



Article

Design Parameters for the Early Development Phase of Battery Electric Vehicles

Lorenzo Nicoletti *, Sebastian Mayer, Matthias Brönnner, Ferdinand Schockenhoff and Markus Lienkamp

Institute for Automotive Technology, Technical University of Munich, Boltzmannstraße 15, 85748 Garching, Germany; ga96bup@mytum.de (S.M.); broenner@ftm.mw.tum.de (M.B.); schockenhoff@ftm.mw.tum.de (F.S.); lienkamp@ftm.mw.tum.de (M.L.)

* Correspondence: nicoletti@ftm.mw.tum.de

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Abstract: The derivation of a battery electric vehicle (BEV) architecture represents a challenging task for car manufacturers. For the early development of combustion engine architectures, the required design parameters can be derived from the analysis of previously-built model series. Regarding BEV architectures, the manufacturers do not yet have a reference series of vehicles on the basis of which they can derive the essential design parameters. Therefore, these parameters are mainly estimated at high cost in the early development phase. To avoid cost-intensive changes in the further course of development it is crucial to choose the right set of design parameters. For this reason, the aim of this paper is the identification of a minimum set of design parameters, derived from the current state-of-the-art of vehicle development by a structured literature comparison. We group the results according to our definition of vehicle architecture and discuss each identified parameter to explain its relevance. The sum of all parameters presented in this paper builds a minimum set of design parameters, which can be employed as a guideline for the definition of BEV architectures in the early development stage.

Keywords: design parameters; early development; battery electric vehicles

1. Introduction

The vehicle architecture design in the early development phase is a crucial task as in the first 20% of the developing time, already 80% of the vehicle characteristics are defined [1]. False choices in this step have expensive consequences, as the cost of changes exponentially increases in the later course of the development [2] (p. 159) (Figure 1).

To start the architecture design a selected set of design parameters needs to be estimated. For example, the engineers need to define an acceleration time, necessary to model the further specification of the powertrain. Regarding internal combustion vehicles (ICEVs), many design parameters can be derived considering previous-built model series or similar models from the main competitors. Regarding BEVs, there is nowadays no previous-built model series, and the number of competitor's products on the market is still low. Furthermore, the design parameter cannot be derived from ICEVs, since the BEV powertrain technology and its requirements are completely different [3].

The aim of this paper is the identification of a minimum set of design parameters, which can be employed to fully define a BEV architecture in the early development phase. For this scope, we first define the relevant features that describe a BEV architecture (architectural features). Using the architectural features, we conduct a literature review, researching the authors who model vehicle architectures in the early development phase. Subsequently, through a comparison between the design parameter sets of the different authors, we identify the parameters, which are referenced the most and

group them according to the architectural features. Finally, we discuss the relevance of each of the derived design parameters. Additionally, the results can be grouped in a single set, thus generating a minimum set of design parameters.

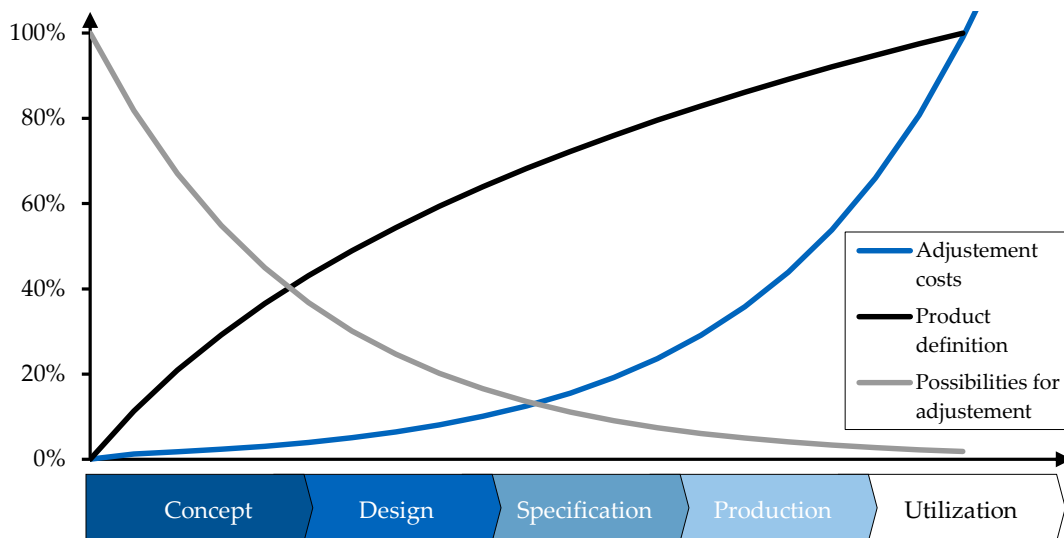


Figure 1. Overview of the costs in the product development cycle, based on [2] (p. 159).

2. BEV Architecture Definition and Identification of the Relevant Authors

To identify the design parameters for the dimensioning of BEVs, it is important to define the features of a BEV architecture. Based on these features, the design parameters derived from the literature review can be categorized in the further course of the paper.

2.1. Vehicle Architecture

A vehicle architecture consists of four architectural features: the dimensional concept, the powertrain topology, the component models, and the dimensional chains [4]. Figure 2 shows the architectural features. In the following, we explain each of the four parts and their importance for the vehicle architecture.

1. **Dimensional concept:** The dimensional concept defines the exterior and interior dimensions of the vehicle. Examples of exterior dimensions are vehicle length, overhangs, ground clearance, and height [4]. The group of interior dimensions includes the passenger layout and the number of seats. More information to this regard can be found in [5]. For the definition of the dimensional concept, the standards defined by the Society of Automotive Engineers SAE such as [6–10] are commonly employed.
2. **Powertrain topology:** The powertrain topology describes the rough layout and location of the BEV powertrain components. For example, the powertrain topology defines the location of the electric machine (front axle, rear axle) and its position regarding the axle (in front of the axle, behind the axle or coaxial). Further topology specifications are the type of gearbox (coaxial or with parallel axes) and the shape of the battery. An overview of the relevant topology components can be found in [11,12].
3. **Component models:** The powertrain topology itself only defines the positioning of the powertrain components. Their volume and weight are derived using component models. In addition to the topology components, which describe the required space for the vehicle powertrain, further components have to be considered, such as wheels and axles. The latter define, with their dimensions, the available space for the powertrain components [4].

4. Dimensional chains: The dimensional chains describe the geometrical interdependencies between the components in the X-, Y-, and Z-directions. Following the components' dimensioning, the available installation space in the vehicle has to be compared with the required installation space using dimensional chains, thus enabling the testing of feasibility and collision. Further information is available in [5].

