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RESEARCH ARTICLE

Research on Economic Benefits and Adaptability of Different ELV Powertrain Topologies

KEXIANG WEI[1,2], HONGGUANG ZHOU[2], XIONG SHU[1,3], SONGLIN XIE[1], AND KONLAYUTT PUNYAWUDHO[4]

[1]Hunan Provincial Key Laboratory of Vehicle Power and Transmission System, Hunan Institute of Engineering, Xiangtan 411104, China
[2]School of Machinery and Mechanics, Xiangtan University, Xiangtan 411104, China
[3]Department of Technology Research and Development, Xiangtan South Locomotive Manufacturing Company Ltd., Xiangtan 411104, China
[4]Department of Mechanical Engineering, Chiang Mai University, Chiang Mai 50200, Thailand

Corresponding author: Xiong Shu (shuxiongkjdx@126.com)

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ABSTRACT Due to the unique feature of zero carbon emissions, electric vehicles (EVs) have attracted increasing interest in recent years. Powertrain as the core system of Electric Logistics Vehicle (ELVs) which has become the focus of current research with the development of the EV. How to design and develop cost-effective powertrains for ELVs is still the focus of current research. The paper takes the powertrain of ELV as the research object. The topology and performance parameters of ELV are classified and calculated first, then comparative analyses are conducted in conjunction with the actual application of ELVs, and the advantages of different type of powertrains on ELVs are explained from the application scenarios, development costs, driving feeling, et al. The research results show that the topology of powertrain depends mainly on the total mass of the vehicle. The motor direct drive system is economically optimal for ELVs with a light payload, and as the payload mass increases the motor with gearbox drive system has a more pronounced cost advantage. In addition, from the point of view of material costs, in the powertrain motor design larger output torque requires more ferromagnetic material and copper wire, resulting in increased costs, which is the main reason why heavy-duty ELVs opt for motors with gearboxes drive system. It is deemed that these research results will be of great importance for the future powertrain design of EVs.

INDEX TERMS Electric vehicle, powertrain, logistics vehicle, economic benefits.

I. INTRODUCTION

Electric vehicles (EVs) are considered carbon-free, which helps mitigate climate change, improve public health, and reduce ecological damage [1], [2]. Coupled with the increasing pressure to meet net-zero targets, the global EV market has grown by huge leaps and bounds in the past decade [3], [4]. In order to further promote the transform of fuel traditional vehicles into electric vehicles, the relevant departments of each country have issued the sales volume of EVs in 2020 to 2030, which give clear signals to manufacturers and other industry stakeholders to mobilize investment to get closer to the EV industry. For example, according to IEA (International Energy Agency) statistics, about 3.3 million EVs will being used in the 8 states of the United States by 2025 [4] and the EU will reach at 30% by 2030 [5], [6].

As the core system of an ELV, the powertrain is as important as the traditional vehicle engine and its drive system. It largely determines the vehicle's performance and plays an important role in the safe operation of the vehicle [7], [8].

To improve the comprehensive performance of EVs. Some scholars have studied the powertrain system of EVs from the view of shifting strategy, structural and control methods. To name a few, a detailed shift mechanism and control strategy for clutchless automated manual transmission (CLAMT) has been carried out in [9]. In [10], a detailed experimental investigation of dual clutch control strategies and drive systems for EVs is presented; In [11], a conventional

