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The development of electric drive systems – How to deal with the challenges

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Summary

Electrification of passenger cars opens up a multitude of solutions for the layout of drivetrain topology. The arrangement of subsystems and its function fulfilment has a non-negligible impact on efficiency, driving performance, cost and installation space. In order to minimize development risks, the first generation of BEV bases on conventional vehicles. Probably, the potential concerning efficiency and comfort is not reached yet. This article stats approaches to deal with the new challenges in the development of BEV by focusing the support of system understanding through analyses of interdependencies between requirements originate from customer, previous product generations and the technical system.

Keywords: BEV, powertrain, transmission, optimization

1 Introduction

Recurring notifications of high CO_2 and fine dust load in urban and interurban areas show the increased need for clean mobility. [1] The electrification in drive systems increased the last years. However, the sales numbers are small. Hybrid-electric vehicles are often upper or luxury segment cars, battery electric vehicles rank among small and mini-class cars. Hence, the consumer group is already limited. In order to increase the sales numbers, one possibility is to offer electric vehicles even in other vehicle segments. Another important point is the lacking acceptance on the part of customers, whereby the main weakness is the low range of actual vehicles in combination with the high costs in comparison to familiar conventional vehicles.

One solution of this matter could be battery cells with a higher ratio of energy per mass. Beside improvement of energy density of batteries there are also approaches to improve the energy efficiency of the powertrain by enlarge the power density and reduce the total mass of the powertrain. An approach to increase the power density is to increase the maximum speed of the electric machine. Nevertheless, raising the maximum speed often leads to decreasing the maximum torque because of the limited possible rotor-diameter at high speed and the limited possible current of the power electronics. Thus, in order to match all performance-requirements of the vehicle, a multi-speed gearbox is needed. Additionally, a multispeed gearbox enables the electric machine to operate in points, which are more efficient. This leads to new requirements for the gearbox and to more degrees of freedom in the design of the powertrain.

One of the resulting questions is how to find suitable combinations of electric machine and gearboxes for different vehicles. [2] Fig. 1 shows the interdependencies between vehicle segments and the used transmission regarding an urban usage scenario. [3] Beside the technical interdependencies, there are additional requirements: Currently the first product generation of small series production electric vehicles is in the market. The next generations are in development. Thus, the users' and as well as the developers' experiences base on a relatively small number of vehicles.

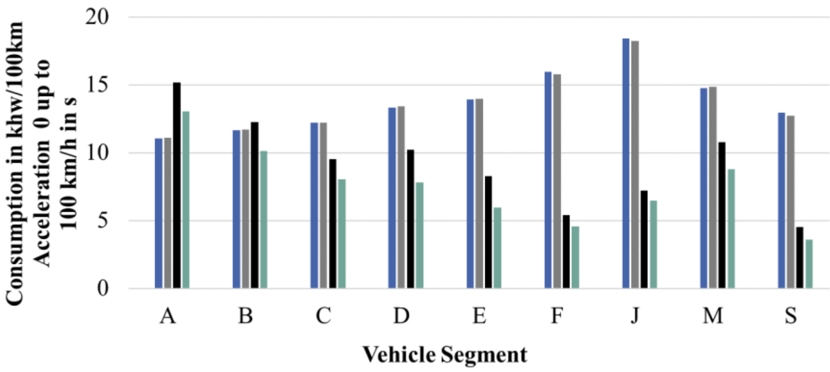


Figure 1: Energy consumption and acceleration referred to vehicle segments (blue: consumption single speed, grey: consumption multi-speed, black: acceleration single speed, green: acceleration multi-speed) [4]

In order to have a comparison: Toyota launched the fourth product generation in the market. Within the development of each of these generations, knowledge could be gained, variations – in order to carryover from existing products on one hand and in order to develop new on the other hand – could be identified and by this, customer acceptance and satisfaction could be increased.

The OEM respectively developers face the task of developing drive systems, whereby they cannot benefit from the knowledge originating from the development of many product generations. In addition, customer needs and expectations are rarely known – even the customers are not aware of their expectations. The question is: How to deal with the challenges and to develop the right product in the right way?

2 State of art

2.1 Actual electric vehicles

Although the sales numbers of electric vehicles are low, there is a certain diversity in models. Most of manufactures have vehicles in serial production. Many of the cars are small to mini-sized cars. But there are also indications that lead to the presumption that battery electric vehicles will prevail in high class respective sport cars. It is obvious that the majority of drive systems point out the same topology. Normally a permanent mutated synchronous machine with a single speed transmission is used as a central drive. The drives could be differed into front and rear axle drives. It is not obvious, if this is the best solution for the specific vehicle and estimated usage scenario – in short: to fulfil the customer expectations and needs.

2.2 Development approaches

Most manufactures pursue the development strategy "conversion design" in order to minimize development risks. Based on an existing (conventional) modular design, an electric vehicle is synthesised. In these cases, the percentage of carryover systems is relatively high. Thus, compromises concerning range, performance, comfort … occur within the development. Another, competing approach is the purpose design. One example is the BMW i3 as well as all models of Tesla. The purpose design is described as the development of a new product. [5] In context of product generation development[1], it could be understood as a development consisting of a low percentage of carryover systems. Subsystems could be harmonized to each other, which increases the complexity. Simultaneously, it offers the possibility to increase customer benefits. Tab. 1 shows possible solutions of drive system integration in electric vehicles.