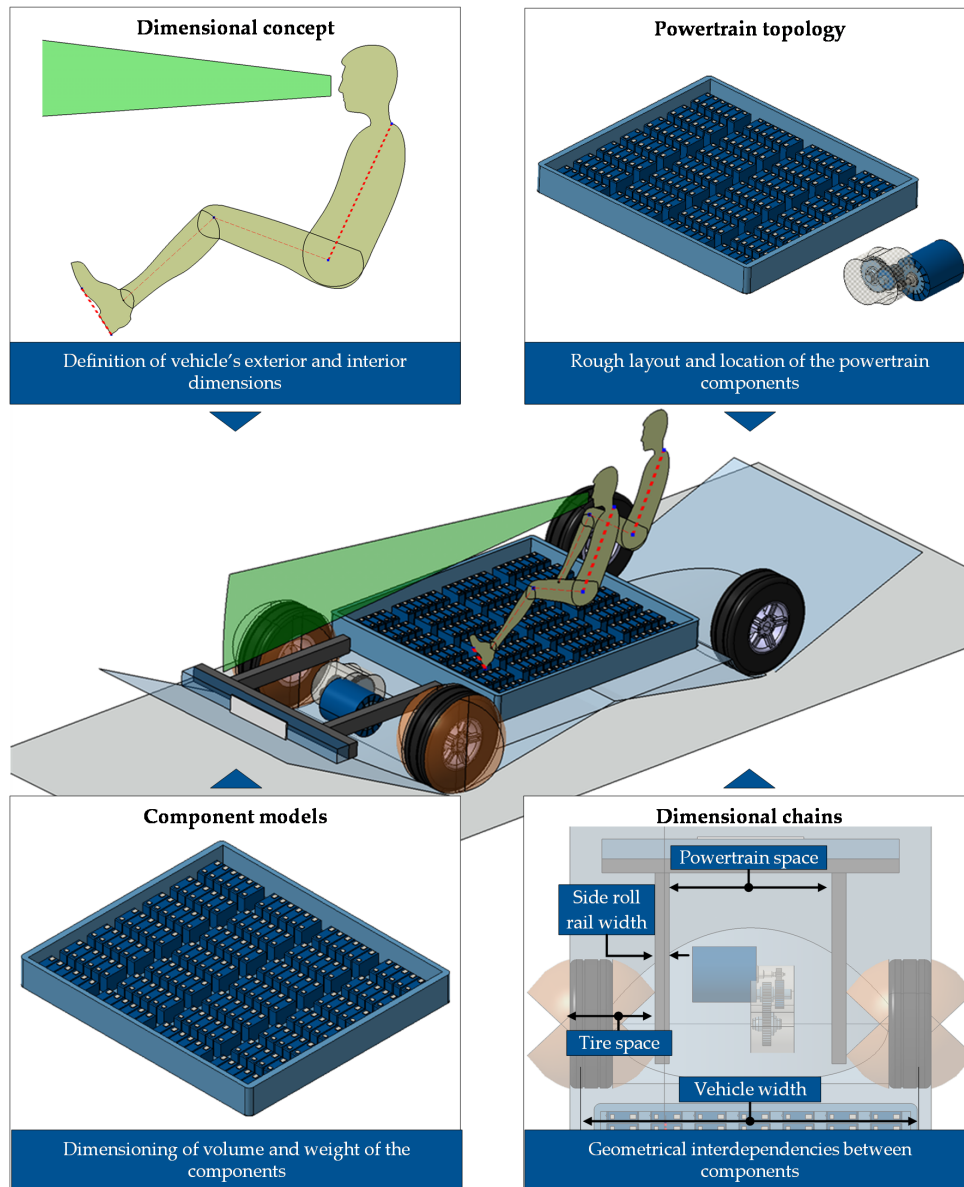


Figure 2. Overview of the architectural features, based on [4].

2.2. Complete Modeling of the Vehicle Architecture

Following the definition of the architectural features, we conduct research to identify the authors, who model at least three architectural features. The authors have been derived from analysis and cross-references of Ph.D. theses published between the years 2000–2020 and with a focus on the vehicle architecture modeling. Table 1 summarizes the authors. In Table 1 we employ as categories the architectural features and represent the depth of description of each category using the Harvey ball visualization. The classification method is explained as follows:

1. Modeling dimensional concept: We evaluate this category as fulfilled (●) if the author considers and models the main dimensions of the dimensional concept. Furthermore, the author needs to

- take into account the location of the passengers and their position. We consider this category as not entirely fulfilled (●), if the author models only a part of the dimensional concept (for example only the first row of seats) and not fulfilled (○) if the dimensional concept is completely ignored.
2. Modeling powertrain topology: We evaluate this category as fulfilled (●) if the author models all the possible BEV topologies, describing the position and rough location of the battery, electric machine, and gearbox. If only a limited number of components is modeled (for example, only the positioning of the battery), we consider this category as not entirely fulfilled (●). An unfulfilled powertrain topology (○) means that the positioning and layout of the powertrain components are completely ignored.
 3. Modeling component models: We evaluate this category as fulfilled (●) if the author models the main vehicle components, including wheels, axles, and powertrain. Furthermore, an estimation of the required and available installation space must be possible. The category is not entirely fulfilled (●) or not fulfilled (○), respectively, if the author models only a part or none of the relevant components.
 4. Modeling dimensional chains: We evaluate this category as fulfilled (●) if the author considers the relevant dimensional chains. The whole vehicle and not just specific areas (e.g., vehicle front, battery installation space, or interior) need to be considered. If only specific areas are modeled, the category is evaluated as not entirely fulfilled (●). If the components are not positioned using dimensional chains, the category is not fulfilled (○).

Table 1. Overview of the authors who model at least three features of the BEV architecture.

| Author | Modeling Dimensional Concept | Modeling Powertrain Topology | Modeling Component Models | Modeling Dimensional Chains |
|-------------------------------------|------------------------------|------------------------------|---------------------------|-----------------------------|
| Angerer [13–15] | ○ | ● | ● | ● |
| Felgenhauer [16–18] | ● | ● | ● | ● |
| J. Fuchs [19,20] | ● | ● | ● | ● |
| Fabian, Stadler, Rossbacher [21–23] | ● | ● | ● | ● |
| Kuchenbuch [24–26] | ● | ● | ● | ● |
| Matz [27,28] | ● | ● | ● | ● |
| Raabe [1,29] | ● | ○ | ● | ● |
| Ried [30,31] | ● | ● | ● | ● |
| Sethuraman [32] | ● | ● | ● | ● |
| Stefaniak [33,34] | ● | ● | ○ | ● |
| Wiedemann [35,36] | ● | ● | ● | ● |

After introducing the categorization method, we briefly describe the identified authors.

Angerer [13] models the longitudinal and transversal dynamic of all-wheel drive BEVs. The focus lays on the model optimization, testing of design parameters variation, and researching their influence on vehicle dynamics, costs, and consumption. The author models the powertrain topology and the wheels precisely, dimensioning all the relevant components. The dimensional chains are modeled marginally, as the feasibility- and collision-check is not the main scope of the model. For the same reason, the dimensional concept is not considered.

Felgenhauer [18] develops the PACE (Parametric Automotive Concept Engineering) tool to identify architectural standards and cross-vehicle modules. The approach includes combustion, hybrid, and electric powertrains. Nevertheless, the author only focuses on the vehicle front and does not include the overall vehicle architecture. Therefore, it is not possible to fully describe the powertrain topology, nor the dimensional concept. Furthermore, as the method only focuses on the front-end of the vehicle, it does not include the modeling of the traction battery and considers only a part of the dimensional chains.

J. Fuchs [19] develops a method for the derivation of BEV and plug-in hybrid architectures. The author subsequently researches the interactions between the different components and the architecture. The components are modeled and positioned with empirical relations and dimensional chains. The approach enables the generation of different powertrain topologies but uses a simplified dimensional concept that only includes some interior and exterior dimensions.

Fabian et al. [21], Stadler et al. [22], and Rossbacher et al. [23] describe a 3D digital mock-up to test the geometric feasibility of different vehicle concepts. The digital mock-up can be exported as a two-dimensional layout. Hence, it is possible to derive a dimensional concept, which includes all relevant dimensional chains. Considering the powertrain topology, the approach models different layouts. Nevertheless, a static component library (e.g., electric machines, dummies for different energy storage systems, suspension systems) is used instead of component models.