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planetary gear mechanism was used to design an interruption-free electric vehicle drive system; In [12] and [13], 2-speed four-wheel drive system is proposed. To improve drivability, Galvagno et al. [14] proposed a torque-assisted AMT (Automated Manual Transmission); In [15], a modified AMT is proposed in which the friction clutch is placed after the gears instead of before them. In [16], a dual-motor powertrain for battery electric vehicles was proposed, and test results show that the powertrain can improve vehicle overall performance. In [17], a novel powertrain system of EV was proposed. An innovative two-speed Uninterrupted Mechanical Transmission (UMT) was proposed in [18], which consists of an epicyclic gearing system, a centrifugal clutch and a brake band, the test results show that the UMT can improve the energy efficiency, dynamic performance and shifting com fort for EV. To improve the overall reliability, a reliability study of electric vehicle battery from the perspective of power supply system in [19]. In [20], a powertrain control method for a series-parallel hybrid $8 * 8$ vehicle equipped with a mechanical transmission was proposed. Co-simulations demonstrate that the proposed control approach is capable of controlling vehicle planar motion. In [21], a two-gear transmission was subjected to investigation, and it was demonstrated that the output power can be continuously utilised without interruption. Fang et al. [22] investigated the possibility of enhancing vehicle dynamics and economy in pure electric vehicles if more than two gear transmissions are used. In [23] and [24], a two-in-one system with motor and transmission integration was investigate. Roozegar et.al. [25], [26], [27] has developed a multi-gear planetary gear transmission, which uses planetary rows for torque transfer, enables the motor shaft to be coaxial with the output shaft of the transmission, reduces the Y-direction of the vehicle, is easy to lay out, and improves the efficiency of the electric drive system. A seamless mode shift control strategy for a dual-motor powertrain based on Simpson's planetary gearset is presented in [28]. In [29], a coordinated control of hydraulic hub-motor auxiliary system for heavy truck was proposed which provides a new way for wheel-driven electric vehicles. In [30], a systematic design and optimization method of transmission system and power management for a plug-in hybrid electric vehicle was conducted, the research results show that when the 6-speed ratio AMT can be reduced to 4, and the fuel economy of the redesigned transmission system can be improved by 2.9% compared to the current transmission system. In [31], a comprehensive forward-looking powertrain model with an efficiency-based control strategy was developed to achieve real-time optimization of electric buses. In [32], a new powertrain system was designed for heavy duty trucks and its energy supply system was analyzed. In [33], the developments and challenges associated with wireless charging pad design was analyzes, and the potential parameters which improve the performance of a DWPT was investigate. In [34], a dual electric powertrain system control scheme is proposed for urban bus systems and the results of the study show that electric buses can reduce CO_2 emissions and save on total and operating costs. In [35], the innovative approach of dual-motor power coupling drive systems for electric tractors was developed, and the test rig and real vehicle with the dual-motor power coupled drive system as the core can simultaneously meet the multiple verification indexes of power and economy. To further improve the operating efficiency of a dual-motor-driven electric bus, a simple and robust power-management strategy was proposed in [36]. An optimal structure selection and parameter design approach for a dual-motor-driven system used in an electric bus was proposed in [37]. The new topology with two clutches reduces energy losses by 12.4% compared to the original design, while the optimised design of the original topology results in a reduction of 3.36%. Real-time and hierarchical energy management-control framework for electric vehicles with dual-motor powertrain system was developed in [38], and the actual vehicle experimental results demonstrate that the proposed framework significantly outperforms rule-based strategies in real-time applications, which can reduce the energy consumption and average shock by 7.7% and 12.6%.

Apart from that, some scholars have conducted research on the reliability of powertrain and the fatigue life of vehicle components, which has significant implications for the design of reliable powertrains. To cite a few examples, the reliability of EVs powertrain was studied in [39] and [40] by using a combined fault tree and Petri net approach, and the fault logical causes by the insulation of electronic components with higher fault rate were investigated in [41] by the approach of fault tree analysis and Bayesian theory. The reliability of motor controller of EVs was studied in [42]; the age and life of power converter components were estimated in [43] based on survey, the fatigue life of automobile stabiliser bars was studied in [44], a novel multiaxis fatigue life model based on the critical plane approach was proposed in [45], and the error ellipse combined with the bootstrap method was proposed in [46] in order to reduce the prediction error of the model under small sample conditions.