[1] Developing a new generation of technical products by combining specific variations, in order to carryover (CV) from existing products on one the hand and in order to develop new on the other, is understood as PGE. [6]

Table 1: Possible topologies corresponding to KASPER and SCHUENEMANN [7]

Front Axle / Rear Axle		F1	F2	F3	F4	F5	F6	F7
R1		✓	✓	✓	✓	✓	✓	✓
R7		✓	✗	✗	✗	✗	✗	✗

2.2.1 Conversion Design

As mentioned above, most electric vehicles base on ICE vehicles‘ platforms and are built up with their modular design. In order to minimize development risks and costs, manufacturers use the development strategy „conversion design“. Thereby, an electric machine combined with a fixed ratio (often integrated in the differential) substitutes the conventional drivetrain (ICE, shiftable gearbox, differential). The usage of a central drive is not caused by being the best solution regarding efficiency; rather it is caused by the usage of existing platforms and modular design. [8] Because the platform was designed for another application, it is not as suitable for application of BEV as it could be. The mechanical part – the gears and differential – is as easy as it could be. Different operating points and new power characteristics (higher input speed, less torque, no torsional excitation) result in new type of load for a „known“ system (like gearboxes). The adaption to these new requirements and conditions is too high for the required time to market, which is caused by the pressure of the legacy and the world market. Another reason are the low number of vehicles sold, which make a new development caused by high cost unattractive.

2.2.2 Purpose Design

A competing approach is the purpose design, which increases the functionality as well as the system complexity by the possibility to harmonize subsystems to each other.

Daimler presented the AMG SLS electric drive that offers new functionalities and by this, it is able to meet customer demands. At once, the development of these cars offers the manufacturers the possibility to gain experiences by developing new drive system topologies under these requirements. FEUSTEL points out, that this vehicle is an object lesson and a technology demonstrator. Daimler will profit from the gained knowledge many years. [9]

STAHL presents a two-speed gearbox with two electric machines to increase the range of electric vehicle. [10] REICHERT ET AL. designed a three-speed gearbox that is driven by an electric machine with input speed up to 30,000 rpm. [11] This concept focussed on increase power density and as well as the efficiency. HORCH ET. AL. presents a wheel hub drive. The engines are even used to decelerate the vehicle, which offers the possibility to renounce the wheel brake system and reduces particulate matter emission. [12]

2.2.3 Holistic view on electric drive systems

In order to increase system competencies and improve the potential of electric drive systems, few approaches have been presented.

EGHTESSAD presents a method to develop an optimized BEV topology using evolutionary algorithms. Starting with nine topologies, the following aspects are varied: driven axle and installation point. These topologies and its subsystems are optimized. The focus is on the assessment of these topologies using an evaluation function, which considers vehicle mass, driving power and energy consumption. Neither costs nor installation space are considered. [13] FUCHS ET. AL. focusses on modelling interdependencies between weight and efficiency depending on the driving power within the development of new vehicle concepts. The considerations are performed using a longitudinal dynamics model of small segment vehicle. [14] WIEDEMANN ET AL. concentrate on derive technical parameters from customer demand like range, driving power and costs. The simulation focusses on the correlation of the technical properties like battery capacity with the customer demands like range. The possibilities and customer benefits by using various topologies is part of the consideration. [15] KUCHENBUCH ET AL. focus on installation space and packaging of battery systems. Via genetic algorithm the component layout considering the drivetrain topology are gained. Whereby, control levers to adjust vehicle properties are identified. There is no focus on efficiency or driving performance. [16]

KUHLMANNN ET AL. published a methodical selection of drivetrains concerning electric machine and gearbox for small segment electric vehicle. Within this work, they aim to convert a conventional driven vehicle into an electric driven vehicle without changing the cassis and interfaces. The approach is oriented on the methodology after PAHL & BEITZ and VDI 2225. [17]

The presented methods focus on the optimization of subsystems for one topology regarding the criteria efficiency and performance. Few of them regarding installation space or costs. The topologies' diversity or various vehicle segments are not in focus.

Thus, the presented work is regarding the complete solution space including all vehicle segments and topologies in interaction with the customer demands. The aim is to support the development process beginning with the selection and design on the level "whole vehicle" down to the optimization of subsystems for a current product profile by correlating the customer demands with the technical solution space before the first decision point.

3 Methodical Approach

While analysing the development processes of electric drive systems, the objective of further work is defined: Aim is the development of a holistic approach, which supports the development process within the modelling of principle and embodiment realisation and product validation over all system levels – from the whole vehicle level down to subsystem level.

3.1 Evaluation of interdependencies and deduction of system of objectives (SoO)

In order to deal with the challenges pointed out in the previous sections, the focus is to support system understanding through the analyses of interdependencies between the requirements originate from customer demands and usage scenario, previous product generations and the technical system with its subsystems. Thus, it enables the evaluation of potential and eligibility of drive system topologies in context of usage scenarios and customer satisfaction. Within a multi-step process, whole system interdependencies are analysed in order to gain quantitative system specifications and define objectives for the development. The methodology is shown in Fig. 2.

