Potentials to reduce the Energy Consumption of Electric Vehicles in Urban Traffic

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Abstract

By means of a parameter study using a detailed backwards facing model of the longitudinal vehicle dynamics, the design of the transmission ratio in battery electric vehicles (BEV) is analyzed for different driving cycles and it is shown that the electric consumption in urban operation can be significantly reduced by up-speeding the electric machine (EM) using a high 1st transmission ratio. But this potential currently remains unused in fixed-speed BEV due to various additional driving requirements of extra-urban driving with higher vehicle speeds. For this reason, multi-speed BEV are further investigated as a solution to the conflicting design objectives. An additional parameter study for multi-speed BEV with two transmission ratios shows further potentials for the reduction of electric consumption both in urban and extra-urban driving scenarios. Furthermore, the more complex "Two-Drive-Transmission" (TDT) concept is investigated as a multi-speed BEV powertrain with two downsized EMs instead of one high-power EM and it is compared with the other BEV variants using a comparative optimization approach. The TDT uses low-cost and energetically efficient shifting devices based on the technology of an automated manual transmission with simple dog clutches without friction surfaces, allowing shifting without interruption of traction force. Dynamic programming is applied as operational strategy for all simulations considering shifting losses to achieve a benchmarking of the potentials of fixed-speed and multi-speed BEV.

1. Introduction and Motivation

Battery electric vehicles are entering the market with increasing momentum to meet legislative requirements and the demand of society for emission-free and climate-friendly mobility. BEV are particularly suitable for operation in urban traffic, especially with regard to clean air and noise reduction in cities. Furthermore, the frequent braking and acceleration situations in urban areas can be performed particularly efficient by electric (and also electrified) powertrain concepts. Current BEV are usually driven by a central drive unit consisting of a single electric machine (EM) with a fixed-speed transmission, examples are the VW ID3, Renault Zoe or Hyundai Kona. Other available models also use a fixed transmission ratio but two EM, one EM for each axle.

The design of the transmission ratio in fixed-speed BEV must take the overall driving requirements into account, which are essentially composed of top speeds on the highway, the required maximum launch-torque and the electric consumption in various driving situations. In general, the dimensioning of the EM and the transmission ratio are subject to a conflict of objectives resulting from these various design requirements and as a result, the energy-saving potential in urban traffic cannot be fully exploited. As will be shown within this contribution, the electric consumption in urban operation can be reduced significantly by increasing the speed of the EM by means of a high transmission ratio. This “up-speeding” of the EM in electric concepts for urban traffic in order to achieve increased efficiency stands in contrast to the well-known “down-speeding” of the internal combustion engine (ICE) in conventional powertrains. Unfortunately, despite the significant potential of the up-speeding of the EM, this solution is insufficient in fixed-speed transmissions for typical driving requirements of real passenger cars and is therefore currently not exploited.

To solve this problem of conflicting development goals, two-speed BEV can be used. In previous research it has been shown that two-speed BEV transmissions allow for a reduction of electric consumption [1–8] as well as for a potential downsizing of the EM [8–10]. Various concepts for multi-speed BEV with one EM have been presented by academia and industry (overviews are given in [11] and [12]). Such concepts allow for a fully capable vehicle with high efficiency in urban operation enabled by a high 1st transmission ratio and the fulfilment of all further driving requirements. In order to enable shifting without interruption of traction force, a single-EM concept with two transmission ratios is equipped with an inverse-automated transmission (I-AMT) or a dual-clutch transmission (DCT). The friction clutch(es) and its periphery are cost-intensive and lead to relatively high losses compared to a simple dog-clutch and the use of active synchronization to engage the gears, which, on the other hand, leads to an interruption of traction force during gear-shifts if used in a concept with a single EM.

To solve this problem and fully exploit the potential of multi-speed BEV concepts, the "Two-Drive Transmission" (TDT) has been developed at IMS (Institute for Mechatronic Systems in Mechanical Engineering) and was first introduced in [13]. The TDT is a multi-speed BEV powertrain with two downsized EMs instead of one high-power EM. The TDT uses active synchronization of the EMs during shifting and simple, low-cost and energy-efficient dog-clutches without friction surfaces. Seamless shifting without reduction of traction force is possible for most driving situations by using the second EM during the gearchange of the first sub-transmission. Additionally, the TDT profits from the benefit of using just one of the downsized EMs with high-utilization in part load driving scenarios which in general results in a higher efficiency compared to the use of a single high-power EM in part load. Based on the generic topology of the TDT, multiple purely electric and also hybrid vehicles have been derived and investigated in public funded projects (Speed2E, Speed4E [14], DE-REX [10] & DE4LORA [15]). Besides the TDT-concept, other multi-speed BEV-concepts with two EM are under research (like [16]) or even already entering the market.

The purpose of this contribution is to further investigate the energy-saving potentials of BEV-concepts with a focus on urban driving. As will be shown, the possible up-speeding of the EM using a high 1st transmission ratio enables significant reduction of electric consumption in urban driving scenarios, but the potential remains unused due to the various additional driving requirements. Multi-speed BEV on the other hand allow for a fully capable vehicle with highest efficiency in urban operation and fulfilment of extra-urban driving requirements.

2. Vehicle model and operating strategy

To enable the extensive parameter studies in the design of BEV-powertrains that are necessary for this study, the DrOPs environment ("Driving-Optimal Powertrains") is used, which has been developed at IMS and been used for various publications [9, 17–19]. Details concerning the models used in this work are given in the following.