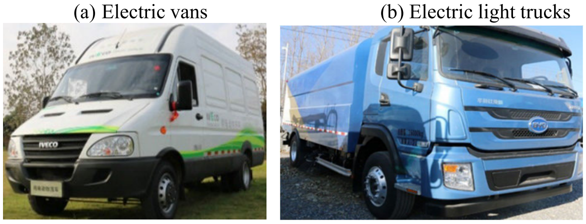
There is no doubt that the aforementioned studies make great contribution to understanding the powertrain of EVs. However, most of research considered the transmission control and shifting strategy of powertrain. While the powertrain topology, in particular the topology of ELV, has not been studied. More importantly, the cost of different ELV powertrain topologies can be significantly different, which becomes particularly important for the pursuit of optimal cost of ELVs, and greatly affects the promotion and application of ELVs. To minimise ELV development costs and design the optimal ELV powertrain. The paper conducted research on the economic benefits of different ELV powertrain topologies. Firstly, the current topologies of ELVs and their assemblies are classified, and then the operating characteristics of assemblies with different topologies are analysed, as well as their impact on vehicle performance. Finally, by combining the vehicle dynamics model and cost estimation model, the optimal powertrain structure scheme for different ELV models is given under the premise of meeting the performance indexes, which provides an important reference for the design and promotion of ELV.

II. CLASSIFICATION OF ECLVS AND THEIR POWERTRAIN TOPOLOGY

A. CLASSIFICATION OF ECLVS

Generally, ELVs can be divided into electric vans, electric light trucks, electric MPVs (multi-purpose vehicles) and electric heavy trucks (as show in Fig.1). Depending on the structure and function of different types of ELVs, these models are used in different application scenarios. For example, with the exponential growth of the e-commerce express industry, electric vans have been widely utilized in urban logistics and distribution. The electric light truck is a more typical and universal logistics vehicle, suitable for the distribution of electrical products in large shopping centers and other suburban logistics. The electric MPV is well-suited to a variety of applications, including transportation of people and as a logistics and distribution vehicle for small outdoor events. Its large interior space allows for the efficient transportation of goods and materials. Heavy-duty electric trucks, designed for the transportation of heavy loads, are primarily employed in the construction industry. According to the Ministry of Industry and Information Technology of China (MIITC), the total sales volume of ELVs reached 108,000 in 2018. Among these models, the electric van was the most popular, with an annual sales figure of approximately 53,000 units, representing a 49% share of the total sales. In a close second place was the light truck, which accounted for 29% of total sales with 32,000 units sold. In third place, electric MPVs sold over 11,000 units, representing approximately 11% of the total sales. Therefore, this paper will scrutinize the powertrain systems of the most successful electric vehicle models according to the sales data mentioned.

(a) Electric vans (b) Electric light trucks



(c) Electric MPV (d) Electric heavy truck

FIGURE 1. **Electric logistics vehicles [9].**

B. POWERTRAIN TOPOLOGY

For ELVs, the powertrain topology can be broadly divided into two categories according to the number of drive motors, i.e., the single-motor drive system and the multi-motor drive system. A reasonable powertrain topology not only improves energy return efficiency and driving stability of the vehicle, but also reduces the cost of electric vehicles [47]. So, in the next step, we will analyze the different powertrain topologies in detail.

1) SINGLE-MOTOR DRIVE SYSTEM

Generally, a single-motor drive system refers to only one drive motor in the powertrain. According to whether it has a gearbox or the position of the motor on the chassis, its topology structure can be divided into three types, namely single-motor direct drive system (shown in Fig. 2(a).), single-motor with gearbox drive system (shown in Fig. 2(b).) and single-motor with rear axle integrated drive system (shown in Fig. 2(c).) [43], [48].