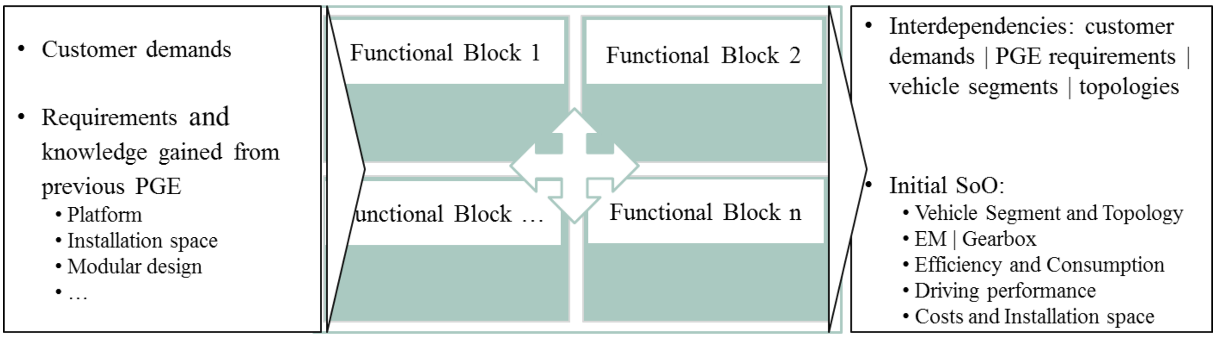
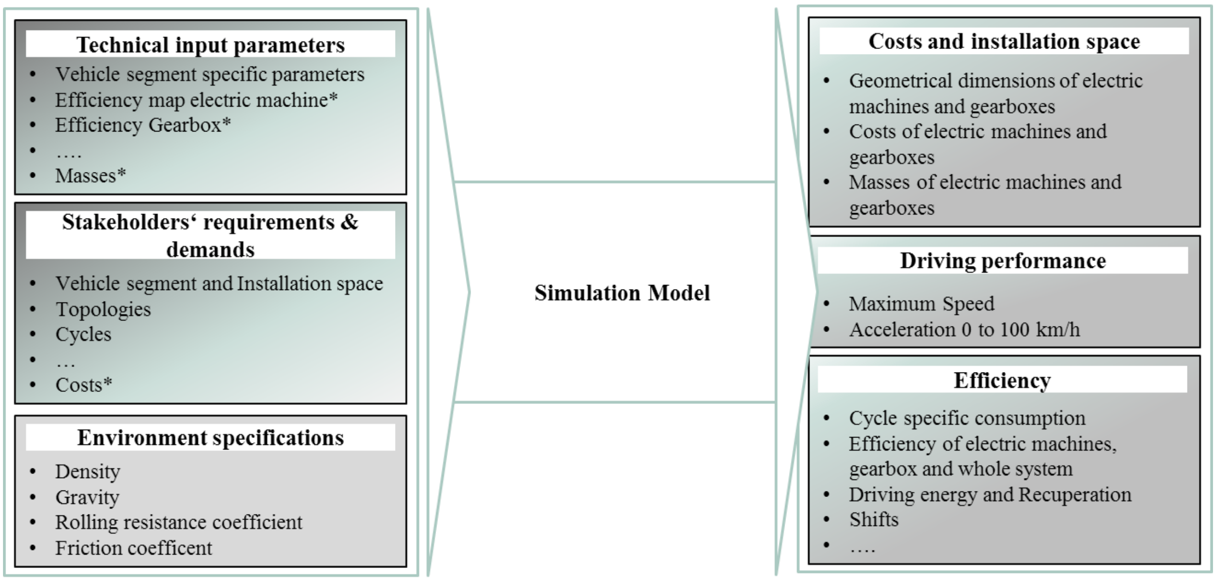


Figure 2: Methodology for the understanding of interdependencies and determination of initial SoO

Based on the requirements, quantitative parameters (e.g. free installation space, costs, and power and performance demands) are specified for the whole vehicle in a first step. For the further calculations and evaluation a mathematical model is built up, which consists of modular functional blocks. Whereby, some are necessary like the input masks for the parameters shown in Fig. 3 and some are optional like the modelling of additional functions like performing the synchronisation by the electric machine.



* Partly function-based, scalable models

Figure 3: Basic structure of modular simulation model [4]

Thus, based on the inputs the topologies respectively their subsystems and subsystems' interdependencies are modelled. Thereby, the parametrization of models has to enable an easy variation of parameters within a certain range in order to perform sensitivity analyses. Beside the efficiency, every subsystem is described by functions and parameters like masses, costs, installation space, ratios, … Using a central drive for example, the structure of simulation model is displayed in Fig. 4.

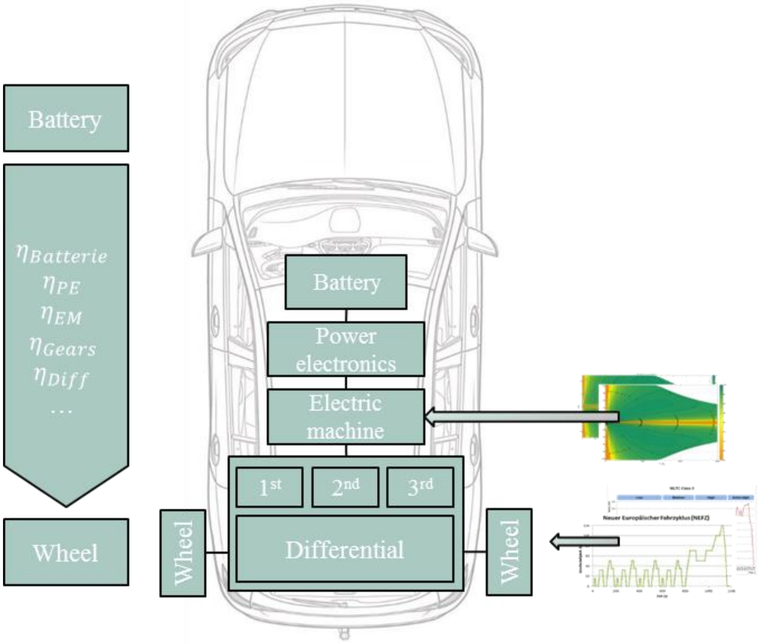


Figure 4: Structure of simulation model [4]

Within the last step, indicators for the evaluation are determined. (s. Fig. 3) These steps are performed for different input variables. Thus, it is possible to evaluate different topologies as well as the same topology integrating various function (electric machine supports synchronization or integration of the vehicle deceleration into gearbox [18] [19]). The parameters of the best topology lead to objectives for the further drivetrain development.