After an introduction of three BEV-concepts considered in this work, the implementation of the vehicle model, the characterization of the powertrain components and corresponding powerloss-models as well as the applied operating strategy are presented. Finally, exemplary simulation results are discussed to show the behavior of the overall model.

Investigated BEV-concepts

Within this contribution, three different BEV-powertrains are investigated that are illustrated in Fig. 1. The BEV-1 represents the typical architecture with a single EM and a fixed transmission ratio. Advantages of this architecture are the simplicity and available traction force under all operating conditions. The BEV-2 is used to analyze the potentials of two-speed BEV concepts. For this purpose, the BEV-2 is considered with active synchronization via the EM and a simple dog-clutch to engage the gears (AMT-concept). Note that this architecture leads to interruptions of traction force during shifting. Normally, a two-speed BEV with a single EM requires a transmission system including a friction clutch (like I-AMT or DCT) to prevent interruptions of traction force during shifting for reasons of comfort. But such transmissions systems generally result in higher costs and a reduced overall efficiency in comparison to a simple dog-clutch (AMT). The reasons for this are the friction losses in the multidisc clutch, the possible drag torque of a wet dual-clutch in open position and the ongoing delivery of the necessary clutch pressure for torque-transfer, that is required in a normally-open clutch. For the purpose of the investigation of the potential energy savings, the simple BEV-2 (AMT) architecture from Fig. 1 is chosen since it enables a high efficiency, even if comfort requirements are not fulfilled.

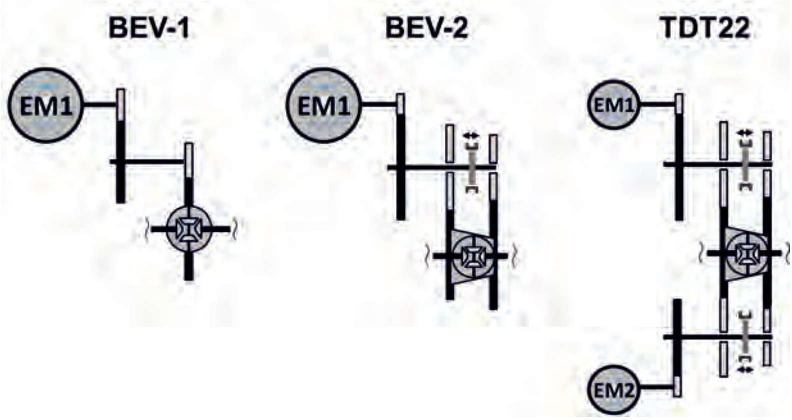


Fig. 1: Architectures of the three investigated BEV-concepts.

Furthermore, a specific realization of the “Two-Drive-Transmission” is investigated, which is referred to as TDT22 within this work. The TDT22 uses two downsized EMs which are connected to the differential via two two-speed sub-transmissions. The TDT22 has the already discussed benefits of active synchronization and a simple dog-clutch. At the same time, it enables shifting between the gears without reduction of traction force for most driving situations by using the second EM. Only for shifting during very high-power demands, that exceed the power of a single EM, the resulting traction force is partly reduced.

Implementation of the vehicle model

A backwards facing implementation of the longitudinal dynamics of the vehicle is used, which is based on the driving resistances Equation, see (2.1), while lateral and vertical dynamics are neglected due to a minor influence on the electric consumption. This model type has been shown to be best suited for larger parameter studies and comparisons on system level since it enables to strictly follow a given driving cycle for each vehicle-parametrization, avoids the use of an potentially sub-optimal driver model and offers significant benefits concerning the computational effort compared to forward-facing models, which in contrast are better suited for detailed studies of certain components [17].

$$T_{\mathrm{Wheel}} = r_{\mathrm{dyn}} \left(m_{\mathrm{veh}}\, \dot{v} + f_{\mathrm{R}} m_{\mathrm{veh}}\, g \cos\alpha + \frac{1}{2} \rho c_{\mathrm{w}} A v^2 + m_{\mathrm{veh}}\, g \sin\alpha \right) \tag{2.1}$$

The parameters used for the driving resistances equation within this work are listed in Tab. 1 and correspond to a typical compact-class vehicle.

Tab. 1: Vehicle parameters used for the driving resistances equation.

Parameter	**symbol**	**value**	**unit**
Vehicle speed	v	time-dependent	m/s
Road slope	α	0	rad
Vehicle mass	m_{veh}	variable	kg
Rotational inertia of the EM	Θ_{EM}	variable	kgm²
Dyn. wheel radius	r_{dyn}	0.3	m
Air density	ρ	1.2	kg/m³
Projected surface	A	2.2	m²
Air resistance coefficient	c_{w}	0.3	-
Roll resistance coefficient	f_{R}	0.008	-
Gravity constant	g	9.81	m/s²

The resulting torque of the EM T_{EM} is calculated dependent on the direction of transmitted power under consideration of the transmission-efficiency η_{trans}, the transmission ratio i, the rotational inertia of the EM Θ_{EM} and the rotational acceleration of the EM as seen in Equation (2.2) for the example of a concept with a single EM. Note that for the term containing the rotational inertia of the EM, no power is transmitted through the gearbox, hence the efficiency of the transmission must not be considered for this term.

