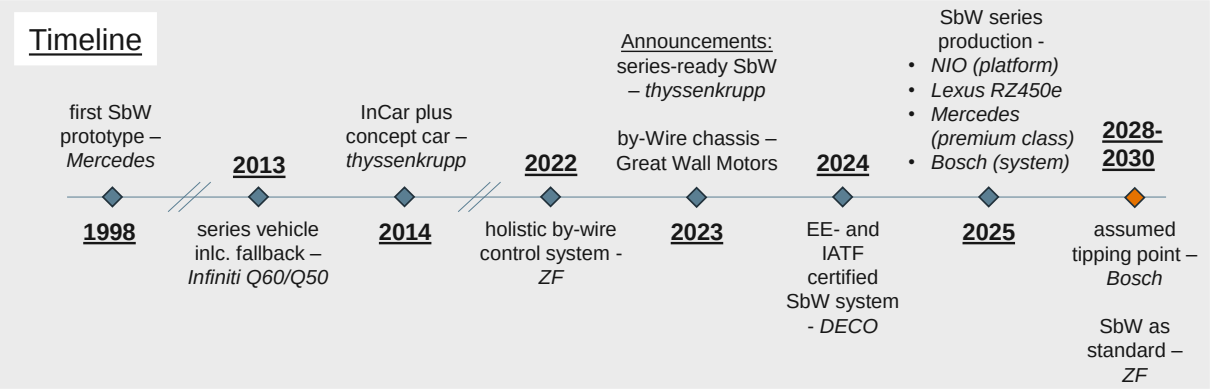

FIGURE 4: TIMELINE OF SBW MARKET INTRODUCTION

For the commercial vehicles market the cost of the implementation of a Steer-by-Wire system is the dominating factor for the speed of introduction. Due to the huge benefits regarding comfort and operability as well as to the broader range of steering control unit concepts in existence, such as joystick-control, the diffusion of SbW-technology into the commercial vehicle market will most presumably be faster than into the passenger vehicle segment. System suppliers will manifest their market position in the commercial vehicle sector as well trough the ability to transfer knowledge and competences from on- to off-highway and vice versa. A tenable forecast, of when Steer-by-Wire systems will be accessible in larger numbers in off-highway vehicle and thereby will be the economically reasonable variant in the cost-driven commercial vehicle market, can be derived from a scenario-based analysis. An increase in the number of commercial vehicles being equipped with SbW in the upcoming years taken as a valid assumption already. The transition towards Steer-by-Wire will assumingly be faster in the commercial vehicle sector than in the passenger vehicle sector. The gained benefits for various use cases are prioritized and the skepticism against the new steering concept will thereby be subordinate, as the environment of operation is different for the personal and the commercial sector.

Value Chain

An evaluation of the value chain of a steering system depicts a large number of same steps in value creation for an EPS-system than for a SbW-system but also some major differences which have to be outlined. Out of the discussion of the technological and technical switch from EPS to SbW the two most significant changes for the value chain are the omission of the steering column and the increase in software demand. The perceived shift of share in value creation from hardware to software is only valid on first sight, as mainly hardware components are still needed for the steering system. For the hardware part the demand for electric motors and sensors compensates the value of the omitted steering column. A system, which turns the

wheels individually by a single electric motor at each wheel, makes the steering gear obsolete, too. However, for the near future the system without both components, steering column and steering gear, will not be the dominant variant for passenger vehicles but rather for commercial vehicles due to different requirements.

The share of value creation through software is higher for a Steer-by-Wire system because an EPS system transfers forces, feedback, and actuations mainly mechanically and does not require such extensive steering algorithms to be able to function. (See orange section in Fig. 5) Besides the actual programming effort for the basic software itself there must be a setup and adaption process of the software for every model or type for passenger and commercial vehicle. While this is an additional labor-intensive step in the value chain of a SbW system, it facilitates the variant management and safes development efforts for individual setup of different vehicle versions with a complete mechanical steering. The result is a shift in the depth of value creation, with a more extensive efforts in an earlier, upstream process step. (See blue section in Fig. 5)