3.2 Determination of the number of gears and the gear ratio

General subsystems of an electric drivetrain are battery system, power electronics, electric machine and gearbox. As described above, manifold topologies are possible by combining diverse numbers of these basic elements. In order to fulfil the main function of a drivetrain, minimum one of each subsystem is needed. Considering this configuration, the further steps of the methodical approach are described. In order to fulfil the power demands at the wheels, the torque and speed of the electric machine is transferred via the gearbox. Initial target values respectively a target range is already defined in the previous step. For the dimensioning of an electric drivetrain, the gear ratios are one of the important issues to fulfil the requirements. Through the choice of the gear ratios, considering the vehicle requirements like maximum speed and acceleration and for multi-speed gearboxes the gear stepping, the requirements and interdependencies of the subsystems are changing. Through the choice of the gear ratios and the number of gears, the requirements on the other subsystems are changing, e.g. the maximum torque and resulting the volume and mass of the electric machine. Increasing volume and losses of a multispeed gearbox counteract to the decreasing volume of the electric machine. Challenge is to develop an optimal combination of electric machine and gearbox that enables a high power-density and same time an equal efficiency by fulfilling all performance requirements.

The determination of the number of gears und the gear ratios is the first important step to develop an installation space and efficiency optimal gearbox for an electric drivetrain. The number of gears and the gear ratios depend on several parameters. Fig. 5 shows the parameters for calculating the gear ratios.

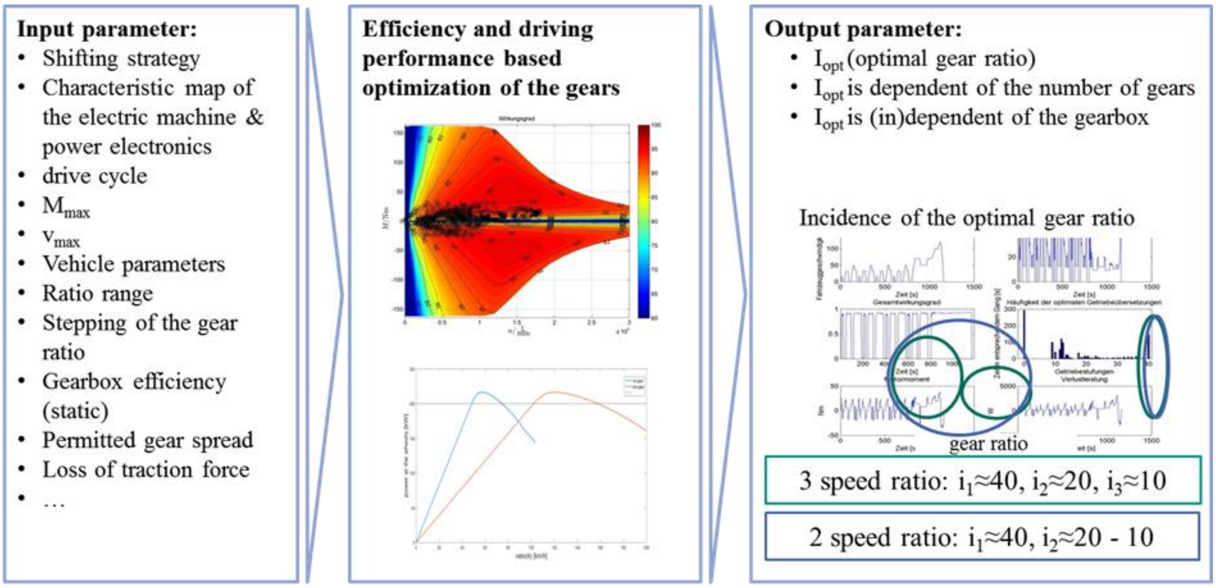


Figure 5: Methodology for the determination of the number of gears and the gear ratios

For the determination of the efficiency optimal powertrain configuration, the previous determined minimum and maximum gear ratios are varied in the CVT- functionality [20] with a defined increment size as a function of the electric machine and the power electronics. The increment size has to be chosen as a function of the accuracy of the gear ratio. This leads to efficiency optimal gear ratios depending on the used drive cycle, for example the WLTP [21] or NEFZ [22]. Further input parameter is static gearbox efficiency as a function of the type of gearbox. For multi-speed gearboxes, the gear spread is a comfort criterion for the traction interruption by shifting the gearbox. The simulation model developed at IPEK is useable for one, two and three speed gearboxes. In addition to the efficiency optimal gear ratios, another output criteria is the power and traction at the wheels to notice a traction interruption early in the development process. [2] To determine the efficiency optimal gear ratios and their time course, any numbers of shifting in the drive cycle are allowed. In addition, different shifting strategies can be applied to see changes in the gear ratio by using them. The shifting strategies depend on the vehicle speed, the pedal position or the time to hold the engaged gear. Trough parameter studies of the input parameter for one and multi speed gearboxes the efficiency optimal gear ratios can be determined by considering the traction at the wheels. The next step is to identify possible gearbox topologies, which can fulfil the requirements to the needed number of gears, the gear ratios and for multi speed gearboxes the shifting elements.