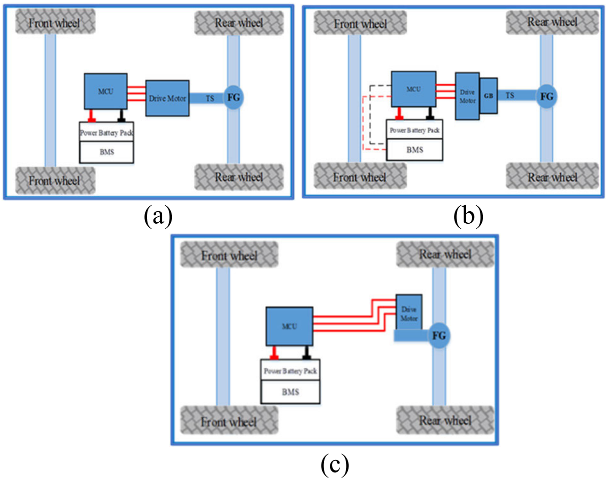
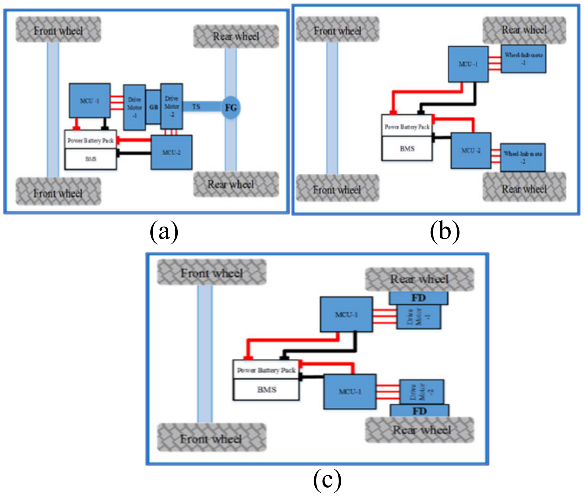


FIGURE 2. **Structure of single-motor drive system. (a) single-motor direct drive system; (b) single-motor with gearbox drive system; (c) single-motor with rear axle integrated drive system; MCU-motor control unit; BMS-battery management system; TS-transmission shaft, FG – final gear.**

Single-motor direct drive system and signal-motor with gearbox drive system are the most common structures for ELVs [49]. This type of topology is the most common topology for both EVs and conventional vehicles. The differences lie in that the internal combustion engine (ICE) is substituted by an electric motor, and the sophisticated multi-speed gearbox is simplified to a single-stage reducer. The mechanical differential and essential drive shafts are still reserved. Therefore, the chassis layout and configuration do not need to be modified excessively. Some existing EVs such as Nissan Leaf and Tesla Model S adopted this topology [50]. In terms of working principle, the single-motor direct drive system output the converted mechanical energy to the rear axle through the shaft. However, for single motor with gearbox drive system, the converted energy from the motor is first input to the transmission and then output to the rear axle via the shaft. The function of the gearbox is to slow down the speed and increase the torsional stiffness to reduce the demand for motor torque when vehicles are overloaded or climbing [11]. Signal-motor with rear axle integrated drive system can not only shorten the drive chain of the powertrain, but also make the chassis structure more compact and provide more available space for the layout of the other parts [51].

2) MULTI-MOTOR DRIVE SYSTEM

The multi-motor drive system refers to two or more motors in the drive train, but from a practical point of view, the multi-motor drive system mainly refers to the dual-motor drive system [47]. The dual motor drive system can be divided into three types according to whether it has a gearbox or the position of the motor on the chassis i.e., dual motor centralized drive system (shown in Fig. 3(a).), dual motor in-wheel drive system (shown in Fig. 3(b).), and hub dual motor drive system (shown in Fig. 3(c).) [48], [49]



(a) (b) (c)

FIGURE 3. **Structure of the dual motor drive system. (a) Dual motor central drive system; (b) Dual motor hub drive system; (c) Dual motor wheelside drive system.**

The dual-motor centralized drive system is consisting of two drive motors that are connected coaxially and have different output characteristics [11]. In the dual-motor centralized drive system (shown in Fig. 3.), motor-2 connect with output shaft, and drive motor-1 connect to drive motor-2 via the 2-ratio speed gearbox. When the vehicle is travelling at a low speed and low load, drive motor-2 working. When the vehicle is climbing with high load or at maximum speed, drive motor-1 comes into operation to compensate for the additional power requirement [52]. This type powertrain is suitable for vehicles operating in special road conditions, such as a scenic tourist area. In the off-season, the vehicle can be powered by just one motor, when there are fewer passengers and the vehicle has a low operating load [53], [54]. However, during the peak tourist season, due to the many passengers and the vehicle is heavily loaded, the two-drive motor need to run simultaneously to meet the working conditions. In addition, by judiciously adjusting the output torque and speed of the two motors, this type of powertrain can not only operate in the high efficiency range for a long time, but also avoid power interruption during transmission shifting [55].