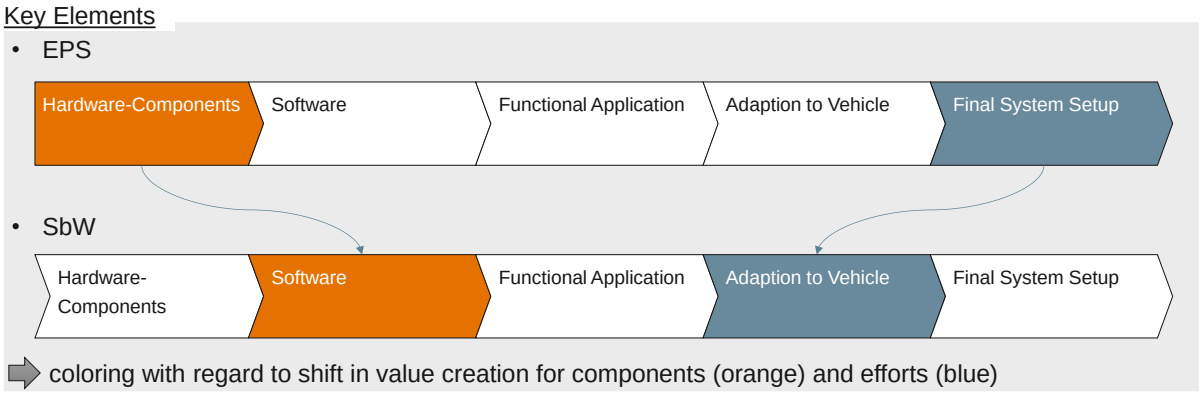

FIGURE 5: SHIFT IN VALUE CREATION

Alongside the switch from EPS to SbW the design and shape of the steering control unit in the vehicle cockpit will possibly change due to different input requirements. By using a Steer-by-Wire system it is possible to reduce the turning angel of the steering control unit (e.g., steering wheel). As a result, the steering control unit does not necessarily have to be completely round, to cover the complete turning radius, but can be similar to the steering wheels used in race cars already. This confirmed design trend is not only an additional indicator for a broader Steer-by-Wire application in future. It is also a reminder for interior suppliers, that they are affected secondarily by a system switch, too.

FIGURE 6: STEERING CONTROL UNIT EXAMPLES - MERCEDES, TESLA, LEXUS

To sum up the changes in the value chain it can be said that the switch form EPS to SbW of course means a cut for e.g., producers of components like the steering column. However, it adds value in form of different components needed (electric motors) and by the necessary expansion of the underlying software structure. The linkage between the SbW technology and AD-functions automatically leads to a joint and necessarily harmonized share in value creation as well. Overall, there is a shift in value creation for some hardware suppliers and a new, larger space for companies with an extensive software product portfolio.

Does a switch in the steering technology mean a switch in competences?

The outcome of an analysis of the deltas in value chain highlight different demands at the development and production level caused by different requirements. Together with the different technology-caused layout of the steering system it becomes clear that the needs in technology competences do change as well. The change becomes most obvious when evaluating the system architecture in general. New technological competence in the form of an improved understanding of system architectures and domain-based vehicle layouts are highly recommended, as can be seen in the following analysis.

In an EPS system there are isolated units for each functional group such as steering and braking (longitudinal dynamics) and the suspension (vertical dynamics). Sensors collect the information needed and transfers these to the ECU unit to analyze and digitally depict the driving situation. However, there is no information exchange and consecutive adaption of the functional groups to each other. The middle option on the way to a complete interlinked domain based SbW is a system which is built on individual domains. Each function addresses a single Domain-Control Unit (DCU) for each domain like the drivetrain, chassis, or the Advances Driver-Assistance System (ADAS). (See Figure 7) The data from e.g., the steering system causes individual adaptions of each domain. A Steer-by-Wire system is typically based on an interlinked system layout enabled by software. In simple terms it can be assumed that the domains are all connected to a superordinate High Performance Computer (HPC) which collects input information of each of the domains and transfers it into an output via algorithms. A change of perspective from the technical view towards the required competences justifies the assumption that a Steer-by-Wire system requires a much broader understanding of the

overall vehicle system dynamics. The information stream is not only single-routed but the allocation of the according information to every domain involved in the vehicle dynamics must be reached within the shortest time. Otherwise, the digital and software-defined character of a Steer-by-Wire system would be the weak spot of the vehicle, due to the not coordinated processing of the data. While experts for the different domains are still irreplaceable, the position of a system expert gains more relevance in the development of a SbW system.