3.3 Design of different gearboxes

In this context, the gearbox must contain a sufficient number of gears, gear ratios and topology. Derived question is how to define the gearbox-design systematically, considering the interactions and resulting requirements for the subsystem of the drive system. [2] On subsystem level, in comparison to a single speed gearbox a multi-speed gearbox has more components. Not only gearwheels but also gear shift elements, more shafts, more bearings, a more complex greasing system etc. This increases gearbox volume and losses. For example, the layout of the clutches in a multi-speed gearbox without traction interruption affects close to the gear ratio the dimensioning of the clutches through parameters like transmittable torque und the differential speed.

The MATLAB tool has a number of one-speed, two-speed and three-speed gearbox topologies, which are checked for their suitability for the defined number of gears, gear ratios and shifting elements. For example, a one speed gearbox with a gear ratio of 15 cannot be realized with a single staged gearbox. The MATLAB tool can be easily extended by any gearbox topology. On basis of defined requirements like the maximum speed, torque und the gear ratio, the chosen gearbox topology is dimensioned automatically in detail. Further input parameters are gear values like pressure angle, helix angle and the profile displacement. On basis of these parameters, the gear wheels are dimensioned according DIN 3990 [23]. If not all gear parameters are available, a simplified dimensioning is possible. In the detailed dimensioning, NVH optimized gearings can be taken into account during the early development phase. The gearbox shafts are dimensioned according to DIN 743 [24]. In addition to the safety factors for shaft dimensioning, different steel materials can be selected. Each gear shaft is parametrically stored and is dimensioned according to the load (Fig. 6 left).

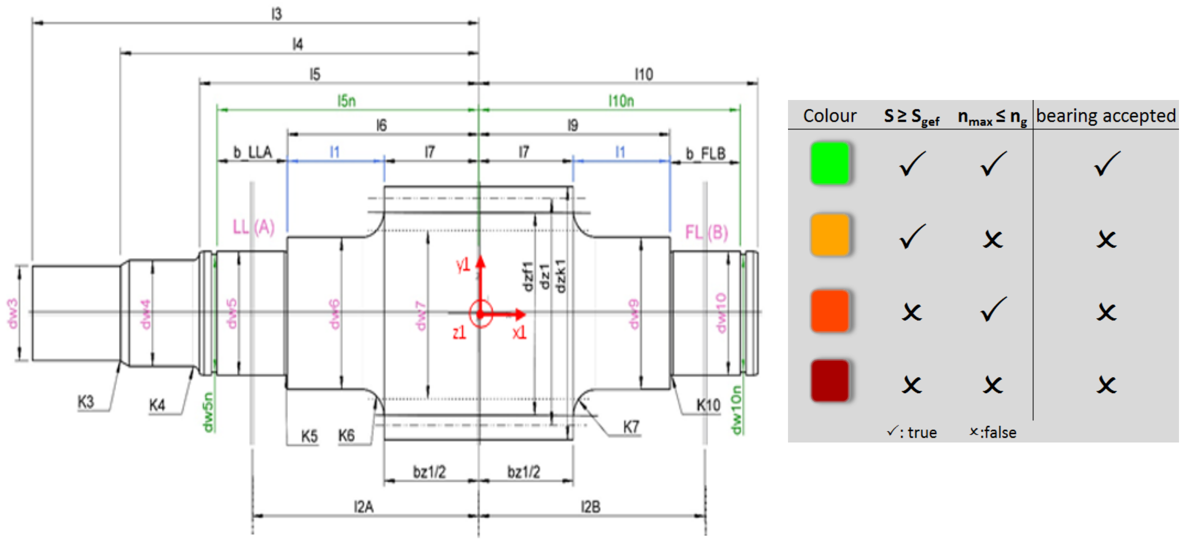


Figure 6: parametrical model of a gear shaft (left); suitability of different bearings (right)

The dimensioning takes place with consideration of notches, grooves, bearing and sealing seats. In an iterative process, bearings are automatically selected from the electronically stored bearing catalogue after the shaft dimensioning and, if necessary, the shaft diameter is adapted. It is also possible to check specific bearings for suitability in the selected gearbox. The bearings are selected according to the load and the speed and are issued according to their suitability (Fig. 6 right). In the case of multi speed load-shifting transmissions, the clutches are additionally dimensioned according to the clutch torque, the differential speed and the friction material.

To reduce the clutch losses and the designed space of the clutch, a pre-synchronization with the electric machine can also be realised. With an increasing percentage of synchronizing with the electric machine, the clutch losses can be reduced. The smaller differential speed, which is synchronized by the clutch, causes a lower frictional power and energy. In combination with the lower peak torque as a function of the inertia by adjusting the speed with the electric machine, it is possible to reduce the diameter or the number of friction plates of the clutch to increase the power density. [18]

After the dimensioning of the gearbox has been carried out, detailed information about the designed space and the mass can be made. The benefit is the dimensioning of the transmission components taking into account the interactions to determine the smallest and lightest gearbox under given boundary conditions. The mass and the designed space of the entire drivetrain can be determined by the previously selected electric machine. A further benefit of the automatically detailed dimensioning of the gearbox are the determined inertia of each subsystem, the loss parameters of bearings, gearings, sealing and shifting elements for calculation the efficiency of the drivetrain. The next step is the efficiency rating of the different drivetrains.