The difference between the dual-motor wheelside powertrain and the dual-motor hub powertrain is that the hub drive system integrates the motor with the hub, while the wheelside drive system retains the vehicle's hub, which is usually driven by the motor combination with the gear [56], [57], [58]. This type of powertrain allows the independent control of each driving wheel and the traction torque distribution can be determined intelligently and precisely. Thus, the vehicle dynamics, steering performance and driving safety can be optimized and improved without additional hardware implementation. Additionally, eliminating mechanical transmission such as the gearbox, mechanical differential, and redundant drive shafts, may provide significant improvements on weight reduction, and cost saving. Although the hub drive system and wheelside powertrain eliminating mechanical transmission such as the gearbox, mechanical differential, and redundant drive shafts, and then the cost saving is shortened, the transmission efficiency is improved and the chassis structure of the vehicle becomes more concise. But its shortcomings are also obvious, for example, in terms of structural arrangement, the wheelside drive system and the hub drive system required to change the chassis structure of vehicle, and the structure is completely different from that of a conventional fuel vehicle. So, if these powertrains are adopted, it will be necessary to make a major change to the chassis structure and suspension system of traditional vehicles, which will result in an increase in the development cycle, cost and technical difficulty of the vehicles. The major shortcoming of those two wheel-hub drive powertrain topologies is that the unsprung mass of the suspension will be increased, which adversely affects the handling and ride, especially during fast oscillating motions over bumps. In addition, as this type of powertrain is close to the ground and vibrate frequently when working, which puts higher requirements on the heat dissipation, dustproof and waterproof of its components. Moreover, the differential control of the wheels when the vehicle operated in complex conditions has not been completely solved [59].

III. POWERTRAIN DESIGN AND ITS APPLICATIONS

A. *ANALYSING AND DESIGNING OF ELV POWERTRAIN*

The power performance of vehicle is significantly influenced by powertrain. When designing a vehicle, we need to meet the vehicle's need for maximum speed, maximum gradeability and maximum acceleration [61], [62], [63]. In terms of powertrain performance requirements, the majority of light trucks and vans work in the city, the maximum gradient of the vehicle is 25%, and the maximum speed is around 90km/h. For heavy trucks with a high total mass, which generally operate in suburban areas and in specific environments, the maximum gradient in the design of the whole vehicle is

TABLE 1. Vehicle parameters for various eclvs [6].

Item	Vans		Light trucks and MPV			Medium heavy trucks			Heavy trucks	
Total mass (kg)	2000	2500	3000	3500	4500	7000	8000	12000	16000	20000
Mass for accelerate (kg)	1500	1700	1900	2000	2600	4500	5000	8000	10000	15000
Acceleration of gravity (m/s2)	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
Rolling radius(m)	0.286	0.298	0.310	0.322	0.334	0.346	0.356	0.364	0.368	0.368
Air resistance coefficient	0.31	0.386	0.42	0.47	0.48	0.56	0.58	0.65	0.68	0.71
Windward area (m2)	3.49	3.84	4.12	4.82	5.28	6.35	6.56	7.12	7.5	7.68
Air density (kg/m3)	1.225	1.225	1.225	1.225	1.225	1.225	1.225	1.225	1.225	1.225
Rolling resistance coefficient	0.010	0.011	0.011	0.011	0.011	0.011	0.011	0.010	0.012	0.012
Maximum speed (km/h)	100	100	95.00	95.00	95.00	90	90	90	90	90
Acceleration time from 0 to 50km/h	10	10	10	15.00	15.00	15.00	15.00	15.00	15.00	15.00
Maximum gradeability%	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00

generally required to be 30% [63], [64]. In order to facilitate the calculation of the performance requirements of the different powertrain systems of ELVs, the paper provides statistics on the basic parameters and performance parameters of ELVs, as shown in Table 1. It should be noted that the data presented in this paper is based on an analysis of actual vehicle sales data in China. The data for models with the highest sales volume were analysed and obtained.