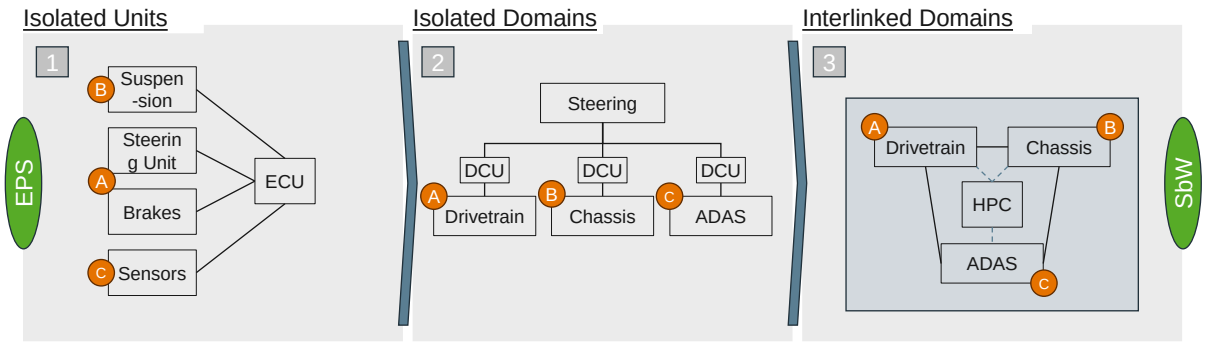

FIGURE 7: DEVELOPMENT OF ARCHITECTURE IN CONTEXT OF A SWITCH FROM EPS TO SBW

fka's approach towards SbW development

As outlined in the previous sections, the introduction of SbW technology will fundamentally change not only the technical architecture of the steering system but also the underlying development methods and competence requirements. As a research and development partner for the automotive industry, fka has been involved in various SbW development projects in recent years. Figure 8 summarizes selected aspects of the development of SbW systems. A crucial aspect of development is the ability to understand the system holistically. On the one hand, this requires a comprehensive technical understanding of the overall system, including the interfaces and interactions with the vehicle. On the other hand, interdisciplinary cooperation between various experts is required along the entire process chain. Continuous exchange between development engineers, software developers, functional safety experts, test engineers and user experience specialists can significantly reduce problems across process interfaces. The workflow of identifying and analyzing the topic from a strategy-driven perspective and addressing the derived questions to the specialized department, or working in pair from the beginning, is our key capability for an efficient project handling in an interdisciplinary topic such as Steer-by-Wire.

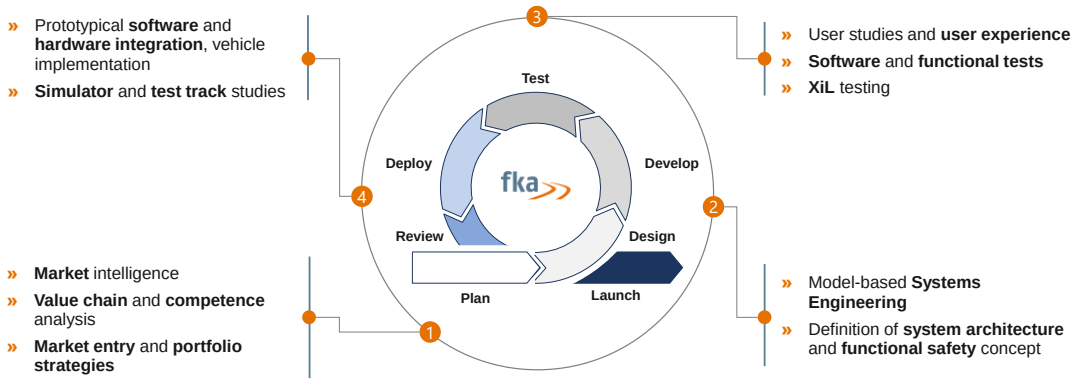

FIGURE 8: OVERVIEW OF FKA COMPETENCIES FOR THE DEVELOPMENT OF STEER-BY-WIRE SYSTEMS

At the beginning of an SbW development project, detailed planning of the technology development is required in addition to a clear definition of the objective. It is helpful to conduct market intelligence, for example, to identify market developments, assess the target market or identify potential risks from competitive activities. Competence analysis should be used to describe competence needs and gaps for the development and commercialization of the system at an early stage. A value chain analysis provides an overview of required value creation activities and potential partners. The definition of the market entry and portfolio strategy influences, among other things, the end date of technology development and the technical system scope.

Due to the substantial number of requirements, the safety criticality and the complexity of the SbW system, the use of suitable development methods is necessary. For this purpose, fka uses, the method of model-based systems engineering (MBSE) along the entire development process. By applying the methodological approach of MBSE, the highly complex SbW system can be represented in digital models concerning its structure, behavior, and requirements, with the system broken down to each individual component. With all elements interconnected in these models, decisions or changes can be easily traced, and their implications can be derived. The system model also aids in achieving an improved understanding of the system and helps all involved areas supporting the development of the SbW system to gain a unified understanding. In the initial phase of system design, fka's hardware and software architects also support in defining and evaluating system architectures and in creating a functional safety concept. This is elaborated along the guidelines of standards like ISO26262 or DIN70065 and is also supported by the brought experience of chassis engineering and vehicle dynamics specialists. Testing is of crucial importance in SbW development. In addition to performing software and functional tests, fka has various X-in-the-loop test environments and a multi-body-simulation tool chain. A distinctive feature is the possibility to conduct user studies and user experience investigations during the development process e.g., in a dynamic driving simulator. For the practical testing of SbW systems, fka takes over the prototypical integration on the target hardware up to the implementation in the complete vehicle. This means that, in addition to pure simulator studies, SbW systems can also be experienced in real test drives on fka's test track and on the road.

Image Sources:

Figure 3:
Lexus RZ450e - Example On-Highway
https://www.lexus.de/lexus-welt/news/der-neue-vollelektrische-lexus-rz-450e

Danfoss Flex-Steer - Example Off-Highway
https://www.danfoss.com/en/service-and-support/case-stories/cf/farmers-farewell-to-fatigue/

Schaeffler Space Drive - Example Racetrack
https://www.schaeffler.com/de/technologie-innovation/motorsport/why-we-race/steer-by-wire-technologie/

Figure 6:
Steering Control unit examples - Lexus
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Steering Control unit examples - Mercedes
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Steering Control unit examples - Tesla
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