3.4 Efficiency determination of different gearboxes

For the efficiency determination, it is necessary to compare all loses in the overall drivetrain. The drivetrain losses are determined by simulation. The losses of the electric machine and the power electronics are determined with a power loss characteristic map and the actual motor torque and speed. The gearbox losses are composed of the gearing, bearing, sealing, clutch, synchronizer and actuation losses. Each gearbox type in the simulation uses its own loss-model and gets the necessary parameters to calculate the losses automatically for the dimensioning of the gearbox. The simulation model of the single-speed gearbox considers all load-dependent and load-independent bearing and gearing losses and the sealing losses. The two-speed simulation model is extended with a transmission controller, which operates the clutches by the gear changes as a function of the shifting strategy. Thus, it is possible to record the power and energy losses of the overlapping phases and the synchronisation phases by the shifting operation. Additionally, the actuating losses are considered. Thus, through the addition of all losses, the whole power and energy loss can be determined as a function of the shifting strategy. For the three-speed simulation model, the transmission controller is extended with a synchronizer for the first and third gear. These losses are also included.

For the determination of the subsystem losses, different loss models are used. Fig. 7 shows for example the bearing losses. As a function of the actual speed and torque and the bearing type, different loss models are used. The bearing type and the required loss parameter are transferred from the MATLAB tool.

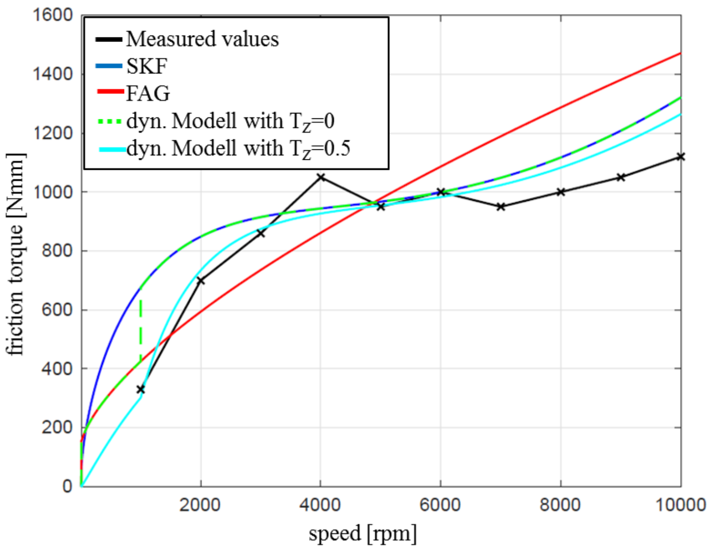


Figure 7: Discontinuities in the friction moment of the dynamic simulation model (Cylindrical roller bearing NU 212 with C/P = 20, = 113 mm2/s, measured values of [Wan15]) [25]

The result of the simulation model is an overall efficiency analysis of the chosen drivetrain. Different drivetrains can be compared and the efficiency optimal drivetrain can be determined. The results of the complete method with the steps determination of the number of gears and the gear ratios, the dimensioning of the gearbox including shafts, bearings, gearings, sealings and clutches and the efficiency analysis are the rating of the different drivetrains with the equal vehicle requirements concerning the mass, designed space, power density and efficiency.

4 Excerpt of results

This methodical approach has been performed within two product development processes, which aim to develop an efficient drivetrain for elect vehicles.

4.1 First excerpt: The development of a drive system for urban small vehicle segment

In the following, the achievable knowledge by the presented approach (section 3.1) is pointed out. As example, the development which has been done within the project REM 2030 [26] is taken. So, the reference drivetrain consists of a permanent mutated electric machine combined with a two-speed planetary gear. The properties and results are compared with two three-speed drivetrains. The first on is driven by a machine, which is power equivalent to the reference drivetrain. The second one was designed in order to evaluate the benefit of an electric machine, which meet the power demands more exact. This results in waiver of power reserves. Tab. 2 shows an excerpt of the properties and results, by which the evaluation of the drivetrain's potential is possible.

All configurations of drivetrains fulfil the requirements, whereby the three-speed drivetrains overtake the requirements concerning driving performance and the reference drivetrain is the most efficient. Taking a briefer look on the efficiency, the efficiency of electric machine increases with the number of gears. Thus, one possible solution for the further steps should be the optimization of the gearbox efficiency in order to reduce the divergence of whole system efficiency. The potential of the power-reduced drivetrain is the reduction of costs for electric machine and power electronics, which are – beside battery system – the cost drivers.

Table 2: Excerpts of results and comparison

	Reference drivetrain	**Power equivalent three-speed drivetrain**	**Power-reduced three-speed drivetrain**
Driving performance			
Power electric machine	70.42 kW	70.14 kW	62.95 kW
Acceleration 0…100 km/h	11.30 s	10.31 s	11.37 s
Maximum speed	135.02 km/h	191.44 km/h	184.67 km/h
Consumption and efficiency			
Consumption in REM 2030 cycle[2]	7.063 kWh	7.13 kWh	7.15 kWh
Efficiency electric machine	95.25 %	97,04 %	96.81 %
Efficiency drivetrain	76.94 %	76,40 %	76.30 %
Installation space and costs			
Costs of electric machine	704.22 €	701.35 €	629.49 €
Costs of power electronics	2,008.40 €	2,002.70 €	1,859.00 €
Mass of electric machine	22,59 kg	22.49 kg	20,19 kg

[2] Interurban cycle, developed within the project REM 2030 [3]

4.2 Second excerpt: The development of a middle-segment vehicle with a high power density drive

Through the in section 3 presented holistic method, the most suitable drivetrain can be selected on the basis of the criteria designed space, mass and efficiency and allows the detailed and time reduced dimensioning and choice of a gearbox for a BEV considering all interdependencies with the residual system. Fig. 8 exemplarily shows the results of the method for a medium sized car by using a one speed and three speed gearbox different electric machines and power electronics. Depending on the selection criterion and given boundary conditions, a gearbox can be designed in conjunction with the electric machine and the power electronics.