Kuchenbuch [24] develops the tool EVA-OS (Electric Vehicle Architecture Optimization System) which enables the generation of BEV architectures. By using an optimizer, the method can derive Pareto fronts between two vehicle characteristics, such as consumption and range. Furthermore, the author works with a detailed dimensional concept. The tool enables a comparison between different powertrain topologies with particular focus on the traction battery. Nevertheless, the author does not detail other components like the electric machine or gearbox, for which simplified geometric bodies are used.

Matz [27] implements a tool for the generation of BEV architectures based on vehicle characteristics and the customer's modal split. The description of vehicle characteristics is derived from the work of [35]. Using an optimization algorithm, the author identifies the architecture, which optimally fulfills a given set of customer requirements. A detailed geometric substitute model for the battery is implemented, while the other components are modeled with a component library. The approach uses a simplified dimensional concept model.

Raabe [29] develops a software for generating dimensional layouts and package-specification models. The author uses nearly 100 parameters to implement a highly detailed dimensional concept model. The author considers a wide set of dimensional chains but does not model any components of the vehicle's powertrain nor includes BEV powertrain topologies. However, parametric models are used for modeling tires, steering wheel, and pedals.

Ried [31] implements a method for the derivation of plug-in hybrids architectures. The focus lies on the available space for the traction battery. The author implements a geometric substitute model to estimate the volume and the position of the battery. Despite this, the approach does not consider other component models, nor the powertrain topology. The dimensional concept is simplified and focuses on the available installation space for energy storage. Due to this, some relevant dimensional chains (e.g., at the vehicle's front and back-end) are not taken into account.

Sethuraman et al. [32] present a holistic parametric packaging tool, which focuses on the design of buses for urban areas and their topologies. The tool contains a library for modeling the components and enables a component sizing. Regarding the dimensional concept, the authors focus on the passenger's positioning and ergonomics. Only the overall vehicle dimensions are described in the dimensional concept.

Stefaniak et al. [33,34] focus on BEV topologies and the derivation of the available solution space for the battery. The authors use a simplified dimensional concept to derive the installation space for the battery. Regarding the powertrain topology, the authors only consider the near-to-wheel and hub-wheel machine locations. Regarding the dimensional chains, the main focus is on the battery; the vehicle front- and back-end are modeled marginally.

Wiedemann [35] develops a method for the derivation of BEV characteristics. The author uses a simplified dimensional concept that only includes the main external dimensions and employs a component-library for the component dimensioning. For the powertrain topology, the author focuses on the two-dimensional positioning of the powertrain components. Hence, the method does not consider all the relevant dimensional chains.

The literature overview highlights, that none of the authors model all the architectural features. This means, that none of the authors identifies a complete set of design parameters. Therefore, we identify a set of design parameters through a comparison of the different authors. To obtain a better result, we extend our analysis also on authors, who model BEV architectures but only focus on specific architectural features. These authors were mainly identified through a cross-reference of the authors in Table 1. We group them into two categories: focus on dimensional concept and dimensional chains, and focus on component models and powertrain topology.

2.3. Focus on Dimensional Concept and Dimensional Chains

Bhise et al. [37,38] present an approach for the parametric design of new vehicle concepts. More than 70 input parameters are used for defining the vehicle's interior and a rough estimation of its exterior. Furthermore, the authors focus on the ergonomic analysis and positioning of the passengers. Nevertheless, they do not model any components. Relevant dimensional chains at the front- and back-end of the vehicle are not included.

Hahn [39] focuses on vehicle-characteristics-based design in the early development phase. The author creates a tool that enables a rough estimation of the vehicle's dimensional concept. The tool derives different vehicle variants by changing specific design parameters. The approach considers only a limited amount of dimensional chains and the powertrain topology and its components are not taken into account.

Mau and Yanni et al. [40–42] present a set of equations to describe the vehicle interior and exterior. Despite the simplified approach, the authors present different dimensional chains, which can be employed for the early development phase.

Müller [43] describes an approach for modeling the dimensional concept while focusing on the ergonomics of the passengers. Nevertheless, the author does not consider BEVs topologies nor the influence of components, such as the battery on the dimensional concept.

Prinz [44] models part of the dimensional concept, considering the seating layout, and the fields of view of the driver. The scope of the model is describing the mutual interactions between the design parameters. The author further groups the parameters in different modules (packaging, aerodynamics, weight, suspensions, driving power, and chassis) and researches the effect of a design parameter variation on the vehicle properties.

2.4. Focus on Component Models and Powertrain Topology

Domingues et al. [45–47] focus on the modeling of the electric machine, power electronics, and gearbox. In particular, the authors model permanent magnet synchronous machines. Furthermore, they present a method for optimizing the powertrain's components focusing on the powertrain costs.

Eghtessad et al. [48,49] implement a tool for the optimization of BEV powertrains. The tool models the main powertrain components (battery, electric machine, and gearbox) while considering different powertrain topologies. The approach enables an optimization with a focus on different vehicle properties, such as acceleration, maximum velocity, costs, and consumption.

S. Fuchs et al. [50,51] describe a methodology for estimating the vehicle weight in the early development phase. For this scope, the authors divide the vehicle into eight modules and model empirically the weight of the single components of each module. The sum of the weight of the modules corresponds to the vehicle weight. Furthermore, the approach can estimate the influence of different input parameters, such as electric vehicle range, on the weight, and quantify secondary mass effects.

Hogt et al. [52,53] implement a model that derives the battery mass and volume from vehicle performance parameters. Furthermore, the effects of different battery positions on the vehicle's dynamics can be tested. The other vehicle components are not considered.

Nemeth et al. [54] develop a tool for the simulation and optimization of BEV powertrains. This includes the electric machine, power electronics, and battery. Moreover, the authors evaluate the advantages and disadvantages of different powertrain topologies.

Pesce et al. [55,56] present a methodology for optimizing BEV powertrains. The methodology models all the relevant powertrain components. For this scope, the authors employ semi-physical and empirical component models. Optimizing the vehicle's energy consumption, the authors identify the most efficient powertrain topology.

3. Results

An overview of the above-cited authors is summarized in Table A1 in Appendix A. The table clearly shows that the different methodologies focus on one or two architectural features, while the remaining features are modeled marginally or not at all. Each author uses different design parameter sets. For the overall modeling of the vehicle architecture, the different sets need to be taken into account. In the following sections, we compare the design parameters of the different authors. To minimize the number of parameters we summarize those used by three or more authors. Further information about the less relevant parameters can be found in [57].

3.1. Relevant Parameters for the Dimensional Concept

Table 2 summarizes the design parameters for the description of the dimensional concept. Figure 3 illustrates schematically the design parameters. In the following, we briefly discuss the relevance of the identified design parameters.

The measures vehicle length, overhangs, and wheelbase are required for the definition of the vehicle's front-end, its back-end, and its passenger compartment. Furthermore, they are necessary to describe the vehicle segment, calculate the axle loads, and derive the available space for the powertrain components.

The vehicle width is required to dimension the vehicle's front-end, its back-end, its passenger compartment, and to derive the front area. All the authors assume that the width is constant on the whole vehicle length. This assumption does not correspond to reality, as one can see from the different width definitions documented in [7], but is justified for the early development. The track width can be employed to derive the static stability factor (SSF) [58], thus allowing the estimation of the vehicle's rollover safety.

The position of the seating reference point (SgRP) can be defined in different ways. Typical measures are L53-1, H30-1, or W20-1 [7]. The position of the SgRP is required to define other important dimensional concept features, such as the headroom [9] and the driver's field of view [10,59].

