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Article

Effect of Different Types of Electric Drive Units on the Energy Consumption of Heavy Commercial Electric Vehicles

Metin Yildirim * and Serpil Kurt

Department of Mechanical Engineering, Faculty of Mechanical Engineering, Istanbul Technical University, Beyoglu, 34437 Istanbul, Turkey; kurtserp@itu.edu.tr
* Correspondence: metinyildirim@itu.edu.tr

Abstract: The increasing demand for electric vehicles (EVs) in the transportation industry, especially for efficient battery–electric trucks, has led to an increase in studies on the efficiency or energy consumption of commercial vehicles. In this paper, average energy consumption was investigated in terms of the effect of different transmission types in vehicle models considering three routes, and the effect of the number of gears on energy consumption for each transmission type was analyzed. Target performance specifications and packaging were also evaluated. The optimal design could be identified in terms of transmission type, the number of gears, vehicle performance, and packaging. Vehicle models with two types of electric drive units (EDUs) were developed in a MATLAB/Simulink environment. Driving cycles were obtained from collected road load data of municipal, intercity, and regional areas operated by heavy-duty trucks using nCode software. The battery model was developed based on the electric circuit network (ECN) modeling technique. The main research purpose of this study was to investigate the effect of multispeed and multimodal EDUs and the number of gears on the energy consumption of heavy commercial electric vehicles from actual road conditions in Turkey. The three-speed EDU was the optimal design, providing 7.83, 7.26, and 7.21% less energy consumption on the three routes, compared with three-mode electric drive units. Consequently, the energy consumption difference was 7.5% for combined real road conditions.

Keywords: battery–electric truck; energy consumption; transmission; electric drive unit

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1. Introduction

Vehicle electrification is gaining traction in an effort to reduce greenhouse emissions and mitigate climate change. A total of 27% of all energy consumed and 33% of greenhouse gas emissions to the atmosphere are caused by vehicles on highways [1]. One solution to reduce harmful gas levels in cities is to reduce the number of vehicles with internal combustion engines and replace them with electric vehicles (EVs). EVs are the vehicles of the future, as they are highly efficient, produce no local pollution, and are silent [2]. Moreover, because it is environmentally friendly and contributes to the economy, the use of electrical energy for motion has increased interest in electric vehicles [3]. In one study, the authors compared the influence of CVT and MT transmissions [4]. Many energy consumption studies have been conducted that developed vehicle models for different transmission types, such as manual gearbox and continuously variable transmission (CVT), and for electric and hybrid passenger cars [4–6]. One study compared different powertrain topologies of passenger cars in terms of energy consumption, cost, and acceleration [7]. Energy loss is generally determined for BEVs with standard drive cycles such as the New European Driving Cycle (NEDC) [8]. Study results indicate that most of these studies were conducted to evaluate vehicle energy consumption, especially by passenger cars, using standard drive cycles. In the literature, actual road conditions were not considered to determine the energy consumption of vehicles. However, some studies were conducted to compare internal combustion engine (ICE) vehicles and battery–electric vehicles (BEVs) and evaluate the contribution of EVs in terms of emissions [9]. Comparable studies were published that estimated energy consumption with an energy management system for BEVs and plug-in-hybrid vehicles (PHEVs) as passenger cars [10]. Although vehicle energy consumption has been investigated in the literature, the effect of transmission types has not been considered when evaluating the energy consumption of passenger cars and heavy-duty trucks (HDTs). Only the effect of changing transmission parameters and types on energy consumption was considered. DCT and CVT transmissions in BEVs were compared in terms of energy consumption and manufacturing cost [11]. Simulation results show that CVT consumes 5–20% less energy than multispeed transmissions depending on the drive cycle [12]. However, two-speed and AMT transmissions for buses were tested to examine the efficiency and performance of BEVs [13,14]. Research was also conducted to correlate vehicle kinematic parameters and energy consumption [15]. Range estimation based on driving conditions and predictions was investigated for BEVs [16]. Electrification is crucial for both passenger cars, as well as heavy commercial vehicles (HCVs), which are important for the transport industry. More than 90% of trucks globally use fossil fuels, as stated by the American Transportation Research Institute (ATRI) [17]. Figure 1 shows the forecasted market share for electric and hybrid HCVs in China and Europe by 2030 [18]. In other studies, the authors investigated the use of hybrid trucks to reduce emissions, and fuel and energy consumption for the hybridization of trucks [19,20].

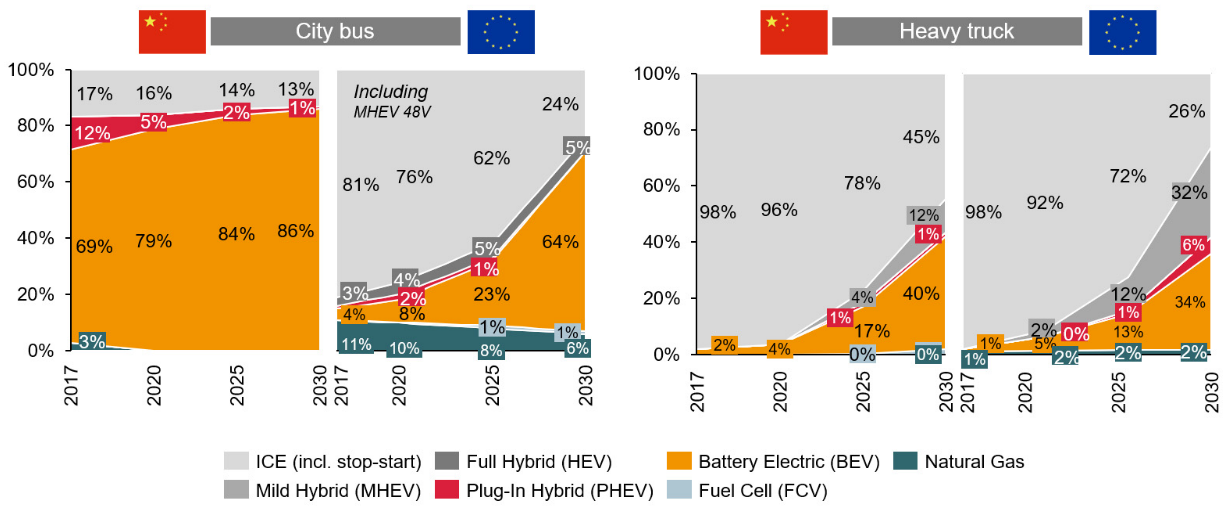


Figure 1. Chinese and European market share estimates for commercial electric and hybrid vehicles.

Many studies estimated the battery state of charge (SoC) and state of health (SoH) using different modeling techniques for the battery management system (BMS) of vehicles. Various models for different types of batteries, such as electrochemical, mathematical, circuit-oriented, and combined models, were comprehensively studied to investigate the advantages and disadvantages of black and gray box-type battery modeling [21]. Lithium–ion (Li–ion) and lithium–sulfur (Li–S) are the most widely used battery types in vehicles, and they have been compared using battery modeling techniques for use in BMS applications [22–24].

Considering the studies mentioned above, this paper investigates the energy consumption of HDTs under actual road conditions. Two transmission types are examined to investigate their effect on energy consumption, and one of them is a new-generation transmission for battery–electric trucks. This study provides a theoretical contribution from two aspects. First, it provides a crucial estimation of energy consumption of HDTs in real driving conditions, which is still unknown and would be beneficial for further studies of predictive shifting. Second, it describes the effects of two types of EDUs on the energy consumption of HDTs, while also aiming to introduce a new configured EDU, referred to in the literature as multimodal EDU for heavy-duty trucks.