$$T_{\mathrm{EM}} = \begin{cases} \dfrac{T_{\mathrm{Wheel}}}{i_{\mathrm{EM2Wheel}}\,\eta_{\mathrm{trans}}} + \Theta_{\mathrm{EM}}\,i\,\dot{\omega}_{\mathrm{Wheel}} & \text{for } T_{\mathrm{Wheel}} > 0 \\ \dfrac{T_{\mathrm{Wheel}}\,\eta_{\mathrm{trans}}}{i_{\mathrm{EM2Wheel}}} + \Theta_{\mathrm{EM}}\,i\,\dot{\omega}_{\mathrm{Wheel}} & \text{for } T_{\mathrm{Wheel}} < 0 \end{cases} \tag{2.2}$$

In addition to the traction requirements of the driving cycles, there are other design requirements that are relevant for the actual use of a vehicle. The design requirements take special situations into account, such as driving onto a curb and desired top-speeds. In this work, a gradeability of 60 % is demanded resulting in a required launch-torque dependent on the specific vehicle mass. The demanded top-speeds will be explicitly noted for the presented results. Each powertrain parameterization of a concept is checked within the simulation model for the fulfillment of these design requirements. If a requirement is not met, the parameterization is invalid.

Battery and secondary consumers

A constant efficiency of the battery of 97.5 % is assumed that applies for output and recuperation of power during driving. Furthermore, an external charging efficiency of 85 % is considered in the presented electric consumption values. Battery degradation is not considered, the battery mass is calculated with a specific energy density on system level of 160°Wh/kg and the useable portion of the battery capacity (net capacity) is set to 95 %. Secondary consumers (like HVAC) are neglected since they do not differ between the three considered concepts and are not relevant for the scope of this work which mainly studies the design of the transmission ratios.

Modelling the EM and the shifting losses

The combined efficiency of the used permanent-magnetic EM and the associated power electronics (PE) is modelled with a measured stationary efficiency map, taken from [20]. A torque scaling approach (as done in [21, p. 103]) is applied to generate EMs with different power-ratings from the given efficiency map. The basis for this scaling method is the assumption of a constant diameter and variable length of the EM, whereby the speed range is not affected and a constant efficiency characteristic is assumed [22]. The resulting combined efficiency maps of the EM and PE and are shown for 60 kW in Fig. 2 and 140 kW in Fig. 5.

For the multi-speed BEV concepts, shifting losses are considered. These consist of the energy demand of the shifting actuator, that engages or disengages the dog-clutch and the energy demand for active synchronization which is required to adapt the speed of the EM to the gear to be engaged. Further shifting losses associated with friction clutches are not relevant in this work since only concepts based on AMT-technology are considered. To enable shifting without interruption of traction force in the TDT22-concept, a short handover of traction force to the second EM is required during certain shifting events which would lead to an additional energy demand. These losses are neglected within this work, since they are only relevant for certain shifting events, but should be incorporated for refined future research.

The demand of the shifting actuators is modelled independently of the current driving situation with a simplified constant energy demand of 30 J per shifting process (magnitude estimated based on [1, 23, 24]). The energy demand for active synchronization of the EM is modelled according to Equation (2.4) by calculating the difference in kinetic energy using the rotational speed and a simplified constant efficiency of $\eta_{\mathrm{activesync}}$ =85% for accelerating and decelerating (under partly recuperation of energy) of the EM based on own estimations and [25]. In case of the TDT22 the energy demand for active synchronization is calculated in the same way considering both EM. In analogy to the assumptions of the torque scaling approach described earlier in this section, the rotational inertia of the EM is estimated with Equation (2.5), exemplarily leading to a rotational inertia of 0.105 kgm² for an EM with 140 kW.

$$E_{\text{shift\_actuator}} = 30\ \text{J} \tag{2.3}$$

$$E_{\text{activesync}} = \frac{1}{2}\Theta_{\text{EM}}(\omega_2^2 - \omega_1^2)\begin{cases} {}^{1}/\eta_{\text{activesync}} & \text{for } \omega_2 > \omega_1 \\ \eta_{\text{activesync}} & \text{for } \omega_2 < \omega_1 \end{cases} \tag{2.4}$$

$$\Theta_{\text{EM}} = 8 \cdot\ 10^{-4} \cdot\ P_{\text{EM}} - 7.4 \cdot 10^{-3} \tag{2.5}$$

In case of the TDT22, the whole driving demand can often be fulfilled by using a single EM only. The unused second EM is either towed or put to neutral position if possible and beneficial. If an EM is towed, speed dependent towing losses are taken into account, since permanent-magnetic EMs are considered. The towing losses are modeled with a quadratic function of machine speed according to Equation (2.6) based on measurement data of different PSMs, exemplarily leading to tow-losses of 1643 W for an EM with 140 kW at 10000 rpm.

$$P_{\text{tow-loss}} = \left(5.23 \cdot\ 10^{-7} \cdot \frac{n_{\text{EM}}}{\text{rpm}} + 6.45 \cdot 10^{-11} \cdot (\frac{n_{\text{EM}}}{\text{rpm}})^2\right)\ P_{\text{EM}} \tag{2.6}$$

Efficiency of the gearbox

Since two gear-stages are considered for each concept, a constant efficiency of 98 % is used for all three concepts. Additionally, constant transmission losses are considered, that are higher for the multi-speed concepts, due to the increased number of shafts, bearings and loose gearwheels. The assumed values are summarized in Tab. 2. The magnitude of the values is estimated based on the results of [21].