Table 2. Overview of the design parameters for the dimensional concept.

| Parameter | Sources |
|--|--|
| Vehicle length, overhangs, and wheelbase in mm | Angerer [13–15], Bhise [37,38], Felgenhauer [16–18], J. Fuchs [19,20], S. Fuchs [50,51], Hahn [39], Hogt [52,53], Matz [27,28], Pesce [55,56], Prinz [44], Raabe [1,29], Sethuraman [32], Stefaniak [33,34], Wiedemann [35,36] |
| Vehicle width and track width in mm | Angerer [13–15], Bhise [37,38], Felgenhauer [16–18], J. Fuchs [19,20], S. Fuchs [50,51], Hahn [39], Matz [27,28], Raabe [1,29], Ried [30,31], Sethuraman [32], Prinz [44], Stefaniak [33,34] |
| Seating reference point (SgRP) position in mm | Bhise [37,38], Felgenhauer [16–18], J. Fuchs [19,20], Hahn [39], Matz [27,28], Prinz [44], Raabe [1,29], Ried [30,31], Stefaniak [33,34] |
| Vehicle height in mm | Angerer [13–15], Bhise [37,38], J. Fuchs [19,20], S. Fuchs [50,51], Hahn [39], Matz [27,28], Raabe [1,29], Sethuraman [32], Wiedemann [35,36] |
| Ground clearance in mm | J. Fuchs [19,20], Hahn [39], Kuchenbuch [24–26], Raabe [1,29], Ried [30,31], Sethuraman [32], Stefaniak [33,34] |
| Number of seats | S. Fuchs [50,51], Hahn [39], Matz [27,28], Prinz [44], Sethuraman [32], Wiedemann [35,36] |
| Headroom in mm | Bhise [37,38], Hahn [39], Kuchenbuch [24–26], Prinz [44], Raabe [1,29], Wiedemann [35,36] |
| Legroom in mm | Hahn [39], Prinz [44], Raabe [1,29], Sethuraman [32], Wiedemann [35] |
| Front area in m ² | J. Fuchs [19,20], Hahn [39], Nemeth [29], Pesce [55,56], Prinz [44] |
| Acceleration heel point (AHP) position in mm | Bhise [37,38], Hahn [39], Raabe [1,29], Stefaniak [33,34] |
| Length of crash in mm | Kuchenbuch [24–26], Prinz [44], Raabe [1,29] |

The vehicle height defines, in combination with the vehicle width, the vehicle's front area. Furthermore, given the vehicle height, the available vertical space for the battery can be derived [5].

The ground clearance is defined as the distance between the road surface and the lowest point of the vehicle [60]. Different standards exist for the definition of ground clearance requirements [60–64]. This parameter is highly relevant for BEVs since it influences the available battery space in the vertical direction [5].

The number of seats is required for the definition of the seating layout. Furthermore, it influences the length of the passenger compartment (L99-2 as in [7]), the dimensions of the tunnel, and the overall wheelbase and width of the vehicle.

Headroom, legroom, and position of AHP are employed to define the position of the driver and to derive the required driver's space in the passenger compartment. To define these design parameters the position of the SgRP is required. The authors [19,24,27,35] use the required space of the passenger compartment to derive, given a vehicle height, the remaining space for the traction battery.

The front area determines, in combination with the drag coefficient, and the vehicle's speed, the drag losses of the vehicle [65]. It can be roughly estimated through multiplication between the vehicle width and height. S. Fuchs [51] uses more detailed modeling, including the window side angle and empirical correction factors [66].

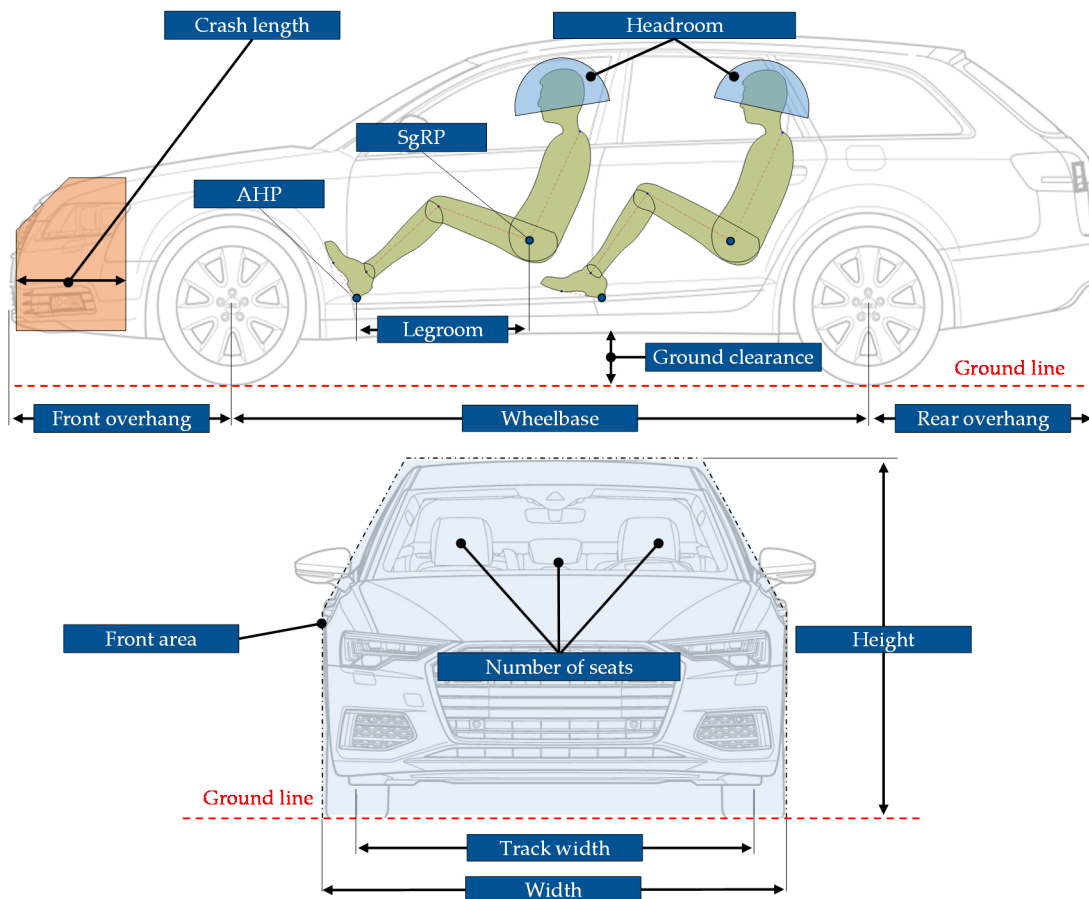


Figure 3. Overview of the design parameters for the dimensional concept, based on [67].

The length of crash is used to define the crash-safe areas for the components positioning at the front-end of the vehicle. This is important for authors like Kuchenbuch [24] and Felgenhauer [18], who derive crash-safe areas for placing the powertrain components at the front-end compartment.

3.2. Relevant Parameters for the Powertrain Topology

Table 3 summarizes the identified design parameters for the description of the powertrain topology. Figure 4 illustrates the design parameters. In the following sections, we briefly discuss the relevance of the identified design parameters.