According to the theory of vehicle dynamics, the power required for the vehicle to reach maximum speed, minimum acceleration time and maximum gradeability is

$$\begin{cases} P_1 = \dfrac{1}{\eta_t}\left(\dfrac{mgfu_{a1}}{3600} + \dfrac{C_D A u_{a1}^3}{76140}\right) \\ u = u_m\left(\dfrac{t}{t_m}\right)^x \\ P_2 = \dfrac{1}{3600\eta_t^2}\left(\dfrac{\delta m u_m^2}{3.6\,dt}\left[1-\left(\dfrac{t_m - dt}{t_m}\right)^x\right]\right. \\ \left. +mgfu_m + \dfrac{C_D A u_m^3}{21.15}\right) \\ \quad P_3 = \dfrac{1}{\eta_t}\left(\dfrac{mgfu_{a3}cos\alpha}{3600} + \dfrac{mgu_{a3}sin\alpha}{3600} + \dfrac{C_D A u_{a3}^3}{76140}\right) \end{cases} \tag{1}$$

where, η_t is the mechanical transmission efficiency; u_{a1} is the maximum speed of the vehicle; x is the speed combination factor; δ is the vehicle rotational mass conversion factor; m is the vehicle mass; u_m is the vehicle end speed; t_m is the acceleration time; g is the gravitational acceleration; f is the rolling resistance coefficient; C_D is the air resistance coefficient; u_{a3} is the vehicle speed at the time of climbing, A is the windward area; ρ is the air density; α is the slope angle.

The output torque when climbing a gradient can be expressed as follows.

$$\begin{cases} F_t \geq mgfcos\alpha_{max} + mgsin\alpha_{max} + \dfrac{C_D A u_m^3}{21.15} \\ T_{max} = \dfrac{F_t r}{i_g i_0 \eta_t} \end{cases} \tag{2}$$

where F_t is the drive force; m is the total mass of the vehicle; f is the rolling resistance coefficient; C_D is the air resistance coefficient; A is the windward area; α_{max} is the large slope angle; g is the gravity acceleration; η_t is the mechanical transmission efficiency; i_g is the transmission ratio; i_0 is the final gear ratio; r is the wheel rolling radius.

According to Table 1, we calculate the powertrain performance parameters by combining Equ. (1) and (2), and obtain the corresponding performance parameter for different ELVs as shown in Table 2.

From Table 2, we can see that the electric vans, primarily used for logistics, demand a power output ranging from 40-70 kW. Electric light trucks, which serve a broader spectrum of logistics needs, require a higher power output of 75-120 kW. For heavy-duty electric vehicles, which are integral to the construction machinery industry, the powertrain must deliver a substantial 410 kW to handle the increased loads effectively. For torque demand of powertrain is directly proportional to the vehicle's load capacity, and this relationship is particularly pronounced in heavy-duty trucks, where inadequate transmission matching or a single motor configuration struggle to meet the operational needs.

In order to further validate the above counting results, the next step, we will take the actual application of electric vehicles in China as an example to study and analyse the powertrain topologies and parameters adopted for ELVs, so as to provide a basis for the subsequent analysis of the economic benefits of the powertrain with different topologies.

B. POWERTRAIN APPLICATIONS

1) ELECTRIC VANS

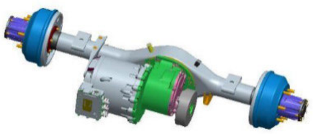
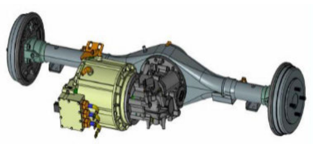
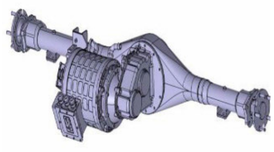
To study the application of the powertrain in electric vans, a statistical analysis of the powertrain of this model in the current Chinese EV market was conducted, and the analysis results are shown in Table 3.