Tab. 2: Assumed loss-characteristics of the transmission of the three BEV concepts. Shifting losses are considered separately and not part of these values.

	BEV-1	BEV-2	TDT22
Efficiency gearbox η_{EM2W}	98 %	98 %	98 %
Const. losses gearbox	20 W	30 W	40 W

Operating Strategy

In order to identify the maximum potential of each powertrain parametrization, a global optimal operation strategy is best suited. For this purpose, dynamic programming is applied to identify the global optimal operational behavior for a minimal electric consumption of the vehicles for each driving cycle. Starting at the end of the cycle, the optimal gear choice and torque distribution between the EMs (if two are available) are calculated and saved for each gear. By subsequently solving the decision in the current time-step under knowledge of the optimal operation of the remaining cycle the operation behavior for the whole driving cycle is determined. The algorithm automatically determines whether the additional energy demand of a shifting process is over-compensated by an increased efficiency or not. Another example would be the question if an unused EM (in a two-EM concept) should be turned to neutral position or towed in an engaged gear position despite the corresponding losses for a short time.

Exemplary Simulation results

In Fig. 2 the exemplary simulation results of a TDT22 parametrization in the WLTC are displayed. EM1 and EM2 are color-coded identically between the three subplots (EM1 = purple & EM2 = yellow). The time-dependent results, displayed in subfigure a) show that EM2 is typically used for vehicle launch from stand still using the 1st gear with a high transmission ratio (examples are at 140 s or 600 s in the WLTC) and for accelerations towards higher speeds using the 2nd gear of EM2 (examples are at ~1150 s or ~1500 s in the WLTC). EM1 on the other hand is typically used for cruising at high speeds with the long second gear of EM1. A boosting with both EM is possible but not beneficial in this example and therefore not used. Furthermore, the torques of both EM, the gear choices in the sub-transmissions and the state of charge (SOC) are displayed over time. The last subplot shows the energy demand during shifting processes and for towing of the EMs.

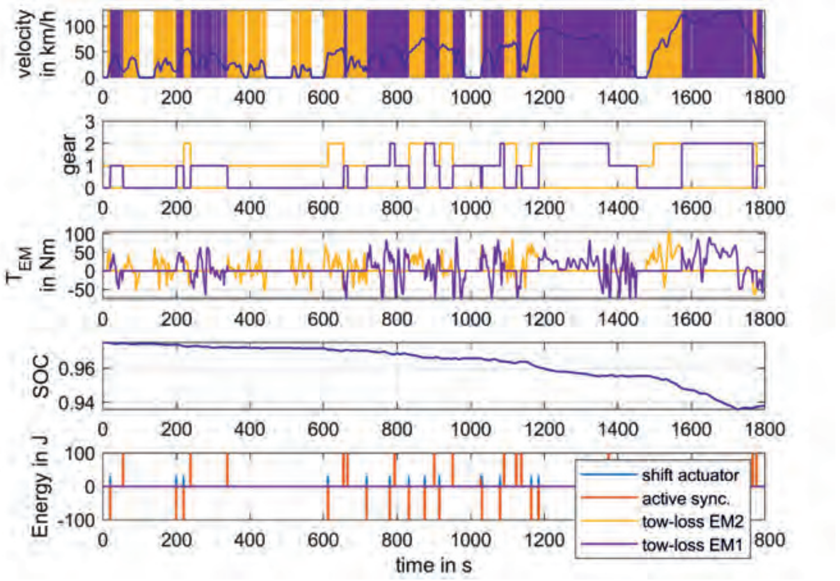
In total, 31 gear-shifts are performed in this simulation as a result of the global optimal operation which has been determined via dynamic programming. The number of gear-shifts is greatly reduced compared to the simple choice of the most efficient gear in each time-step.

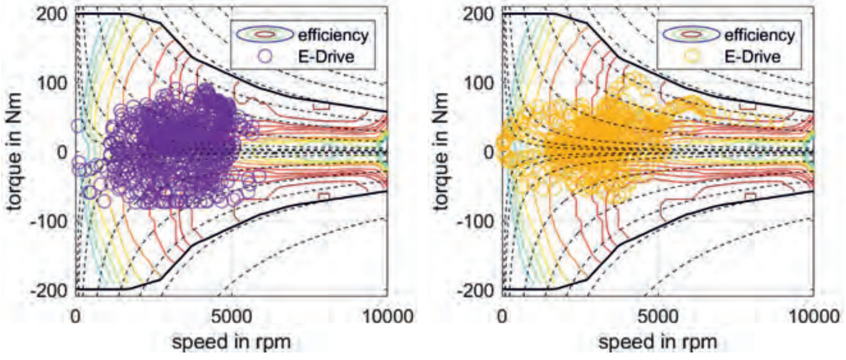
The maximum power demand of the WLTC can be delivered by each of the EMs during the whole cycle. Therefore, no interruption or reduction of traction force would arise during the shifting processes.

Due to the significant towing losses, the non-driving EM is always put to neutral position by the operating strategy instead of being towed, therefore no towing losses occur. With smaller towing losses or different driving cycles it can occur that an EM is towed instead of being put to neutral position if its use is only shortly interrupted and two shifting processes would lead to higher overall losses.