The main problem in the literature is that there is no convenient solution for the effects of real road conditions, new-generation transmission types for EDUs, and the number of gears on energy consumption considering the two objectives of packaging and vehicle performance of HDTs. This study aims to provide insights into the effects of different transmission types in real road conditions. It also aims to find the optimal solution by changing the transmission type and the number of gears based on packaging and vehicle performance.

The novelty of this study is in determining the effects of two types of EDU, one of which is a multimodal EDU, which is new in the literature. It does not have a complex architecture and enables seamless power transfer to the wheels, owing to the use of electric motors (EMs) independently, by using a dog clutch shifting mechanism instead of a multi-plate clutch, as in dual-clutch transmissions (DCTs). Similar papers can be found in the literature; however, they all focus on passenger cars with standard driving cycles.

In this paper, EVs, transmissions, and battery models were developed using MATLAB/Simulink software to determine energy consumption with different transmission types and speeds. The transmission types, gear ratios, and layouts are discussed in the Methodology section; the drive cycles and routes are briefly explained in that section as well. The results and their effects in terms of transmission type, number of gears, performance, and packaging are discussed in the Results and Discussion section. Finally, the paper is summarized in the Conclusion, and the optimum transmission type is defined in terms of energy consumption, vehicle performance, and packaging.

2. Methodology

In this study, EVs, transmissions, and battery models were developed using MATLAB/Simulink software to determine energy consumption. The road-load data were collected from municipal, intercity, and regional areas, and the driving cycle was determined using nCode software to obtain realistic energy consumption values. The average estimated efficiency for transmissions found in the literature and from industry experience was 97% for both transmissions. Inverter efficiency was not considered, since this study only investigated the effects of transmission type and speed.

EDUs, also called electric drive systems (EDSs), are new propulsion systems for EVs that consist of power electronics, EMs, and transmission (drivetrain). In this section, the working principles of each EDU are explained, schematic diagrams are given, and collected road data and routes are briefly described. The routes and mileage information are presented, and the results of processed road load data are extracted as a driving cycle. Then, the vehicle model is developed with sub-models of vehicle, battery, transmission, EM, and driving cycle in MATLAB/Simulink. The vehicle sub-model is created using Equations (1)–(4) describing forces acting on the vehicle together with vehicle parameters, and the battery sub-model is created using Equations (5)–(10). Following the Methodology section, the effect of energy consumption is obtained using a drive cycle created from the collected road data for different routes. Finally, in the Results and Discussion sections, the model is evaluated by considering EM operating points, and the optimum solution is determined by comparing energy consumption, performance, packaging, and speed.

2.1. Multispeed Electric Drive Unit

As stated above, these EDUs are AMT-based, and gear shifting is performed sequentially with the help of a dog clutch actuated by a DC electric motor. EMs do not operate independently in this configuration, which means they do not operate without torque interruption. In other words, they are incapable of powershifting. EDUs can be configured as 2, 3, or 4 speeds based on performance requirements. Generally, HDTs require a minimum of 2 speeds, but the 3-speed transmission was optimum for investigation in this study. Figure 2b shows the layout of the 3-speed EDU. The working principle is that speed in the desired gear is achieved by moving clutches A and B (dog clutches) to the right and left. Power is transmitted through path 1, for the first speed when clutch A is shifted to the left; through path 2 for the second speed when clutch A is shifted to the right; and finally, for the third speed, clutch B is shifted to the right (this clutch works on only one side), and power flows through path 3. The 2-speed transmission can be configured as illustrated in Figure 2a. In this configuration, one clutch and two fewer gear pairs are used, compared with the three-speed configuration. This will lead to a packaging advantage in terms of how the design fits into the space. The working principle is identical to the 3-speed layout; the only difference is that clutch B works bi-directionally. Consequently, 4-speed transmission can be configured, as illustrated in Figure 2c. In this configuration, the width of the dog clutch needs to be increased and one more gear pair added compared with the three-speed layout; thus, the transmission width is increased by at least 50 mm.

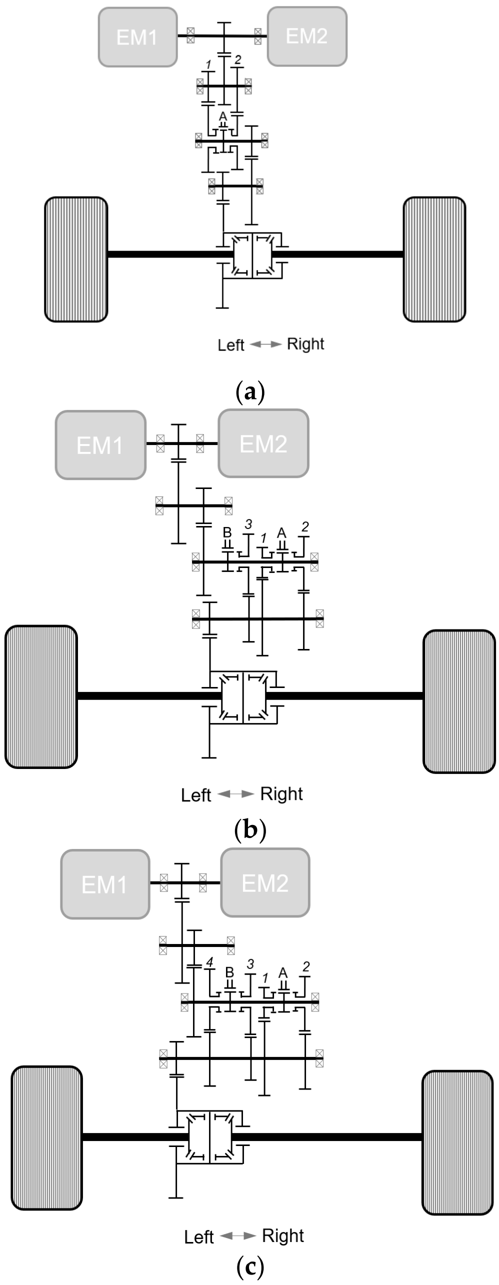
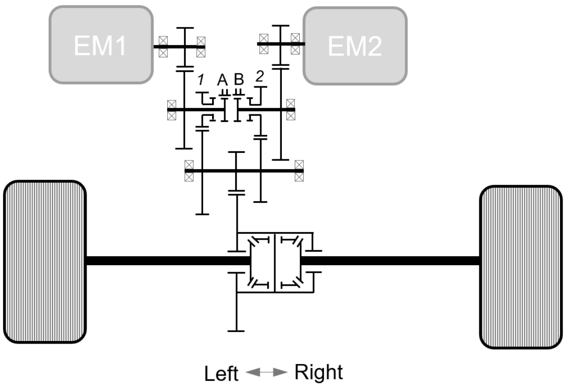


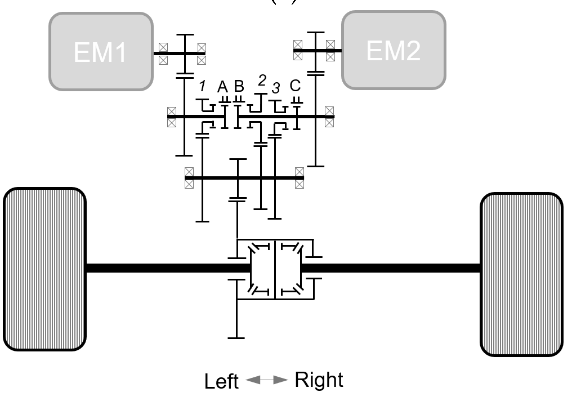
Figure 2. Layout of multispeed electric drive units: (**a**) 2-speed, (**b**) 3-speed, and (**c**) 4-speed.