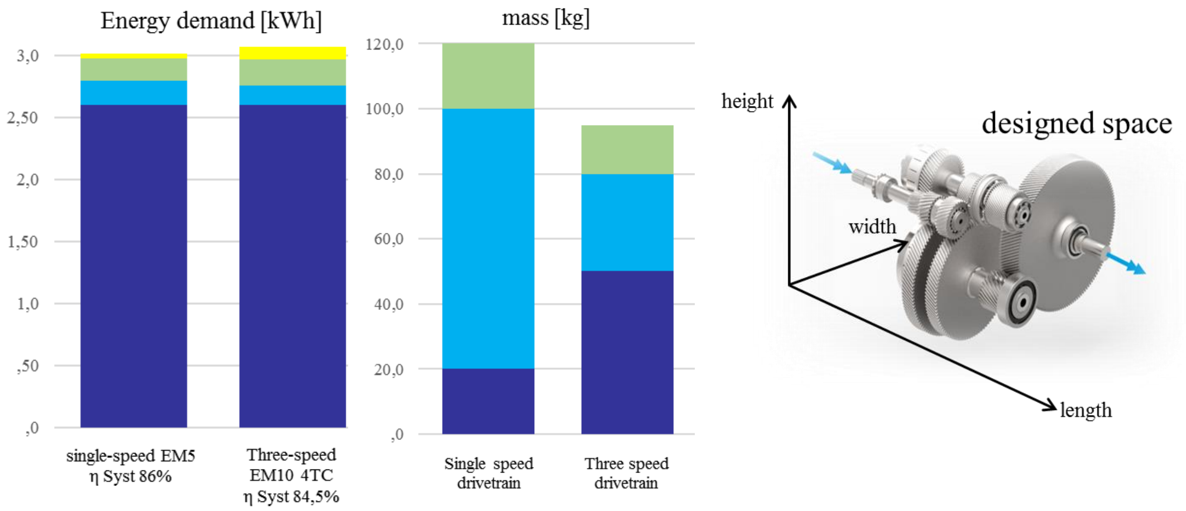


Figure 8: Criteria efficiency (yellow: losses gearbox, green: losses EM, light blue: losses PE, dark blue: energy consumption at the wheels), mass (green: mass PE, light blue: mass EM, dark blue: mass gearbox) and designed space

The energy demand of the drivetrain with a single and three-speed gearbox is approximately the same, while the mass of the three-speed drivetrain is 20% below the mass of the drivetrain with the one speed gearbox. As a result, the power density of the entire drivetrain can be increased. This advantage results from the large gear ratio of the first gear of the multi-speed gearbox, which reduce the torque of the electric machine with constant torque on the wheel for both drivetrains. This reduces the mass of the electric motor. In spite of a heavy gearbox, the mass of the entire drivetrain with a three-speed gearbox is below the one-speed.

5 Conclusion and Outlook

The paper presents a holistic development approach for electric drive systems: starting with the determination of vehicle requirements, defining target values for subsystems, regarding also their interdependencies, ending with the dimensioning and efficiency consideration of the whole drivetrain. It is important to point out that the presented approach enables the evaluation of topologies potential for various stakeholder. Further drivetrain development and optimization base on the so gained basis of decision-making.

References

[1] *Feinstaubalarm Stuttgart* [Online], Verfügbar unter: http://www.stuttgart.de/feinstaubalarm. [Zugegriffen: 17-Jan-2017].

[2] A. Albers, U. Reichert, S. Ott, und A. Radimersky, *Software supported development of a Battery Electric Vehicle powertrain considering the efficiency*, 16th International VDI Congress – Drivetrain for Vehicles 2016, Friedrichshafen, 2016.

[3] L. Berg, M. Schiefer, K. Bause, T. Fischer, und F. Hildenbrand, „*Innovationscluster REM 2030: Innovative Ansätze und Lösungen für den urbanen Verkehr*“, 2014.

[4] E. de la Chaux, Co-Betreuer: K. Bause, Betreuer: A. Albers, „*Quantitative Bewertung und Auswahl von Topologien für Elektrofahrzeuge auf Basis von Antriebsstrangsimulationen*“, Masterthesis IPEK-Institut für Produktentwicklung, 2016.

[5] C. Brünglinghaus, *Fahrzeugkonzepte: Conversion versus Purpose Design*, *springerprofessional.de*, 12-Nov-2012. [Online]. Verfügbar unter: https://www.springerprofessional.de/fahrzeugtechnik/elektrofahrzeuge/fahrzeugkonzepte-conversion-versus-purpose-design/6561908. [Zugegriffen: 17-Jan-2017].

[6] A. Albers, N. Bursac, S. Rapp, *PGE – Product Generation Engineering – Case Study of the Dual mass flywheel*, International Design Conference – DESIGN 2016, 2016, S. 791–800.