The resulting operating points in the combined efficiency maps of EM1 & EM2 (including PE) are displayed in subfigures b) & c). In this example, the simulation results were given for an arbitrary parametrization of the TDT22-concept. Within Section four of this contribution, the results for various powertrain parametrizations will be presented. The detailed results can’t be shown for each simulation, but the modelling approach remains the same as described within this section.

a) Time-dependant operating behavior of an examplary TDT22-parametrization





b) Operating points within the combined efficiency map of EM1 & PE. Transmission ratios i_{EM1}: 10.5 & 4.3

c) Operating points within the combined efficiency map of EM2 & PE. Transmission ratios i_{EM1}: 14.6 & 6.1

Fig. 2: Exemplary simulation results for a TDT22-parametrization on the WLTC. The max power of EM1 and EM2 are ca. 60 kW and the vehicle mass is 1766 kg in this example.

3. Driving cycles for evaluation

For this study the Artemis driving cycles (Urban, Rural and Highway) [26] and the WLTC [27], shown in Fig. 3, are used. These cycles permit a good comprehensibility, since they are widely used and well-known in driving cycle simulations. The Artemis Urban cycle is of main interest in this study as it is used to represent typical urban driving conditions.

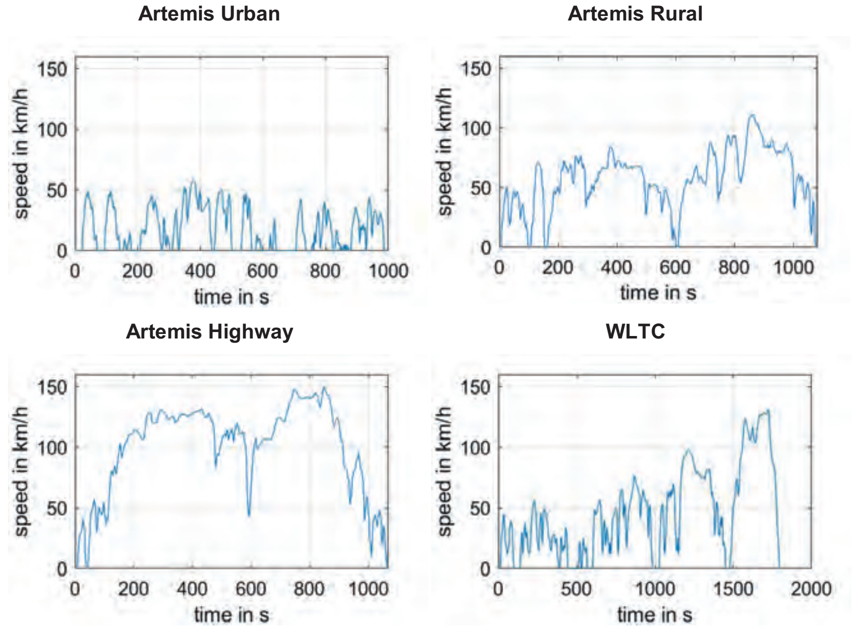


Fig. 3: Driving cycles (Artemis driving cycles and the WLTC) used for the evaluation of powertrain parametrizations in this work.

4. Results: Potentials for reduced energy demand in urban driving

In order to analyze the potentials for a reduction of the electric consumption of BEV in urban traffic following steps are taken: First, the design conflict of the transmission ratio in fixed-speed BEV is shown in Section 4.1. Second, the two-speed BEV (BEV-2) is analyzed in Section 4.2, solving the design conflict and allowing for high efficiency in urban and extra-urban driving conditions.

For these first two parameter-studies, fixed parameters concerning EM-power (140 kW) and battery capacity (80 kWh gross) are used that correspond to a vehicle with higher range, while the transmission ratios are varied. Note that the comparison between the different BEV-concepts based on such fixed parametrizations underestimates the energy saving potential and is questionable, since the reduction of the energy demand for multi-speed-concepts could be used to reduce the battery capacity and further, the multi-speed transmission could possibly enable a downsizing of the EM. But still, these fixed parameters allow for the best comprehensibility of the main results.

Finally, in the third step of the evaluation, the Two-Drive-Transmission concept (TDT22) is included and a proper comparison based on a dedicated optimization of each concept is performed within Section 4.3. For a given vehicle usage profile, the optimal parametrization for each of the three BEV-concepts is identified to achieve a minimal electric consumption, which creates a uniform evaluation basis and enables a fair comparison between the concepts.

4.1. Design conflict in fixed-speed BEV

In this section the fixed-speed BEV-concept (BEV-1) is considered. Fig. 4 a) shows the electric consumption on the different driving cycles in dependency of the chosen transmission ratio, while all other parameters are kept constant. The required launch torque leads to a minimum transmission ratio of 6, given the maximum torque of the EM, which therefore is the lower valid limit. Nevertheless, the results for lower transmission ratios are displayed as well. The maximum speed within the cycles determines (given the max speed of the EM and the wheel radius) the upper limit of possible values for the transmission ratio, for example 7.5 for 150 km/h within the Artemis Highway cycle. As the graph shows the range of possible values for the transmission ratio is further limited when higher top-speeds are required. If a top speed of 180 km/h is desired the possible range of values for the transmission ratio is located between 6 and 6.3, drastically limiting the design range.