From Table 3, we can see that the single-motor with rear axle integrated drive system was widely used. The total mass of these electric vans is generally around 2500kg, the maximum design speed is around 100km/h, the maximum gradient is generally between 20%-30%, and the peak power of the drive motor is generally 45-60kW, the peak output torque of the drive motor is generally 160-260Nm. This fits well with the theoretical calculations in the previous section.

TABLE 2. Vehicle parameters for different ECLVS.

Item	Electric Vans	Electric Light trucks	Electric MPV	Heavy truck
Output Power (kw)	45-70	75-120	85-120	180-410
Gear ratio	6.5-8	7.5-8.5	7.5-8.5	16.2-24.1
Torque at wheel end (Nm)	2126	29987	31027	48980
Motor output torque (Nm)	265-327	375-980	540-1100	1500-2300
Motor output speed (rpm)	5000-7500	4500-5500	4500-5500	3000-4500

TABLE 3. Electric van powertrain structure and parameters [6], [9].

Models	EC35	Qirui Youyou EV	Changan Star
Vehicle images			
Powertrain pictures			
Structure of powertrain	Single-motor with rear axle integrated drive system	Single-motor with rear axle integrated drive system	Single-motor with rear axle integrated drive system
Peak power(kw)	60	60	65
Peak torque (Nm)	200	225	260
Peak rotate speed (rpm)	9000	9000	8500
Vehicle total mass (kg)	2660	2600	2550
Maximum speed(km/h)	100	110	105
Maximum gradeability	20%	25%	30%

2) ELECTRIC LIGHT TRUCKS

Similar to the electric van, in order to investigate the application of powertrains with different topologies to electric light trucks, the basic parameters and powertrain performance of the best-selling electric light truck models in the Chinese EV market were statistically compared, and the results are shown in Table 4.

From Table 4, we can see that the total mass of electric light trucks is generally around 4500kg, the maximum speed is generally 90km/h, the maximum gradient is generally between 25%-30%, the peak power of the driving motor is between 80-120kW, the peak output torque of the motor in the single motor with gearbox drive system is generally 400- 500Nm, and the peak output torque of the motor in the single motor direct drive system is generally 750-1200Nm. In terms of powertrain selection, the single motor direct drive system and the single motor with gearbox drive system are used. However, the single-motor with gearbox drive system is more popular than the single motor direct drive system.

3) ELECTRIC MPV

Unlike electric vans and electric light trucks, MPVs are multi-purpose, all-in-one vehicles that can be used for a wide range of applications, from passenger transport to freight haulage, and Table 5 shows the actual powertrain structures currently used in the market for this type of vehicle.

From Table 5, we can see that the maximum speed is generally 100km/h, the maximum gradient is generally between 25%-30%, the peak power of the driving motor is about 100 kW, the peak output torque of the motor in the single motor with gearbox drive system

TABLE 4. Electric light trucks powertrain structure and parameters [6], [9].