2.2. Multimode Electric Drive Unit

The multimode EDU is a new type of drivetrain, mostly for use in heavy commercial electric vehicles in the near future. Since the electric motors in the EDU can operate independently, they are important in terms of vehicle drivability and provide a smooth driving experience. This EDU is capable of seamless torque transmission and active synchronization; therefore, it enables powershift capability by using a dog clutch without using the wet clutch or brake packages in transmission. It also can be configured as 2, 3, or 4 modes based on performance requirements. In this study, 3-mode EDU was evaluated, and its effect on energy consumption was compared with 3-speed EDU. The configuration of the 3-mode EDU is illustrated in Figure 3a. The shifting process is carried out via dog clutches, and there is no need to use synchromesh. One advantage of multimode transmission is that it provides active control, owing to the independently controlled electric motors. The power flow occurs from either path 1 or path 2, depending on whether dog clutch A is on the right or left side. In the first mode, both clutches are shifted to the left, then the power is transmitted on path 1 from both electric motors. In the second mode, clutch A is still engaged on path 1, and clutch B is shifted to the right, then the power is transmitted on path 1 from electric motor 1 (EM1) and on path 2 from electric motor 2 (EM2). In the final mode, clutch A is shifted from the left to the right while clutch B remains on the right, and then power is transmitted on path 2 from both electric motors. The configuration can also be used for 2-mode transmission, as illustrated in Figure 3a, which uses only the first and third gears. The gear schedule and clutch positions for 2-mode/3-mode EDUs are shown in Table 1.



(**a**)



(**b**)

Figure 3. Layout of (**a**) 2-mode/3-mode and (**b**) 4-mode electric drive unit.

Table 1. Gear schedule table for 2-mode/3-mode EDUs.

Gears	Clutch A			Clutch B		
	Left	Neutral	Right	Left	Neutral	Right
Gear 1 (60–48) *	X			X		
Gear 2 (60–16)	X					X
Gear 3 (19–16) *			X			X

* Gears used for 2-mode EDU.

The 4-mode EDU can be configured as illustrated in Figure 3b. One more clutch and one gear pair need to be added compared with the three-mode configuration. Therefore, the EDU width is increased at least by 70 mm; thus, manufacturing costs increase correspondingly. The working principle of the first three modes is identical to that of a three-mode configuration, and one more mode is added using dog clutch C. In the final mode, clutch B is shifted to the right, and clutch C is shifted to the left while clutch A is in the neutral position; thus, power is transmitted on path 3. Clutch C is operated only one way (left) and has two positions, neutral and left, for 4-mode EDU. Clutch A is operated both ways and has three positions: to the left to engage the gear on its own shaft, to the right to engage the individual shafts, and the neutral position, which stands on its own shaft for both 3-mode and 4-mode EDUs. Clutch B is also operated both ways and has three positions: to the right to engage the gear on its own shaft, to the left to engage the individual shafts, and the neutral position, which stands on its own shaft for both 3-mode and 4-mode EDUs. The gear schedule and clutch positions for 4-mode EDU are shown in Table 2.

Table 2. Gear schedule 4-mode EDU.

Gears	Clutch A			Clutch B			Clutch C		
	Left	Neutral	Right	Left	Neutral	Right	Left	Neutral	Right
Gear 1 (58–48)	X			X				X	
Gear 2 (58–30)	X					X			
Gear 3 (30–24)			X			X			
Gear 4 (30–16)		X		X			X		

2.3. Transmission Gear Ratio

Transmission gear ratios were designed considering two aspects: top speed of 110 km/h and launch gradient of 30%. The first and last gear ratios were defined for these vehicle performance targets, and the intermediate speeds were defined based on the EM speed ratio and vehicle acceleration targets. The gear ratios used in this study are shown in Table 3. As multimode EDUs have two paths for each EM, the gear ratios are calculated by combining the ratios for the two paths. For instance, the first gear ratio for 2-mode EDU is a combination of 60 and 48, and the second gear ratio is a combination of 19 and 16; for the 3-mode EDU, the intermediate gear ratio is a combination of 60 and 16. Similarly, for the 4-mode EDU, the gear ratios are 58–48, 58–30, 30–24, and 30–16.

Table 3. Gear ratios used for EDUs.

EDUs/Gears	Gear 1	Gear 2	Gear 3	Gear 4	Gear 5
2-speed EDU	58	18	-	-	-
2-mode EDU	60	48	19	16	-
3-speed EDU	58	30.3	18	-	-
3-mode EDU	60	48	19	16	-
4-speed EDU	58	42	30.3	18	-
4-mode EDU	58	48	30	24	16

2.4. Driving Cycle

Using real road data for energy consumption is important in terms of both shedding light on predictive shifting and conducting battery sizing studies. Road load data were collected from a conventional heavy-duty truck on 3 routes. These routes were chosen in regions aiming at municipal, intercity, and regional transportation in Turkey. Route 1 was a garbage truck operating in an urban area, on an inner-city route in Eskisehir, and the final driving cycle for route 1 is illustrated in Figure 4a. Route 2 was a long-haul truck operating between Izmit Province and Eskisehir Province, and its final driving cycle is illustrated in Figure 4b. Route 3 was a water tank truck operating regional transportation in the city, in the Province of Gaziantep, and the final driving cycle is illustrated in Figure 4c. The mileage of the routes was 150, 220, and 56.6 km, respectively.

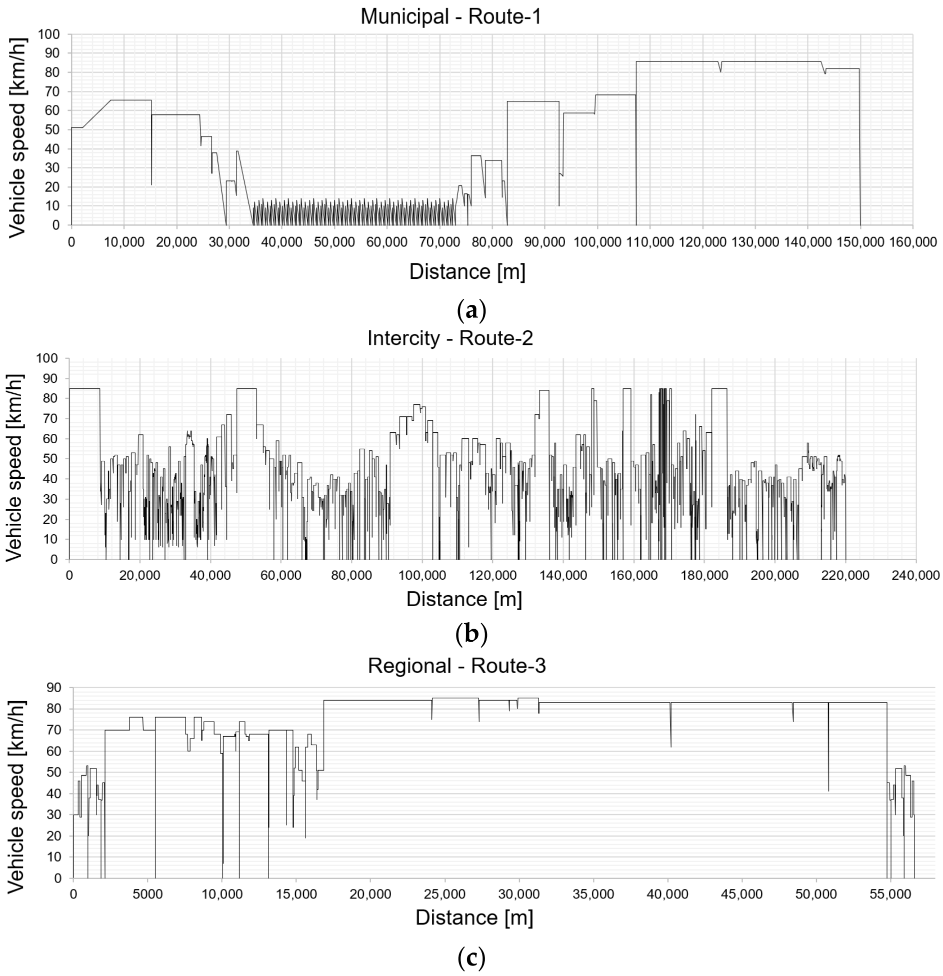


Figure 4. Collected road data: (**a**) route 1: municipal area; (**b**) route 2: intercity area; (**c**) route 3: regional area.