The results show that a higher transmission ratio and a corresponding up-speeding of the EM lead to significant advantages for urban driving, while at the same time, the consumption on extra-urban and highway driving is getting worse. This is especially clear in the percentage-changes (given in subfigure b), normalized to the corresponding consumption of the parametrization with the lowest considered transmission ratio. The best consumption for the urban cycle is achieved for i = 9.67 in this analysis leading to a consumption reduction of ~9 % compared to the transmission ratio of i = 4. Despite the significant potential of up-speeding the EM, this solution is insufficient for typical requirements of real passenger cars, since the maximum speed would be limited to only ~117 km/h.

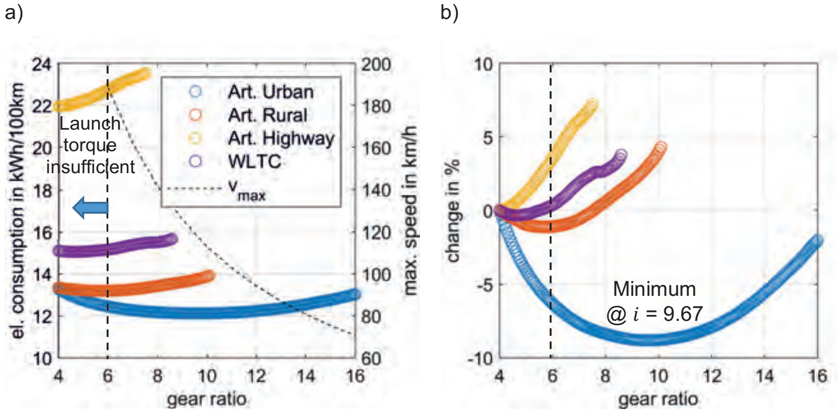
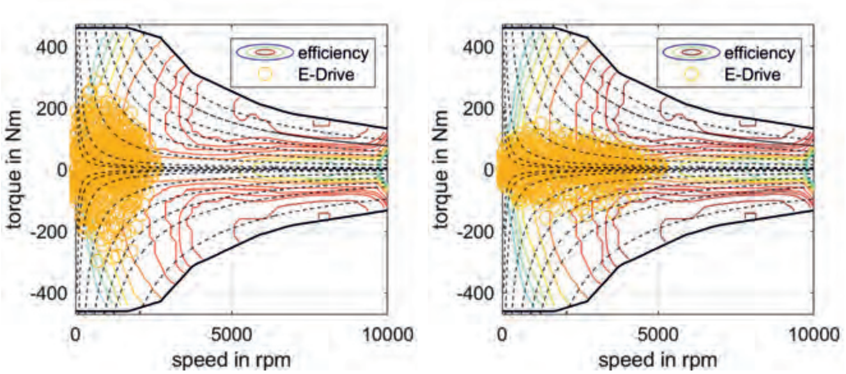


Fig. 4: Electric consumption of the BEV-1 depending on the transmission ratio in different driving cycles. Subfigure a) shows the absolute values while subfigure b) shows the percentual changes. For each driving cycle, there is a maximum possible transmission ratio due to the top-speed in this cycle. For the assumptions in this work, the transmission ratio must be greater than 6 to satisfy the launch-torque requirement. The evaluation is based on a parametrization with a 140 kW EM and 80 kWh battery leading to a total mass of 1746 kg.

The reason for the reduction of energy demand lies in the operating points within the combined efficiency map of the EM and PE, which are shown for two transmission ratios in Fig. 5. Especially the efficiency of the inverter increases with higher machine speeds and equal power due to the reduced ohmic losses. Of course, the identified potentials for a reduction of electric consumption strongly depend on the specific efficiency map of the EM and PE that are considered. Therefore, this study should be repeated with various different characteristics of EM and PE in the future. While the detailed results may vary it is assumed that the overall trend remains the same.



a) BEV with 140 kW and i=5

b) BEV with 140 kW and i=10

Fig. 5: Operating points of a BEV-1 within the efficiency map of the EM (140 kW) in the Artemis Urban cycle for two different transmission ratios.

Furthermore, it is important to note that the reduced consumption, which results from a higher transmission ratio, would enable a reduction of installed battery capacity while keeping the total range. The reduced vehicle mass would even further reduce the electric consumption and also enable a downsizing of the EM. These potentials were not considered in this simple parameter study leading to a conservative estimation of potential savings.

As mentioned before, the efficiency potentials are not leveraged due to the typical requirements of real passenger cars. In order to meet all the requirements of a fully capable vehicle with highest efficiency in urban operation and fulfillment of extra-urban driving with higher vehicle speeds, multi-speed BEV are further investigated.

4.2. Potentials of two-speed BEV

The BEV-2 concept, as presented in Section 2 is analyzed to investigate the potentials of two-speed BEV with a single EM. As before the electric consumption is evaluated in dependency of the chosen transmission ratios. Since two ratios can be determined, a two-dimensional space is evaluated in contrast to the BEV-1. The results are shown in Fig. 6. Each dot represents a parametrization of a BEV-2 that was evaluated while the contour lines were interpolated to better visualize the determined trends. The best parametrization for each cycle is marked with a larger dot in magenta color.