Table 3. Overview of the design parameters for the powertrain topology.

| Parameter | Sources |
|----------------------------|--|
| Cell type | Eghtessad [48], Felgenhauer [16–18], J. Fuchs [19,20], S. Fuchs [50,51], Kuchenbuch [24–26], Matz [27,28], Nemeth [54], Pesce [55,56], Wiedemann [35,36] |
| Electric machine type | Angerer [13–15], Domingues [45–47], Eghtessad [48], Felgenhauer [16–18], J. Fuchs [19,20], S. Fuchs [50,51], Matz [27,28], Nemeth [54], Pesce [55,56], Wiedemann [35,36] |
| Drive type | Angerer [13–15], Eghtessad [48], Felgenhauer [16–18], J. Fuchs [19,20], S. Fuchs [50,51], Hahn [39], Matz [27,28], Wiedemann [35,36] |
| Gearbox type | Angerer [13–15], Domingues [45–47], Eghtessad [48], Felgenhauer [16–18], J. Fuchs [19,20], S. Fuchs [50,51], Wiedemann [35,36] |
| Battery position and shape | Kuchenbuch [24–26], Hogt [52,53], Matz [27,28], Prinz [44], Wiedemann [35,36] |

The parameter cell type includes both cell technology (e.g., lithium ion or nickel-metal hydrides) and cell geometry (prismatic, cylindrical, pouch). Wiedemann [35] and Felgenhauer [18] divide the cells according to technology and shape to assign a volumetric and gravimetric energy density to each category. In the last years, the established cell technology is the lithium-ion technology [3]. Regarding the cell geometry, there is no established form, and, depending on the manufacturer, pouch, prismatic, or cylindrical cells are employed.

Regarding the electric machine type, there are two established technologies: synchronous and asynchronous machines [68]. The two types have different efficiency diagrams and overload factors [28]. Therefore, the authors who model the vehicle's consumption using a longitudinal simulation, such as [13,18,19,27,35,51,55], assign accordingly to the machine type a corresponding efficiency diagram. Furthermore, the two machine types have different materials and dimensions, which means that the distinction is also required for modeling the machine weight and volume [28].

The drive type describes the position and number of electric machines. The possible drive types are front-, rear-, or all-wheel drive. Furthermore, differently from ICEVs, in BEVs it is also possible to install two machines per axle, as it can be seen in concept vehicles, such as [69]. The drive type usually depends on the segment and price of the vehicle [11].

The gearbox type defines the topology of the gearbox (coaxial or parallel axes). This parameter influences the position, dimensions, and weight of the gearbox, as well as the position and dimensions of the electric machine.

The battery position describes the technical space where the battery is placed. The established positioning is in the underbody of the vehicle [11]. Nevertheless, in some vehicles, the battery is partially positioned in the vehicle's tunnel or underneath the second row of seats [69]. The battery shape describes the form of the battery, e.g., rectangular or T-shaped. More information in this regard can be found in [11].

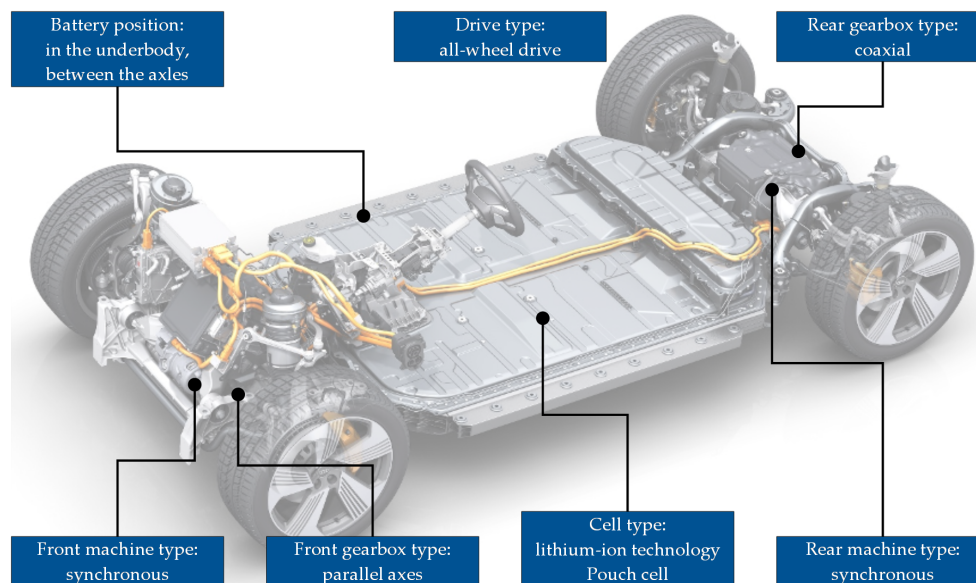


Figure 4. Overview of the design parameters for the powertrain topology, based on [70].

3.3. Relevant Parameters for the Component Models

Regarding the component models, we present the design parameters for traction battery, electric machine, gearbox, and wheels. We also consider the wheel, as the required dimensions of this component define, through dimensional chains, the available space for the electric machine and battery.

3.3.1. Traction Battery

To derive the design parameters for the traction battery we conduct two analyses, one at the cell level (Table 4) and one at the battery level (Table 5). Figure 5 illustrates the results of both analyses. In the following sections, we briefly discuss the relevance of the identified design parameters.

Table 4. Overview of the design parameters for the cell.

| Parameter | Sources |
|--------------------------------------|---|
| Cell energy in Wh | J. Fuchs [19,20], Kuchenbuch [24–26], Matz [27,28], Nemeth [54], Stefaniak [33,34], Wiedemann [35,36] |
| Cell voltage in V | J. Fuchs [19,20], Kuchenbuch [24–26], Matz [27,28], Nemeth [54], Stefaniak [33,34] |
| Cell energy density in Wh/kg or Wh/L | Angerer [13–15], J. Fuchs [19,20], S. Fuchs [50,51], Nemeth [54], Wiedemann [35,36] |
| Cell size in mm | Kuchenbuch [24–26], Matz [27,28], Sethuraman [32], Stefaniak [33,34] |
| C-rate in 1/h | J. Fuchs [19,20], Matz [27,28], Wiedemann [35,36] |

The cell energy defines the energy content of the cell. Authors like Wiedemann [35] and Felgenhauer [18] derive typical values of energy for different cell geometries and technologies. The cell voltage depends on the employed cell technology and is required to derive the battery voltage.

The cell size defines the main dimensions of the cell (length, width, and height) and depends on the cell geometry. The authors [19,27,35] derive typical sizes from empirical analysis and literature research. Combining cell size and energy, it is possible to derive the energy density. The latter can be expressed as the gravimetric (Wh/Kg) or volumetric (Wh/L) energy density. Typical values can be found in [71,72]. Given the cell energy density and the required battery energy, it is possible to estimate the battery weight and volume.

The C-rate (also defined as P/E ratio) describes the performance of the cell [73] and is calculated from the ratio between the cell power and the cell energy. The C-rate describes the maximum current that the cell can safely deliver to the electric machine. Furthermore, it influences the service life of the cell, as higher C-rates cause a higher load of the cell [74]. BEVs usually have a C-rate of approx. 5–6 1/h while plug-in hybrids and hybrid vehicles have C-rates up to 40 1/h [73].

The cell level analysis is required for the battery level analysis. Regarding the battery, the relevant parameters are similar to the cell parameters (Table 5).

Table 5. Overview of the design parameters for the battery.

| Parameter | Sources |
|-----------------------|--|
| Battery voltage in V | Domingues [45–47], J. Fuchs [19,20], Matz [27,28], Pesce [55,56], Stefaniak [33,34], Wiedemann [35,36] |
| Battery energy in kWh | Eghtessad [48], Felgenhauer [16–18], Matz [27,28], Pesce [55,56] |
| Battery size in mm | Felgenhauer [16–18], Kuchenbuch [24–26], Prinz [44], Sethuraman [32] |
| Packaging factors | J. Fuchs [19,20], S. Fuchs [50,51], Matz [27,28], Wiedemann [35,36] |

Given the cell voltage and the required battery voltage, it is possible to derive the required number of serial cells. The battery voltage can vary from manufacturer to manufacturer, although values around 400 V are usually employed [21,35,54].