Wheel speed and distance were obtained from the collected road data using nCode software. Engine torque and speed and conventional transmission gear ratios were used as input channels from the road data. These values were then converted into a driving cycle and embedded into the MATLAB/Simulink environment.

2.5. Longitudinal Vehicle Model Development

Since we investigated energy consumption for two types of EDUs, the principles of longitudinal vehicle dynamics, including the transmission system, were developed. A longitudinal model describes the forward motion of the vehicle. The principles of vehicle dynamics apply to any moving mass whether it is electric or not. The summation of forces acting on a moving vehicle is expressed by [6]

$$\sum F = F_r + F_g + F_a + F_{ac} \tag{1}$$

where F_r is the rolling resistance force, F_g is the gradeability force, F_a is the air resistance force, and F_{ac} is the acceleration force of the vehicle and its rotating parts.

$$F_r = M \times g \times f_r \tag{2}$$

$$F_g = M \times g \times i \tag{3}$$

$$F_a = 0.5 \times \rho_a \times C_D \times A_f \times (v + v_w)^2 \tag{4}$$

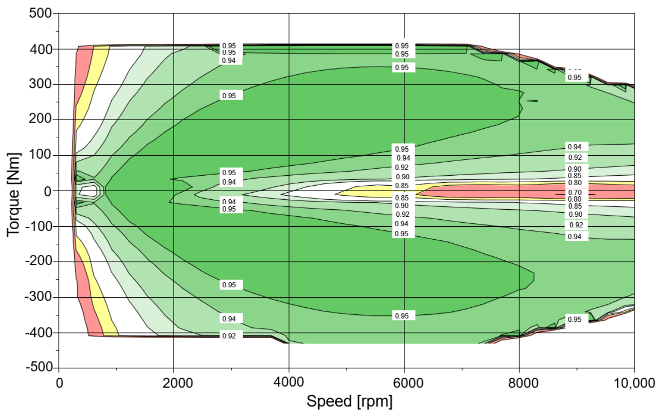
Here, ρ is the density of air, i is the road grade, A_f is the frontal area of a vehicle, C_D is the aerodynamic drag coefficient, v is vehicle speed, v_w is wind speed, g is gravitational acceleration, M is gross vehicle weight (GVW), and f_r is the rolling resistance coefficient. A vehicle longitudinal model was developed based on these formulas, and vehicle parameters were defined for use in the simulations (Table 4).

Table 4. Parameters used in vehicle model.

Parameters	Symbol	Value	Unit
GVW	M		kg
Aerodynamic coefficient	C_D	0.8	-
Frontal area	A_f	10.3	m^2
Rolling resistance coefficient	f_r	0.01	-
Gravitational acceleration	g	9.81	m/s^2
Air density	ρ_a	1.275	kg/m^3

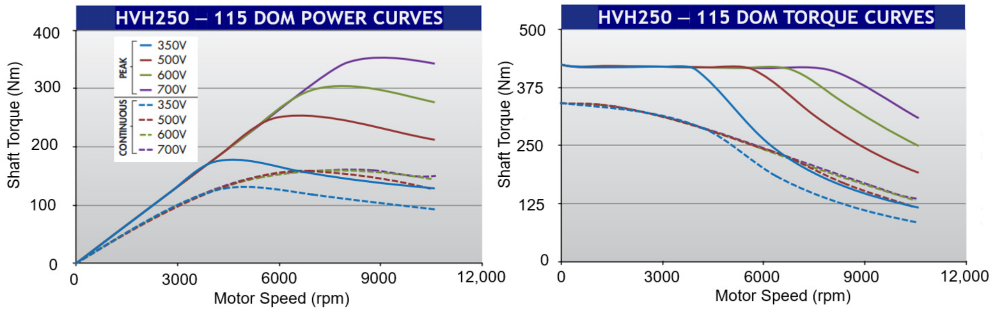
The transmission system in the vehicle model also included two identical BorgWarner HCH250-115 DOM model electric motors, which have 420 Nm peak torque and 330 kW peak power. Figure 5 shows the power and torque curves for different voltage values and efficiency maps. The 700 V electric motor was considered to gain more power [25].

The architecture of the vehicle model was developed using MATLAB/Simulink software to determine energy consumption for battery–electric trucks. The vehicle model consists of several systems, including the driver model, electric motor, drive cycle, battery, and transmission systems, as illustrated in Figure 6.



(**a**)

Figure 5. *Cont.*



(**b**)

Figure 5. (**a**) Efficiency map and (**b**) torque–power curves for BorgWarner HCH250-115 DOM electric motor.

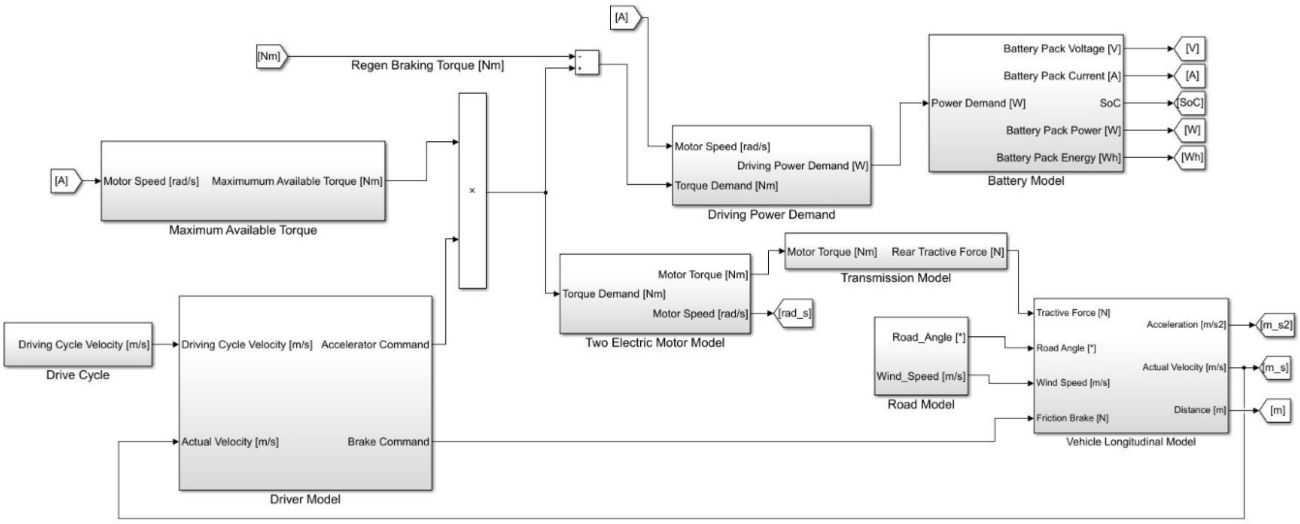


Figure 6. MATLAB/Simulink vehicle model.

Three energy flows were considered in simulations: energy transmitting from the battery to the wheels, from the wheels to the battery during braking (recuperation), and from the battery to other systems, which a=were not considered in this study since they do not have a high impact on the energy consumption of battery–electric trucks.