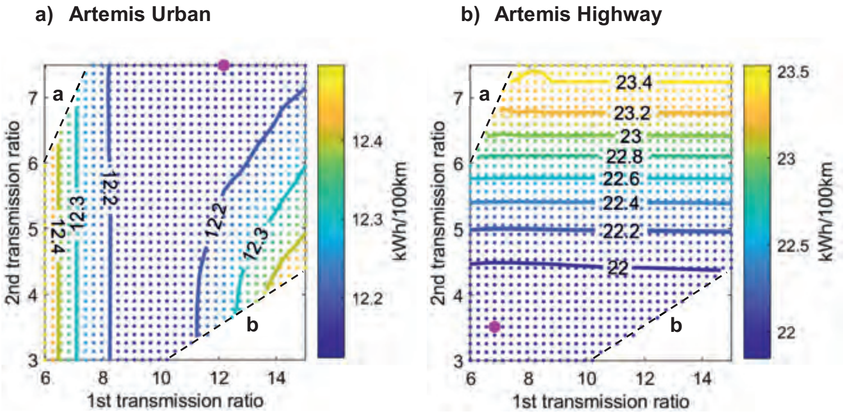


Fig. 6: Electric consumption of the BEV-2 depending on the transmission ratios in the Artemis Urban and Highway cycle. The vehicle is parametrized with a 140 kW EM and 80 kWh battery.

There are several boundaries for the possible design space. Again, the 1st transmission ratio must be higher than 6 to achieve the demanded launch torque with the given EM. The upper limit for the the 1st transmission ratio (15 in this study) was chosen to limit the transmission ratio of each gear stage to reasonable values. The second transmission ratio must be smaller than 7.5 in order to achieve the required maximum speed in the Artemis Highway cycle while the lower end value is arbitrarily set to 3. The results show that lower transmission ratios are not beneficial. The design space boundary labelled as “a” in Fig. 6 represents the constraint that the 1st transmission ratio shall be higher than the 2nd while the boundary “b” results from the maximum spread between the gears to avoid a gap of deliverable traction power.

Fig. 6 a) shows the consumption on the Artemis Urban cycle. The consumption is mainly influenced by the 1st tranmission ratio while the 2nd gear has little impact. If the 2nd transmission ratio is relatively high, it offers benefits for the urban driving style but the benefit compared to a low 2nd transmission ratio is small. The results for the Artemis Highway cycle on the other hand show the contrary. The first transmission ratio has almost no impact on the results. They are mainly determined by the 2nd gear, which is primarily used in this cycle. For the Artemis Highway cycle a long (overdrive) gear leads to the best consumption values. These results support the prior findings from the analysis of the BEV-1. But as stated before, the two-speed BEV allows to meet all the requirements of a fully capable vehicle with high top speed and superb efficiency in urban and extra-urban operation by choosing a well-suited design of both transmission ratios.

A potential design could be derived by choosing a transmission ratio that offers highest efficiency for both urban and highway driving like $\boldsymbol{i}$ = [10/3.5]. The electric consumption of this parametrization is just 0.2 % higher in the Artemis Urban cycle and just 0.1 % higher in the Artemis Highway cycle than the corresponding two optimal parametrizations. At the same time, a high top-speed and launch-torque are realized.

A remaining problem of the BEV-2 concept are the interruptions of traction force that were discussed in Section 2, that deteriorate the driving comfort. A DCT or I-AMT concept could solve this problem but would negatively impact the efficiency compared to the AMT concept limiting the potential reduction of electric consumption. A more promising approach is the realization of a Two-Drive-Transmission, which is discussed in the following section.

4.3. Potential of the Two-Drive-Transmission

So far, it has been shown that significant potentials for the reduction of electric consumption in urban driving can be achieved by up-speeding the EM through the use of a higher transmission ratio. In order to still achieve a fully-useable vehicle, the two-speed BEV has shown to satisfy all requirements. But still, more sophisticated solutions can enable even higher efficiency and comfort as will be shown in this section.

The previous results were determined by using fixed parameters for EM-power and battery capacity, which does not allow a fair comparison between the different concepts. In order to achieve a scientifically proper comparison between the three concepts, an environment for the comparative optimization, based on [17], is used. By means of genetic optimization, the optimal parametrizations to achieve a minimal electric consumption are identified. Within the optimization process the battery capacity, the EM-power and the transmission ratios are optimized. Equivalent requirements for top-speed, total range and gradeability are defined for each of the three concepts, described in the following. Since identical requirements are placed and the optimal parametrization is identified for each BEV-concept, the resulting parametrizations are comparable in a strict sense.

Vehicle usage profile

A vehicle usage profile is defined for the optimization. Studies like [28] show that most of the mileage is typically driven on relatively short trips, while longer trips occur less frequent. For this reason, the three Artemis cycles will be evaluated and a weighted consumption c_{total} is calculated according to the following equation with a high weighting of urban driving efficiency.

$$c_{\text{total}} = 0.6 \cdot c_{\text{Art,Urban}} + 0.3 \cdot c_{\text{Art,Rural}} + 0.1 \cdot c_{\text{Art,Highway}} \tag{4.1}$$

Furthermore, a total range of 400 km is required on the Artemis Highway cycle, leading to a relatively high battery capacity. Additionally, a top-speed of 180km/h and multiple acceleration times (9.71 s from 0-100 km/h and 4.76 s from 0 to 60 km/h) as well as a gradeability of 60% are defined as driving requirements. Of course, the results of the concept comparison differ for different assumptions concerning the vehicle usage profile and within this study, just one (relevant) usage profile is exemplarily investigated.