The installed battery energy mainly depends on the vehicle segment, weight, and electric range. Given cell energy, battery energy, and battery voltage, it is possible to derive the total number of cells, as well as the number of parallel cells. In this way, the cell electric schematic is fully defined.

The battery size defines the main measures of the battery (length, width, and height). It can be derived from the outer measures of the vehicle, taking into account the free spaces for the safety requirement, such as [75,76]. For the derivation of the safe areas for the installation of the battery, it is not possible to conduct crash simulations at this early stage of the development. Nevertheless, typical empirical values to derive crash-safe areas can be found in [77].

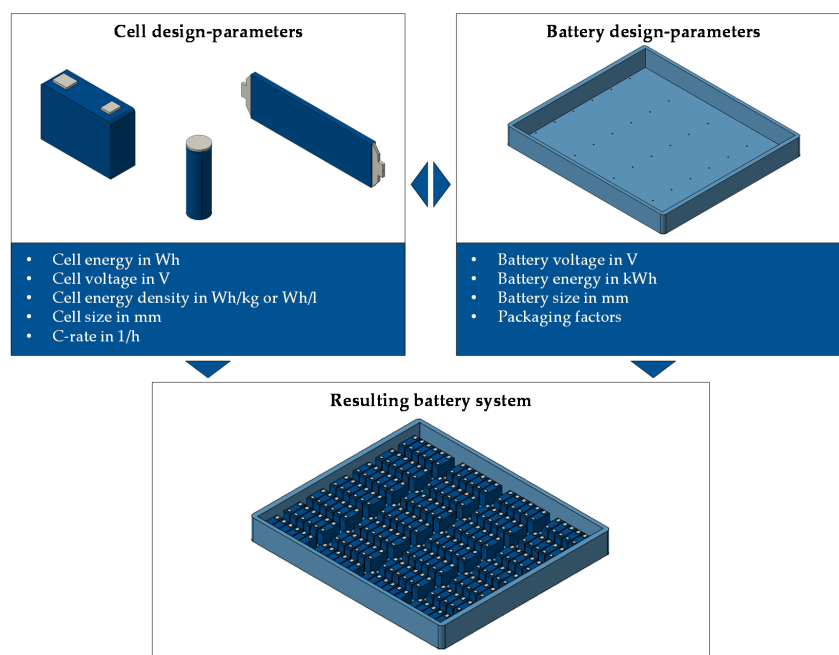


Figure 5. Overview of the design parameters for cell and battery.

Given the required number of cells, the cell size, and the battery size the feasibility of the battery concept can be tested. For this step, it is necessary to also consider the inactive material, such as the cooling system, battery casing, and electrical wires. Packaging factors, as derived by [19,35], are employed to take into account the space loss caused by the inactive material. For example, how to define and derive packaging factors can be found in [5].

3.3.2. Electric Machine and Gearbox

Table 6 presents the identified design parameters for the description of the electric machine and gearbox. Figure 6 illustrates the derived design parameters.

The rotational speed is required to derive the machine's power and to describe its characteristics. The employable variables for the dimensioning of the machine are the nominal rotational speed and the maximal rotational speed. Furthermore, the required maximal rotational speed depends on the gearbox ratio, the wheel diameter, and the maximum vehicle speed. Typical values for both nominal and maximal speed can be found in [78].

The machine torque is required to define, with the rotational speed, the machine characteristics and power. Similarly to the rotational speed, we can distinguish between nominal and maximal torque. The difference between nominal and maximal torque depends on the overload factor of the machine. Typical overload factors can be found in [28].

Given the machine torque and the rotational speed, the machine power can be derived. Therefore, this parameter is not required if the rotational speed and torque are known.

Table 6. Overview of the design parameters for the electric machine and gearbox.

| Parameter | Sources |
|-----------------------------------|---|
| Machine rotational speed in 1/min | Angerer [13–15], Eghtessad [48], J. Fuchs [19,20], S. Fuchs [50,51], Kuchenbuch [24–26], Pesce [55,56], Wiedemann [35,36] |
| Machine torque in Nm | Angerer [13–15], Domingues [45–47], Eghtessad [48], J. Fuchs [19,20], S. Fuchs [50,51], Pesce [55,56], Wiedemann [35,36] |
| Machine power in kW | Domingues [45–47], J. Fuchs [19], Hahn [39], Hogt [52,53], Kuchenbuch [24–26], Wiedemann [35,36] |
| Machine dimensions in mm | Kuchenbuch [24–26], Sethuraman [32], Wiedemann [35,36] |
| Machine weight in kg | J. Fuchs [19,20], Matz [27,28], Prinz [44], Wiedemann [35,36] |
| Gearbox transmission ratio | Angerer [13–15], Eghtessad [48], J. Fuchs [19,20], S. Fuchs [50,51], Matz [27,28], Pesce [55,56], Wiedemann [35,36] |

The machine dimensions and weight are required for the positioning of the electric machine. The shape of the machine can be simplified as a cylinder, and its dimensions can be estimated using its power or torque as in [79]. Some authors [13,51] also focus on the machine weight, as it influences the machine inertia and the vehicle's inertial losses.

The gearbox transmission ratio is required to model the dimensions of the gearbox. BEVs usually mount one-speed gearboxes, therefore in most cases, the gearbox can be described with a single transmission ratio. If the machine torque and maximal rotational speed are given, it is possible to derive the gearbox torque and rotational speed. These variables can be further employed to dimension the gearbox's wheels, thus deriving its dimensions.