The battery is a crucial system in the vehicle model. Battery dynamic characteristics in terms of charging and discharging were designed such that the SoC can be determined by considering the battery's efficiency. According to the literature, the charging/discharging efficiencies of Li–ion and lead–acid battery packs are assumed to be 95% and 80%, respectively [26]. A battery model was developed, as illustrated in Figure 7. There are several battery modeling techniques in the literature, such as electrochemical and equivalent circuit networks (ECN), which is the most commonly used technique [26–28]. Considering the ECN technique, battery terminal voltage V_t can be derived from the Kirchhoff law as a function of current load I_L [26] as follows:

$$V_t = V_{OC} - R_O \times I_L - V_1 \tag{5}$$

$$\frac{dV_1}{dt} = \frac{1}{R_1 C_1} V_1 + \frac{1}{C_1} I_L \tag{6}$$

where parameters V_{OC}, R_O, $R_{1,}$ and C_1 are defined as functions of battery SoC. The output of the model is battery terminal voltage and current, which are obtained from Equations (7) and (8) [26].

$$V_{Bat\_pack} = V_{cell} \times \; N_{Cells\_series} \tag{7}$$

$$I_{Bat\_pack} = I_{cell} \times \; N_{Cells\_parallel} \tag{8}$$

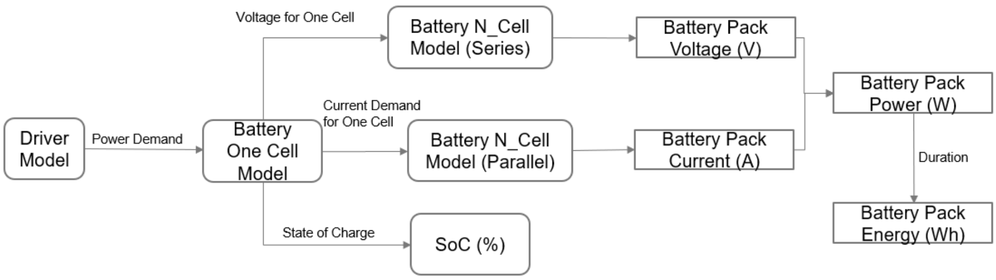


Figure 7. Battery model architecture.

The power request of a single cell in the battery pack is obtained by dividing the total power by the number of cells N_{cell}. After that, the current for a single cell I_{cell} is determined as shown in Equation (9) [26]. Then, SoC is determined using Equation (10), where SoC is the state of battery charge, SoC_0 is the initial state of charge in percentage, C_{cell} is the single-cell capacity, and $I_{cell,dem}$ is the single-cell current demand in (A).

$$I_{cell,dem} = \frac{V_{OC} - \sqrt{V_{OC} - 4 \times \; R_O \times \; P_{cell,dem}}}{2 \times \; R_O} \tag{9}$$

$$SoC = SoC_0 \left(\int_{t_0}^{t} \frac{I_{cell,dem}(\tau)}{C_{cell}} \, d\tau \right) \tag{10}$$

Considering the equations and information above, the battery model was developed in the MATLAB/Simulink environment. A block diagram of the battery model is illustrated in Figure 7.

Vehicle performance specifications are among the most important factors considered when determining the drivetrain configuration of BEVs. Key performance targets for a 26-ton heavy-duty truck are shown in Table 5.

Table 5. Vehicle target performance.

Performance Specifications	Value
Launch grade	30%
Top speed	110 km/h
Speed @ 5% grade	55 km/h
Speed @ 10% grade	35 km/h

Finally, as a shifting strategy, up- and downshifting points were defined by considering the EM efficiency map, which is provided to operate EMs in the most efficient areas, corresponding to EM speeds between 4000 and 10,000 rpm. Thus, the upshifting speed was defined as 9500 rpm and the downshifting speed as 3500 rpm.

3. Results and Discussion

In this study, the main purpose was to compare two types of EDUs in terms of energy consumption, number of gears, and packaging. We used real road data collected from a conventional heavy-duty truck to obtain real energy consumption values, which were embedded into the vehicle model as drive cycles in the MATLAB/Simulink environment. Drive cycles were created from road data collected from three routes in municipal, intercity, and regional areas. We investigated the energy consumption of the two types of EDUs based on three real road conditions, and the obtained values are presented in Table 6.

Table 6. Energy consumption of different types of EDUs based on different routes.

EDU Types	Route 1		Route 2		Route 3	
	Energy Consumption (kWh)	Mileage (km)	Energy Consumption (kWh)	Mileage (km)	Energy Consumption (kWh)	Mileage (km)
2-speed EDU	192.19	150	276.57	220	77.72	56.6
2-mode EDU	207.24	150	303.98	220	84.29	56.6
3-speed EDU	179.60	150	278.12	220	70.71	56.6
3-mode EDU	193.66	150	298.32	220	75.81	56.6
4-Speed EDU	169.90	150	262.84	220	64.56	56.6
4-mode EDU	190.58	150	294.44	220	72.84	56.6

As shown in Table 4, for the municipal route, the energy consumption of the three-speed EDU is 179.60 kWh, and that of the three-mode EDU is 193.66 kWh. For the intercity route, the energy consumption of the three-speed EDU is 278.12 kWh and that of the three-mode EDU is 298.32 kWh. Lastly, for the regional route, the energy consumption of the three-speed EDU as per the regional area is 70.71 kWh, and that of the three-mode EDU is 75.81 kWh. The EM operating points of each EDU for municipal, intercity, and regional routes were obtained from the results and are illustrated in Figures 8–10, respectively. Only EM1 is shown in this paper since EM2 has a similar distribution. Additionally, we investigated transmission types with two and four speeds to evaluate energy consumption by changing the number of gears. It can be seen from the results in Table 4 that two-speed transmission is more inefficient, and four-speed transmission is more efficient than three-speed transmission, as illustrated in Figure 8.

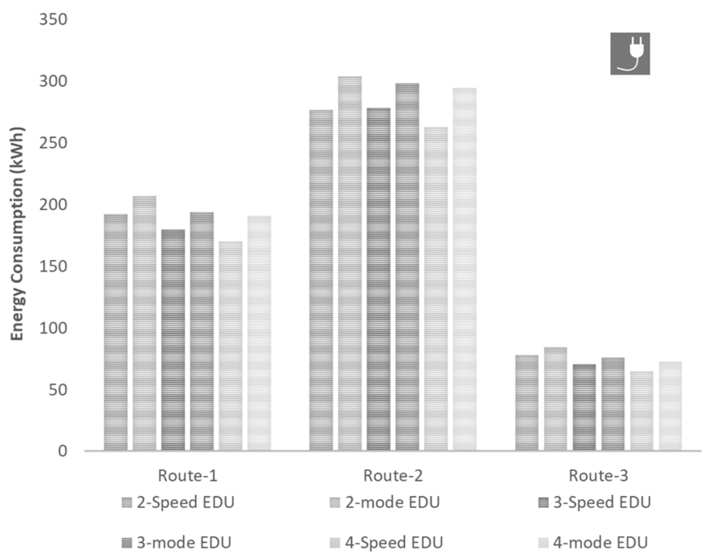


Figure 8. Average energy consumption for each EDU according to route.