Comparison of the three BEV concepts

The resulting optimal powertrain parametrizations for each of the three investigated BEV-concepts for this vehicle usage profile are given in Tab. 3: As can be seen, the required battery capacity for the multi-speed concepts is reduced compared to the BEV-1 because of the enhanced powertrain efficiency that is also shown in Fig. 7 a). Furthermore, the EM-power and transmission ratios, identified by the optimization process, are listed.

Tab. 3: Parametrizations of the three BEV-concepts resulting from the optimization of electric consumption towards the defined usage profile. The percentage changes in electric consumption of the BEV-2 and TDT22 concept are given compared to the BEV-1 concept.

Parameter	Unit	BEV-1	BEV-2	TDT22
Power of EM	kW	141.9	116.6	2x60.7
Battery capacity (gross)	kWh	81.4	77.6	76.8
Transmission ratios	-	5.9	9.5/3.9	14.6/10.5/6.1/4.3
Vehicle mass	kg	1754	1727	1766
El. consump. (Art. Urban)	kWh/100km	12.52	11.87 (-5.2%)	11.47 (-8.3%)
El. consump. (Art. Rural)		13.23	13.01 (-1.7%)	12.78 (-3.4%)
El. consump. (Art. Highway)		22.73	21.69 (-4.6%)	21.47 (-5.6%)
Weighted consumption		13.75	13.19 (-4.1%)	12.86 (-6.5%)

The TDT22 achieves the best electric consumption, despite the fact of being slightly heavier than the other two concepts (detailed information concerning the total mass is given in Fig. 7 b). The TDT22 achieves a significant reduction of electric consumption of 8.3% in the Urban cycle, 3.4% in the Rural cycle and 5. 6% in the Highway cycle compared to the BEV-1 and outperforms the BEV-2 concept in each of the cycles as well.

The main reasons for the good performance of the TDT22 are the various transmission ratios that allow the choice of a suiting operation point for different driving demands and the benefit of using just one of the downsized EMs with high-utilization in part load driving which in general results in a higher efficiency compared to the use of a single high-power EM in part load. Since part-load driving is the dominant operation condition in the driving cycles, this leads to a significant potential to reduce the electric consumption. Additionally, the TDT22 benefits from a high 1st and also relatively high 2nd transmission ratio in urban driving conditions.

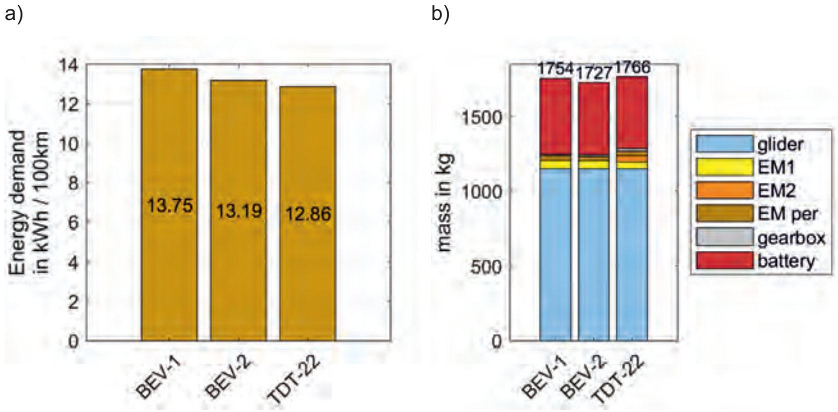


Fig. 7: Subfigure a) shows the weighted consumption of the three BEV concepts. Subfigure b) shows the total vehicle mass and the portions of the different components. Shown are of the glider, EM1 & EM2, the EM periphery containing the power electronics, the gearbox and the traction battery.

Furthermore, as stated before the TDT22 achieves smooth shifting without reduction of traction force (for most driving situations) which the considered BEV-2 concept does not. A BEV-2 with a DCT or I-AMT configuration on the other hand would lead to higher consumption values than the BEV-2 (AMT) considered here.

5. Conclusion

Within this contribution the potential energy-savings of BEV-concepts in urban driving have been analyzed by using a backwards facing implementation of the longitudinal vehicle dynamics and performing parameter studies for the transmission design and a comparative optimization of three different BEV concepts. Dynamic programming was applied as operational strategy for all simulations considering shifting losses to achieve a benchmarking of the potentials of fixed-speed and multi-speed BEV.

As shown, a potential up-speeding of the EM using a high 1st transmission ratio enables a significant reduction of the electric consumption in urban driving scenarios. But these potentials are not leveraged in fixed-speed BEV due to various additional driving requirements. Multi-speed BEV on the other hand allow for a fully capable vehicle with highest efficiency in urban operation and the fulfilment of top-speed requirements.

Additionally, a configuration of the "Two-Drive-Transmission" (TDT) concept was introduced and compared to a fixed-speed and two-speed BEV using comparative optimization. The TDT possesses two downsized EMs instead of one high-power EM and uses low-cost and energetically efficient shifting devices based on the technology of an automated manual transmission with simple dog clutches without friction surfaces enabling shifting without interruption of traction force in most driving situations. The TDT achieved a reduction of the electric consumption in urban driving conditions of 8.3 % compared to the fixed speed BEV and outperformed the two-speed BEV in all driving cycles as well.

In future studies, further characteristics of the electric machine and power electronics should be analyzed and the shifting losses should be modelled more accurately to further validate the findings of this study.

Gratification

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