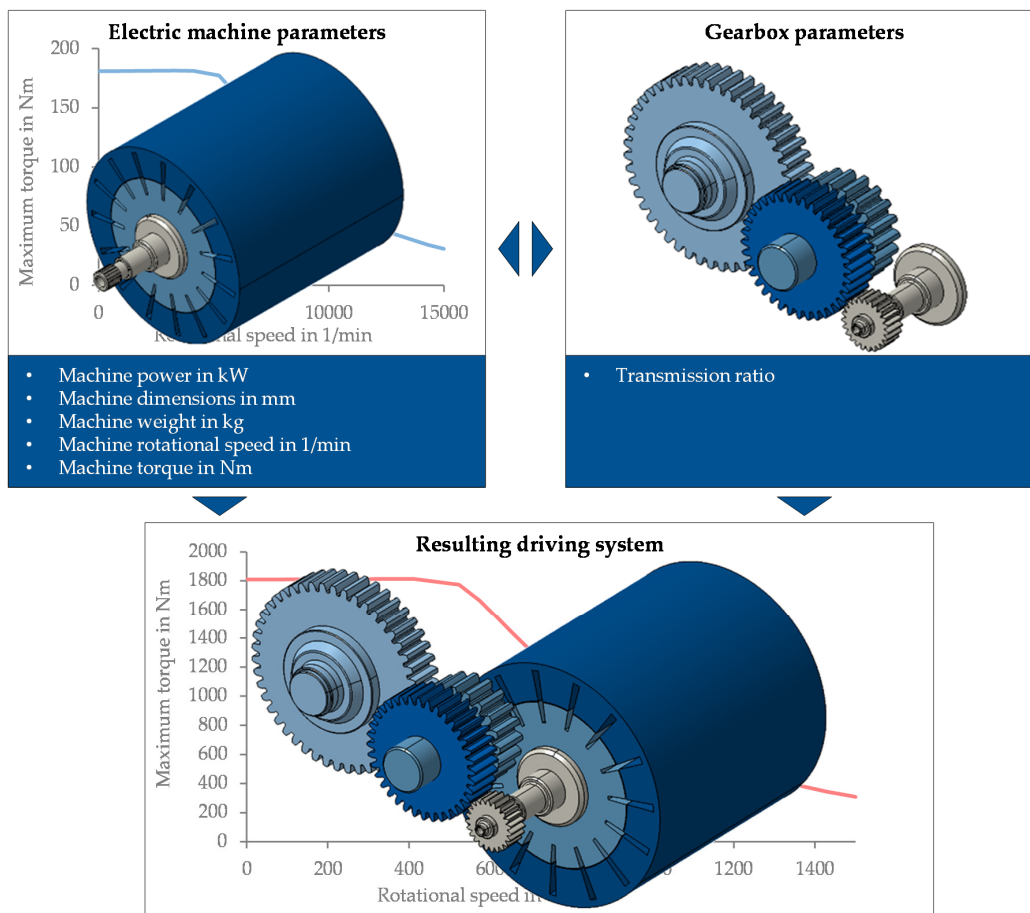


Figure 6. Overview of the design parameters for the electric machine and gearbox.

3.3.3. Wheels and Axles

Table 7 presents the identified design parameters for the description of the tires and axles. In the following sections, we briefly discuss the relevance of the identified design parameters.

The wheels influence, combined with the car body, the vehicle's trim and shape [80]. Therefore, the tire diameter has a high impact on the vehicle's design. Furthermore, the tire diameter, the vehicle's maximum speed, and the gearbox ratio influence the required machine torque and its speed.

Authors such as Matz [27] and S. Fuchs [51], who model the vehicle consumption in detail, consider the rolling resistance factor, as well as its dependency from the tire dimensions, to model the vehicle rolling friction losses.

The tire width defines, together with the diameter, the tire volume. From the tire volume, it is furthermore possible to estimate the tire maximum load. Felgenhauer [18] models the tire dimensions deriving the tire volume from the required axle load. For a correct estimation of the required volume, it is necessary to also define the tire type. There are two main types of tires as defined by the European Tire and Rim Technical Organization (ETRTO): normal and extra load tires [81]. The extra load tires can support higher loads, which results in smaller volumes at the expense of higher costs.

The axle type is required to derive the available powertrain space. For an exact estimation of the axle required space, it is necessary to know its kinematics, but such knowledge is not available in the early development phase. Therefore, the authors [18,27,51] derive the axle dimension using empirical data analysis while categorizing the data according to the axle type.

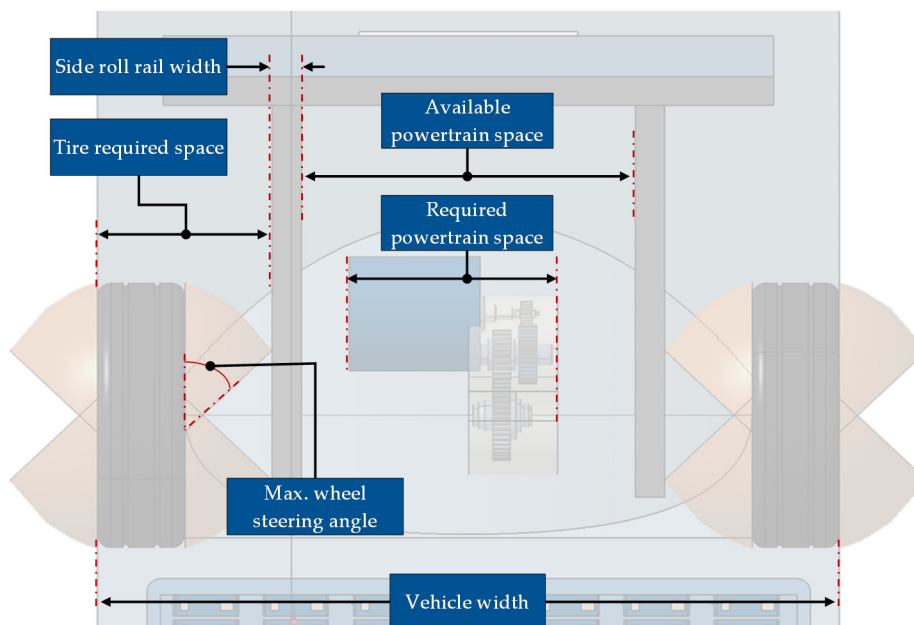
Table 7. Overview of the design parameters for the tires and axles.

| Parameter | Sources |
|---------------------------|--|
| Tire diameter in mm | Angerer [13–15], Bhise [37,38], Felgenhauer [16–18], J. Fuchs [19,20], S. Fuchs [50,51], Kuchenbuch [24–26], Matz [27,28], Nemeth [54], Pesce [55,56], Prinz [44], Raabe [1,29], Ried [30,31], Sethuraman [32], Wiedemann [35] |
| Rolling resistance factor | Angerer [13–15], S. Fuchs [50,51], Kuchenbuch [24–26], Matz [27,28], Nemeth [54] |
| Width in mm | Angerer [13–15], Bhise [37,38], S. Fuchs [50,51], Kuchenbuch [24–26], Matz [27,28] |
| Tire type | Felgenhauer [16–18], S. Fuchs [50,51], Matz [27,28] |
| Axles type | Felgenhauer [16–18], S. Fuchs [50,51], Matz [27,28] |

3.4. Relevant Parameters for the Dimensional Chains

Regarding the dimensional chains, it is not possible to derive a defined set of design parameters, the reason being that the dimensional chains describe the geometrical interdependencies between the components and are, therefore, not defined by any specific design parameter.

Figure 7 shows an example of a dimensional chain. The chain connects the dimensions of the tire, side roll rail, and powertrain components. The components' dimensions are calculated using component models. Subsequently, the electric machine and gearbox are positioned according to the powertrain topology (in this case a front-wheel drive and a gearbox with parallel axes). Subsequently, the chain tests the feasibility while comparing the required space for the powertrain components with the available space. The latter is derived from the vehicle width (defined by the dimensional concept) and the dimensions of tire and side roll rail.

**Figure 7.** Overview of a dimensional chain at the front-end compartment.

The dimensional chains are therefore the link between the other architectural features [4] and allow, through the interdependencies they describe, the derivation of the vehicle architecture. Therefore, the definition of the dimensional chains bases solely on the other three architectural features and not on a predefined set of design parameters.

3.5. Vehicle Characteristics and Properties

Another result of the analysis is that the authors also use a set of parameters, which are not connected to any of the four architectural features. These additional parameters are required since the above-presented geometrical parameters are not sufficient to describe the whole vehicle behavior. For a better understanding and classification, we split them into two classes: vehicle properties and vehicle characteristics. Weber [82] defines the vehicle properties as the customer's view on the product. The vehicle characteristics are their technical implementation, which needs to be designed by the vehicle concept engineer. Every automotive manufacturer has its portfolio of vehicle properties, which needs to be fulfilled to satisfy its customers. Examples of such portfolios can be found in [83,84]. In the following sections, we briefly discuss the relevance of the identified design parameters for vehicle properties and vehicle characteristics.

Table 8 presents the design parameters for the description of the vehicle properties.