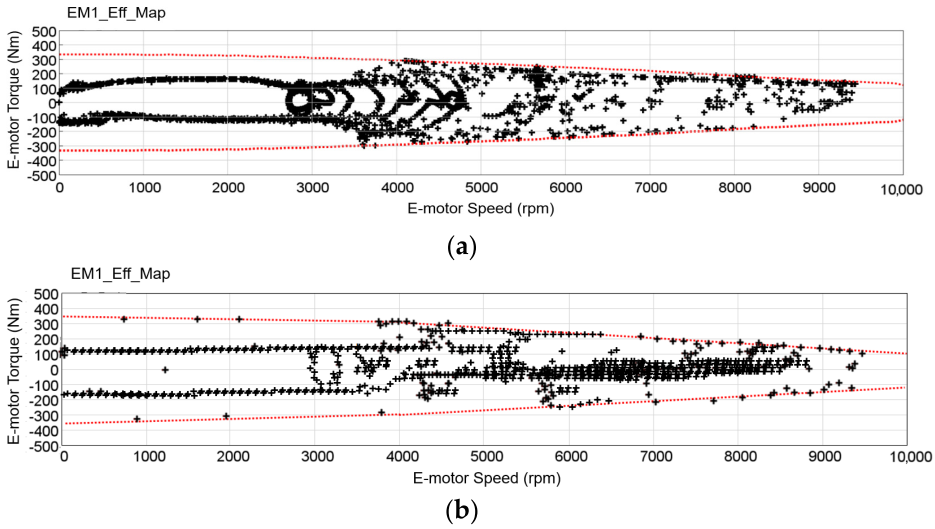


Figure 9. EM operating points of (**a**) 3-speed and (**b**) 3-mode EDU for route 1.

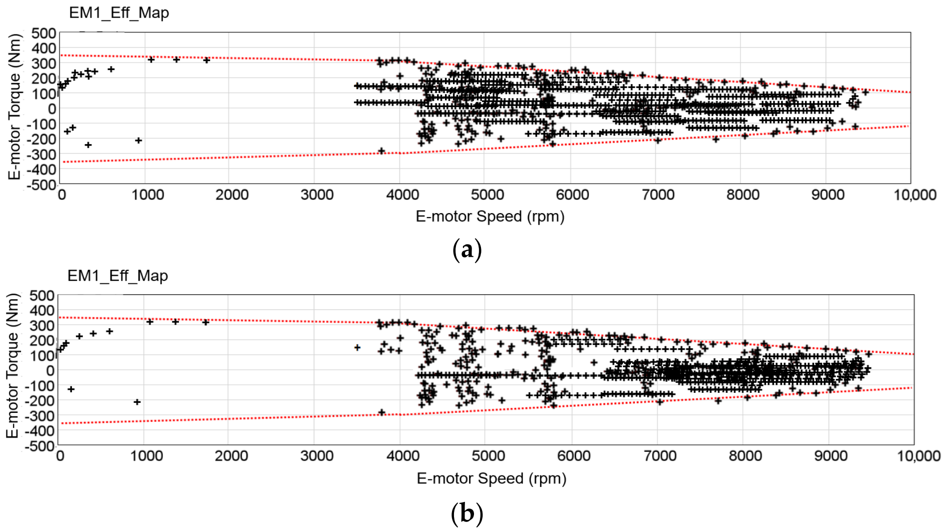


Figure 10. EM operating points of (**a**) 3-speed and (**b**) 3-mode EDU for route 2.

The three-speed EDU is provided to operate EMs in more efficient areas, as illustrated in Figures 9–11. The reason is that EMs do not operate independently, as in multimode EDUs; multispeed EDUs provide the desired torque values at the desired speed range. EM operating points of two- and four-speed transmission for both EDUs can be found in Figures A1–A4 in the Appendix A.

It was determined that multispeed EDUs have less energy consumption, compared with multimode EDUs for heavy-duty trucks. However, we also investigated the performance characteristics of these two EDUs in terms of another crucial aspect besides energy consumption. Generally, the key performance specifications for a 26-ton heavy-duty truck are to launch at a maximum 30% gradient, and to reach 110 km/h top speed, 35 km/h at 10% gradient, and 55 km/h at 5% gradient. The performance characteristics of multispeed and multimode EDUs were investigated for two, three, and four speeds, as illustrated in Figure 12. It can be observed that for multispeed and multimode EDUs, two speeds cannot meet one of the performance requirements, 35 km/h at a 10% gradient (Figure 12a,b). However, for both EDUs, three and four speeds meet all target specifications (Figure 12c–f). In addition, it can also be observed that multispeed EDU covers more area in terms of performance, compared with multimode EDU.

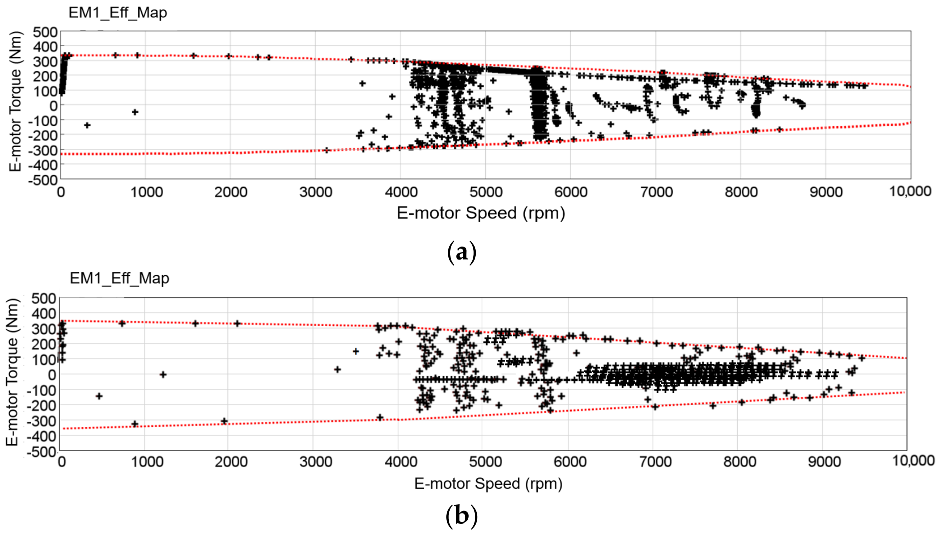


Figure 11. EM operating points of (**a**) 3-speed and (**b**) 3-mode EDU for route 3.