[7] R. Kasper, R. Leidhold, A. Lindemann, und M. Schünemann, *Elektrische Antriebsmaschinen* in Die Elektrifizierung des Antriebsstrangs, H. Tschöke, Hrsg. Springer Fachmedien Wiesbaden, 2015, S. 19–49.

[8] R. Heim, H. Hanselka, und C. El Dsoki, *Potenzial von Radnabenantrieben für Elektrostraßenfahrzeuge*, ATZ - Automobiltechnische Zeitschrift., Nr. 10/2012, S. 752–758, 2012.

[9] T. Grünweg, „*Rekordfahrt mit dem Elektro-Audi: Der Eintags-Sieger - SPIEGEL ONLINE - Auto*“, *SPIEGEL ONLINE*. [Online]. Verfügbar unter: http://www.spiegel.de/auto/fahrkultur/r8-e-tron-rekordfahrt-auf-dem-nuerburgring-a-841682.html. [Zugegriffen: 22-Juni-2017].

[10] K. Stahl und M. Sedlmeier, *Der Speed2E-Hochdrehzahl-Antriebsstrang*, E-MOTIVE Expertenforum, 2016.

[11] U. Reichert, T. Epskamp, S. Ott, und A. Radimersky, „*High speed electric drive with a three-speed gearbox*“, CTI Mag – The Automotive TH, HEV & EV Drives Magazine, 2016.

[12] F. Horch, T. Heiduczek, M. Brüll, R. Graaf, T. Krone, und M. Rauschenbach, *Rekuperation 2.0 – Können Radnabenantriebe mechanische Bremsen an der Hinterachse ersetzen?,* E-MOTIVE Expertenforum, Schweinfurt, 2016.

[13] M. Eghtessad, *Optimale Antriebsstrangkonfigurationen für Elektrofahrzeuge*, Institut für Fahrzeugtechnik an der TU Braunschweig, Braunschweig, 2014.

[14] S. Fuchs und M. Lienkamp, *Parametrische Gewichts- und Effizienzmodellierung für neue Fahrzeugkonzepte*, ATZ - Automobiltechnische Zeitschrift, Bd. 115, Nr. 3, S. 232–239, März 2013.

[15] E. Wiedemann, J. Meurle, und M. Lienkamp, *Optimization of Electric Vehicle Concepts Based on Customer-Relevant Characteristics*“, 2012.

[16] K. Kuchenbuch, T. Vietor, und J. Stieg, *Optimierungsalgorithmen für den Entwurf von Elektrofahrzeugen*, ATZ – Automobiltechnische Zeitschrift, Bd. 113, Nr. 7–8, S. 548–551, Juli 2011.

[17] K. Kuhlmann, D. Schaub, M. Schünemann, und C. Haugwitz, *Methodische Auswahl des Antriebsstrangs hinsichtlich Motoren und Getriebe für ein Elektrofahrzeug*, 11. Magdeburger Maschinenbau - Tage, Magdeburg, 2013.

[18] K. Bause, U. Reichert, S. Ott, und A. Albers, *Effects of driving functions' reorganization on subsystems in electric drive systems*, 17. Internationales Stuttgarter Symposium, Springer Vieweg, Wiesbaden, 2017, S. 607–621.

[19] A. Albers, K. Bause, M. Behrendt, und R. Puls, *Efficient, function-integrating shifting components for EV*, Internationales CTI Symposium - Fahrzeuggetriebe, HEV- und EV-Antriebe, Berlin, 2015.

[20] A. Albers, K. Bause, M. Behrendt, und S. Ott, *Einsatz von Simulationswerkzeugen im Entwicklungsprozess elektrifizierter Antriebssysteme*, FVA SIMPEP 2014 – 4. Kongress zu Einsatz und Validierung von Simulationsmethoden für die Antriebstechnik, Koblenz, 2014, Bd. II, S. 103–115.

[21] *Worldwide harmonized Light vehicles Test Procedure (WLTP) - Transport - Vehicle Regulations - UNECE Wiki* [Online]. Verfügbar unter: https://wiki.unece.org/pages/viewpage.action?pageId=2523179. [Zugegriffen: 25-Juni-2017].

[22] Rat der Europäischen Gemeinschaft, *Richtlinie 70/220/EWG des Rates vom 20. März 1970 zur Angleichung der Rechtsvorschriften der Mitgliedstaaten über Maßnahmen gegen die Verunreinigung der Luft durch Emissionen von Kraftfahrzeugen (70/220/EWG)*. 1972.

[23] Normenausschuss Maschinenbau (NAM), „*DIN 3990: Tragfähigkeitsberechung von Stirnrädern*“. 1987.

[24] Deutsches Institut für Normung, *Tragfähigkeitsberechnung von Wellen und Achsen*. 2012, S. 25.

[25] B. Bopp, Co-Betreuer: U. Reichert, Betreuer: A. Albers, *Modellierung von Wälzlagerverlusten mit MATLAB Simulink*, IPEK-Institut für Produktentwicklung, 2017.

[26] A. Albers, K. Bause, S. Klingler, R. Puls, und M. Behrendt, *Schaltbare Getriebe für Elektrofahrzeuge am Beispiel urbaner Nutzungsszenarien*, Urbane Mobilität der Zukunft: Symposium des Innovationsclusters REM 2030 - Regional Eco Mobility 2030 am 17./18. Juni 2015 in Karlsruhe, Karlsruhe, 2015, S. 53–60.

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