Table 8. Overview of the design parameters for the vehicle properties.

| Parameter | Sources |
|-------------------------|---|
| Acceleration time in s | Felgenhauer [16–18], J. Fuchs [19,20], S. Fuchs [50,51], Hahn [39], Nemeth [54], Pesce [55,56], Prinz [44], Wiedemann [35,36] |
| Maximum velocity in m/s | Domingues [45–47], Felgenhauer [16–18], J. Fuchs [19,20], Hahn [39], Hogt [52,53], Pesce [55,56], Prinz [44], Wiedemann [35,36] Bhise [37,38], Domingues [45–47], |
| Vehicle segment | Felgenhauer [16–18], J. Fuchs [19,20], S. Fuchs [50,51], Prinz [44], Wiedemann [35,36] |
| Range in km | J. Fuchs [19,20], S. Fuchs [50,51], Hogt [52,53], Nemeth [54], Pesce [55,56], Wiedemann [35,36] |
| Turning circle in m | Felgenhauer [16–18], Hahn [39], Prinz [44], Wiedemann [35,36] |

The parameter acceleration time describes the required time to reach a velocity of 100 km/h starting from a vehicle's standstill. Given an acceleration time requirement, it is possible, using longitudinal simulation, to derive the required machine torque (if other design parameters, such as vehicle weight, tire dimensions, and gearbox transmission ratio, are known).

The maximum velocity is another relevant parameter for the powertrain design. Given a velocity requirement, the maximum required rotational speed of the machine can be estimated, as long as the gearbox ratio and the tire dimensions are known. In this way, the maximum rotational speed of the machine is derived from the maximum velocity and the machine torque from the acceleration time.

Another relevant vehicle's property is the segment. It has an impact on the geometrical design, the outer vehicle dimensions, and the passenger compartment dimensions.

The turning circle depends on the wheelbase and segment of the vehicle and is particularly relevant for the dimensional chains at the front-end of the vehicle. Given a wheelbase and a turning circle requirement, the maximum wheel steering angle can be calculated as shown in [35] (p. 83). The maximum wheel steering angle is essential during parking to ensure easy handling of the vehicle. The wheel steering angle, in turn, defines the required space for the steering wheel and therefore limits the available space at the front-end compartment for the powertrain components. If the vehicle width remains constant and the steering angle increases, more space for the wheels is required. This results in smaller available space for the electric machine and gearbox.

Table 9 presents the design parameters for the description of the vehicle characteristics.

Table 9. Overview of the design parameters for the vehicle characteristics.

| Parameter | Sources |
|--|--|
| Vehicle weight in kg | Domingues [45–47], Felgenhauer [16–18], J. Fuchs [19,20], S. Fuchs [50,51], Hahn [39], Hogt [52,53], Nemeth [54], Pesce [55,56], Prinz [44], Wiedemann [35,36] |
| Drag coefficient | J. Fuchs [19,20], Hahn [39], Kuchenbuch [24–26], Nemeth [54], Pesce [55,56], Prinz [44], Wiedemann [35,36] |
| Axle load ratios in% | J. Fuchs [19,20], Matz [27,28], Pesce [55,56], Wiedemann [35,36] |
| Position center of gravity (COG) in mm | Hogt [52,53], Pesce [55,56], Prinz [44] |

The parameter vehicle weight is required to estimate the vehicle consumption, its maximum speed, and the acceleration time. Furthermore, it has a direct influence on the powertrain components, as it influences the vehicle consumption.

The drag coefficient results from the exterior styling and it is an important parameter for the calculation of the drag losses [65]. Given a required vehicle speed and a drag coefficient, it is possible to estimate the required power, to reach the maximum velocity while withstanding the drag losses [65].

The axle load ratio and the position of the COG are required to calculate the tire load, influence the inertia of the vehicle and its handling, and determine the dynamic forces on the axle caused by acceleration or deceleration. Given the axle loads, the position of the COG in the longitudinal direction is defined, for the transversal direction, all authors position the COG in the middle of the vehicle.

The presented portfolio of parameters of vehicle properties and characteristics ensures the user- and target-oriented development of the vehicle architecture.

4. Discussion and Conclusions

The novelty of this paper is the presentation of a minimum set of design parameters derived for the early development phase of BEV architectures. In addition to the analyzed authors, we derive our set of design parameters from a literature review and comparison of different vehicle development methods that have a common scope, i.e., the modeling of a vehicle architecture. To ensure the correctness and quality of the estimation, we only analyze Ph.D. theses and peer-reviewed publications. Many of the analyzed authors [18,19,24,31,35,39,44] worked during their Ph.D. in cooperation with car manufacturers such as Volkswagen, BMW, and Audi. This ensures that the identified parameters are employed by the manufacturer.

We describe for each identified parameter its relevance and, where possible or required, we cite further sources and standards that are useful for its modeling. Table 10 shows the resulting minimum set of design parameters.

Table 10. Minimum set of design parameters for the early development of BEV architectures.

| Group | Number of Parameters |
|--|----------------------|
| Dimensional Concept (Table 2) | 14 |
| Powertrain topology (Table 3) | 6 |
| Component models (Tables 4–7) | 20 |
| Vehicle properties (Table 8) and vehicle characteristics (Table 9) | 9 |

The design parameter set which results from the combination of Tables 2–9 consists of 49 parameters. Table 10 shows that the architectural feature with the highest number of parameters is the component models. This is caused by the high number of variables, which are required to describe the traction

battery and the cells. Only with regard to the traction battery, we identify nine relevant parameters (Tables 4 and 5), which highlights the importance of this component in the early development.

These results can be employed as a basis to further study the interdependencies between the architectural features (Section 2.1). For example, in a previous publication [5] we studied the interdependencies between the dimensional concept (which can be described with the set presented in Table 2) and the traction battery (which can be described with the set presented in Table 5). Furthermore, it is also possible to analyze the interdependencies between the architectural features and the relevant vehicle properties (Table 8) or characteristics (Table 9). This topic will be analyzed in future research.

In conclusion, this paper proposes a definition of the relevant BEV architectural features, explains them, identifies relevant design parameters, and further explains them. The hereby presented design parameter set (Table 10) will be used as an input set for the further development of a parametric BEV architecture model.

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Appendix A

Table A1. Overview of the relevant authors.

| Author | Modeling Dimensional Concept | Modeling Powertrain Topology | Modeling Component Models | Modeling Dimensional Chains |
|-------------------------------------|------------------------------|------------------------------|---------------------------|-----------------------------|
| Angerer [13–15] | ○ | ● | ● | ● |
| Felgenhauer [16–18] | ● | ● | ● | ● |
| J. Fuchs [19,20] | ● | ● | ● | ● |
| Fabian, Stadler, Rossbacher [21–23] | ● | ● | ● | ● |
| Kuchenbuch [24–26] | ● | ● | ● | ● |
| Matz [27,28] | ● | ● | ● | ● |
| Raabe [1,29] | ● | ○ | ● | ● |
| Ried [30,31] | ● | ● | ● | ● |
| Sethuraman [32] | ● | ● | ● | ● |
| Stefaniak [33,34] | ● | ● | ○ | ● |
| Wiedemann [35,36] | ● | ● | ● | ● |
| Bhise [37,38] | ● | ○ | ○ | ● |
| Hahn [39] | ● | ○ | ○ | ● |
| Mau, Yanni [40–42] | ● | ○ | ○ | ● |
| Müller [43,85] | ● | ○ | ○ | ● |
| Prinz [44] | ● | ○ | ○ | ○ |
| Domingues [45–47] | ○ | ○ | ● | ○ |
| Eghtessad [48,49] | ○ | ● | ● | ○ |
| S. Fuchs [50,51] | ○ | ○ | ● | ○ |
| Hogt [52,53] | ○ | ● | ○ | ○ |
| Nemeth [54] | ○ | ● | ● | ○ |
| Pesce [55,56] | ○ | ● | ● | ○ |

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