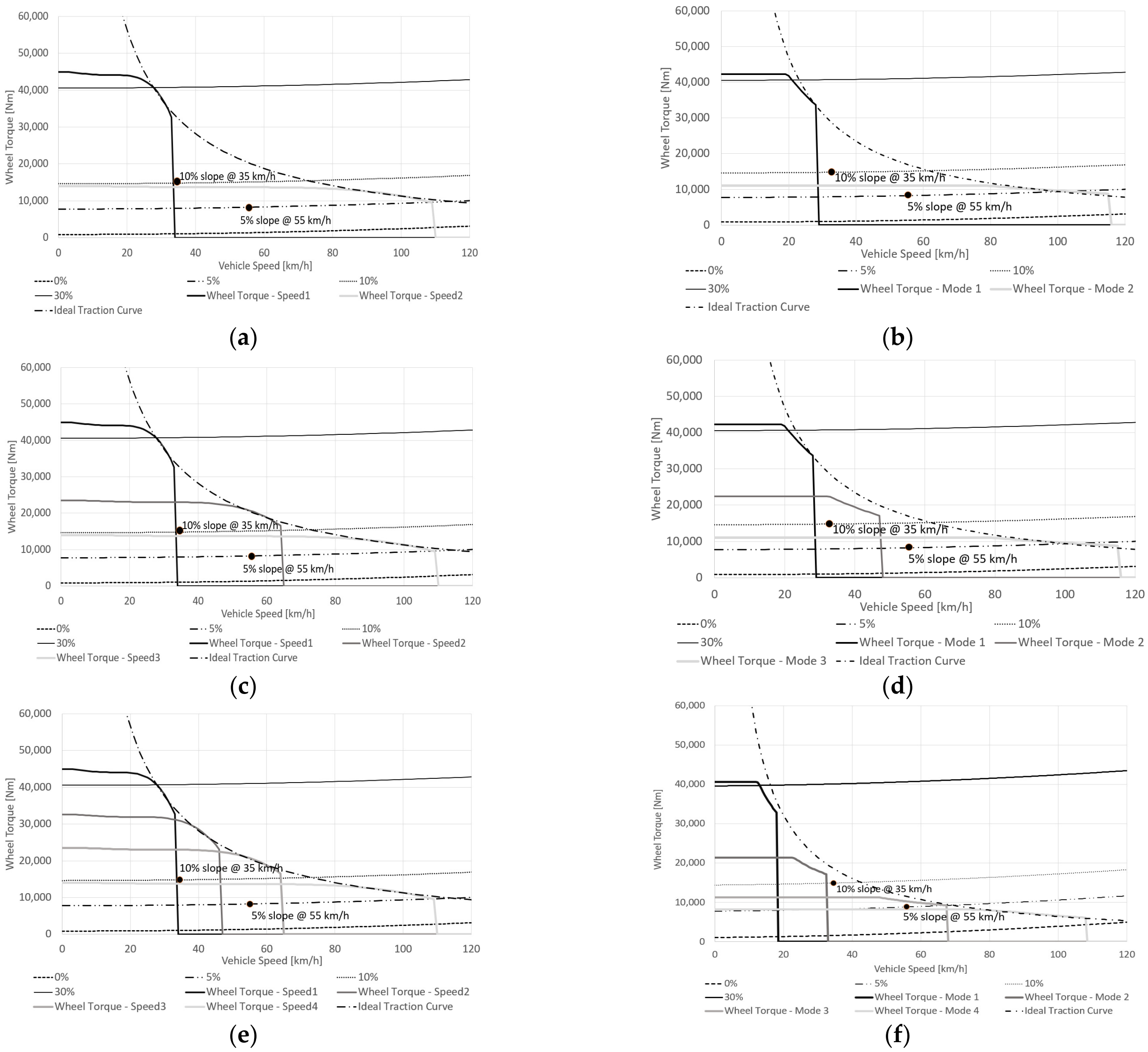


Figure 12. Vehicle performance curves for (**a**) 2-speed EDU, (**b**) 2-mode EDU, (**c**) 3-speed EDU, (**d**) 3-mode EDU, (**e**) 4-speed EDU, and (**f**) 4-mode EDU.

4. Conclusions

In this paper, vehicle models, including battery, transmission, EMs, and drive cycle sub-models, were developed in the MATLAB/Simulink environment to investigate the effects of two EDU types used in heavy-duty electric trucks on energy consumption in the near future. This model was examined under driving cycle conditions created by collected road data from three routes to simulate real driving conditions. Two EDU models were created with two techniques to evaluate energy consumption considering the effect of regenerative braking. SoC was determined using the ECN method for each drive cycle. When examining energy consumption according to the type of EDU for each drive cycle, it was observed that multispeed EDUs had less energy consumption. The average energy consumption values are illustrated in Figure 8. It was found that multispeed EDUs had 7.83, 7.26, and 7.21% less energy consumption in municipal, intercity, and regional areas, respectively, compared with multimode EDUs using a three-speed configuration.

To evaluate the effect of the number of gears on energy consumption for both transmission types, two- and four-speed configurations were also examined. It was found that two-speed EDU had 6.6% and 9% more energy consumption in municipal and regional areas, and was 0.6% more efficient in the intercity area, compared with three-speed EDU. Meanwhile, two-mode EDU had 6.6, 1.9, and 11% more energy consumption for municipal, intercity, and regional areas, respectively, compared with three-mode EDU; furthermore, four-speed EDU had 5.4, 5.5, and 8.7% less energy consumption, compared with three-speed EDU. Four-mode EDU also had 1.6, 1.3, and 3.9% less energy consumption, respectively, compared with three-mode EDU.

Finally, it was also found that two-speed EDU had 8% less energy consumption compared with two-mode EDU, three-speed EDU had 7.5% less energy consumption compared with three-mode EDU, and four-speed EDU had 10.5% less energy consumption compared with four-mode EDU in combined road conditions.

EDUs were examined in terms of vehicle performance. The two-speed configuration of both transmission types did not meet any of the target performance specifications, while the three- and four-speed configurations met all performance specifications. However, they were also evaluated in terms of packaging, and it was observed that the two-speed EDU was at least 75 mm less wide, and the four-speed EDU was 50 mm wider than the three-speed EDU. Thus, two-speed configurations have an advantage in terms of packaging, but they cannot meet all vehicle performance specifications.

As a result of this study, as a general approach, it was observed that an increased number of gears is caused by decreased energy consumption, but they could be fitted into the design space defined for HDTs in terms of packaging. Multispeed EDU types are generally more efficient compared with multimode EDUs. Therefore, the optimal design is identified as three-speed EDU in terms of performance, packaging, and energy consumption.

Multimode EDUs have advantages in terms of drivability by providing smooth driving and gear shifting without torque interruption, compared with multispeed EDUs, since they have powershift capability. It can be concluded that multimode EDUs are preferable to obtain high-quality drivability, while multispeed EDUs are preferable for better efficiency.

The results of this study can be used as a basis for predicting electric HDT ranges and determining battery size. It can also enable fair comparisons of all transmission types and numbers of gears and provides useful knowledge for designers to make multipurpose decisions during the early development phase of battery HDTs. In future research, the driving style of individual drivers could be added, along with weather, in addition to real road conditions including traffic, grade, and cornering. Then, driver- and weather-specific energy consumption values could be obtained. In addition, the battery efficiency decreases with decreasing battery health, which affects energy consumption and auxiliary systems, and this could also be included to investigate energy consumption and be added to future research.

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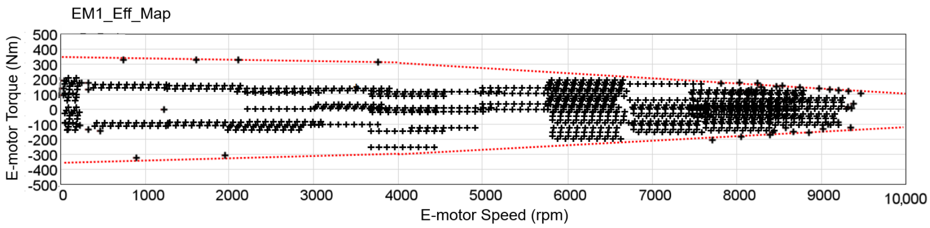
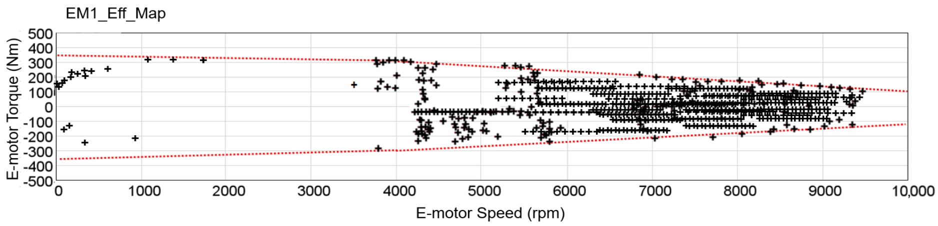
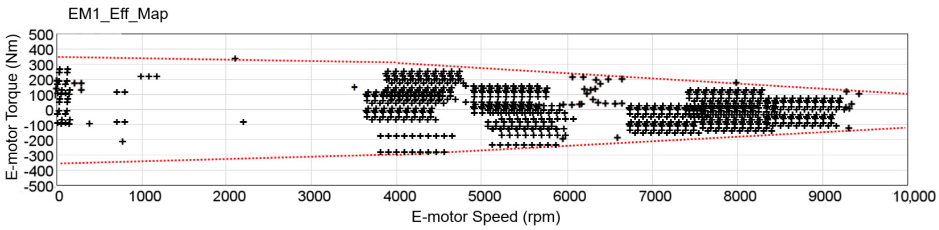
Appendix A



(**a**)

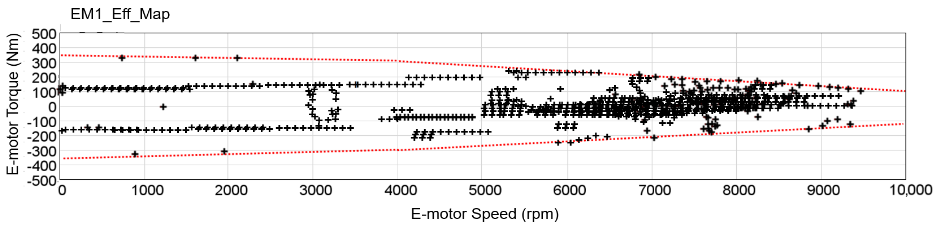


(**b**)



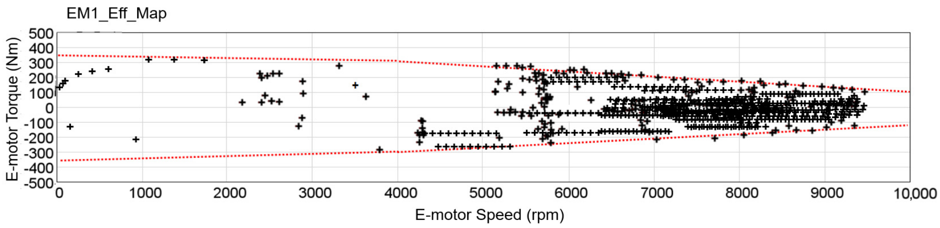
(**c**)

Figure A1. EM operating points of 2-speed EDU for (**a**) municipal, (**b**) intercity, and (**c**) regional routes.

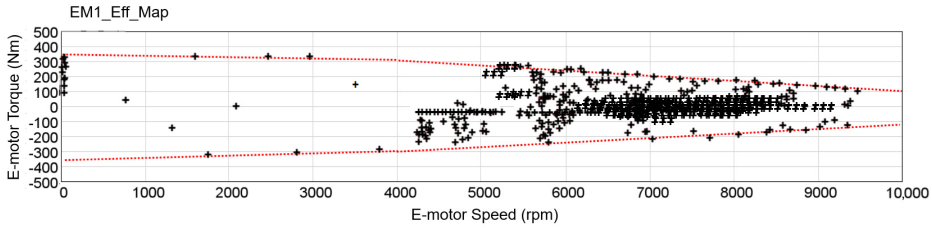


(**a**)

Figure A2. *Cont.*

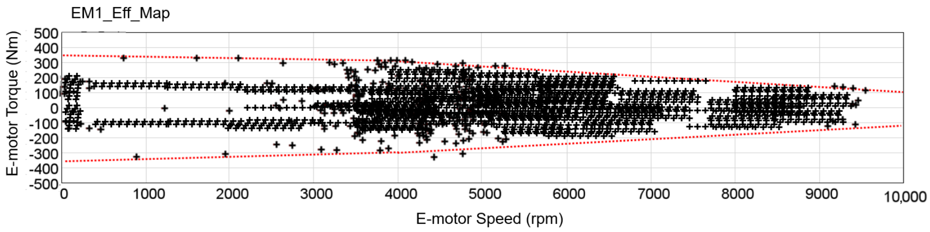


(**b**)

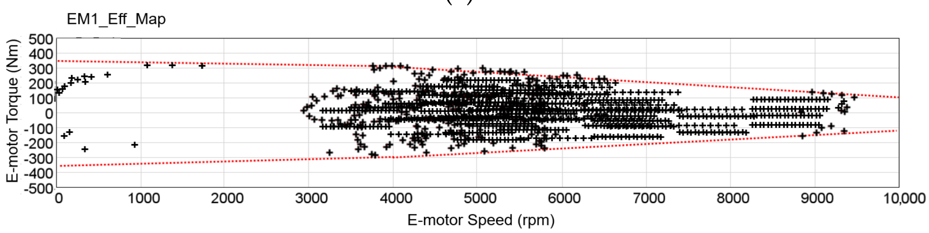


(**c**)

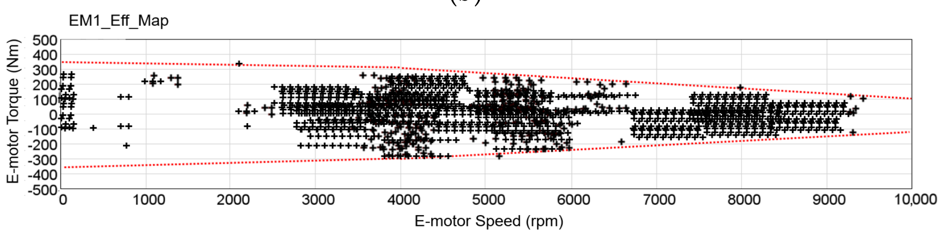
Figure A2. EM operating points of 2-mode EDU for (**a**) municipal, (**b**) intercity, and (**c**) regional routes.



(**a**)



(**b**)



(**c**)

Figure A3. EM operating points of 4-speed EDU for (**a**) municipal, (**b**) intercity, and (**c**) regional routes.

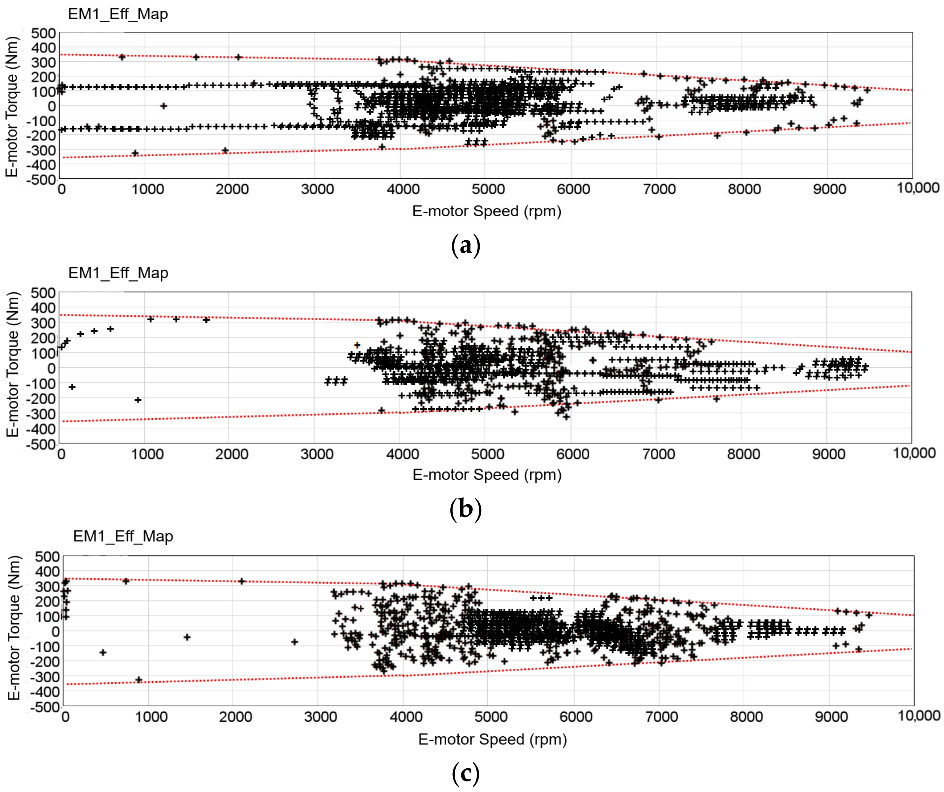


Figure A4. EM operating points of 4-mode EDU for (**a**) municipal, (**b**) intercity, and (**c**) regional routes.

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