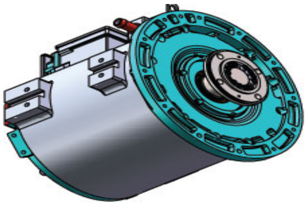
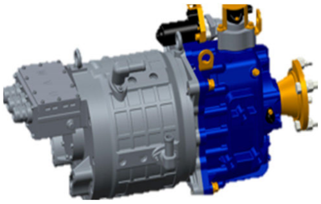
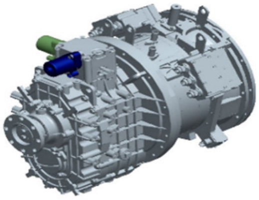
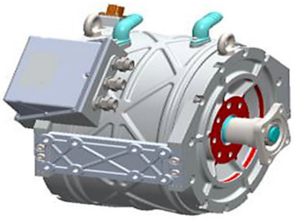
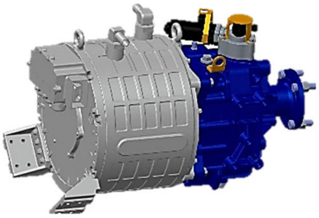
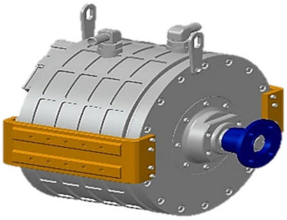
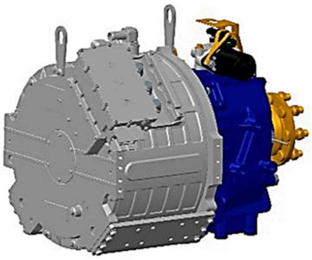
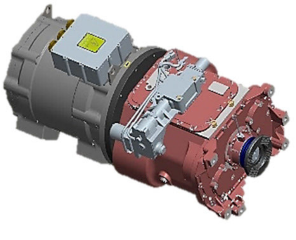
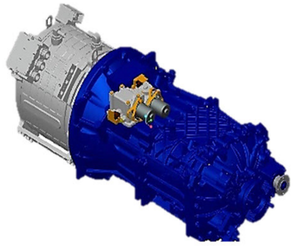
Models	Geely remote-E200	Dongfeng-EV300	Shaanxi Auto XuanDe-E9
Vehicle images			
Powertrain pictures			
Structure of powertrain	Single-motor direct drive system	Single-motor with gearbox drive system	Single-motor with gearbox drive system
Peak power(kw)	100	120	85
Peak torque (Nm)	955	500	360
Peak rotate speed (rpm)	3000	4500	6000
Vehicle total mass (kg)	4495	4495	4495
Maximum speed (km/h)	90	110	10
Maximum gradeability	25%	30%	30%

TABLE 5. Electric MPV powertrain structure and parameters.

Models	Iveco-EV42	Datong-EV80	Kawei-EV4
Vehicle images			
Powertrain pictures			
Structure of powertrain	Single-motor direct drive system	Single-motor with gearbox drive system	Single-motor direct drive system
Peak power (kw)	100	100	100
Peak torque (Nm)	1000	360	980
Peak rotate speed (rpm)	3500	6000	4500
Vehicle total mass (kg)	4490	3495	4000
Maximum speed (km/h)	100	100	100
Maximum gradeability	25%	30%	25%

is generally 360Nm, and the peak output torque of the motor in the single motor direct drive system is generally 1000Nm. In addition, compared with the single motor direct drive system and the single motor with gearbox drive system, the single motor direct drive system is more popular.

TABLE 6. Heavy electric truck powertrain structure and parameters.

Models	BYD16T	Dongfeng-25T	49T electric tractor
Vehicle images			
Powertrain pictures			
Structure of powertrain	single-motor with gearbox drive system	single-motor with gearbox drive system	single-motor with gearbox drive system
Motor power (kw)	100/185	120/240	260/350
Motor torque (Nm)	750/1300	820/1500	1000/2000
Rotate speed (rpm)	1270/3500	1400/3500	3070/3000
Gear number	2	6	8
Speed ratio	2.60/1	8.456/4.913/2.976/1.915/1.238/1	12.7/8.35/5.67/4.07/2.96/2.05/1.39/1
Maximum speed (km/h)	85	80	80
Maximum gradeability	25%	25%	13%

4) HEAVY ELECTRIC TRUCK

In addition to the electric vans, light-duty trucks and MPVs mentioned above, electric heavy-duty trucks have a smaller share of the current market, but their development prospects cannot be ignored [59], [60]. Some promising electric heavy-duty truck models and their powertrain structure are shown in Table 6, and it can be seen that all models use the single-motor with gearbox drive system. It may be interesting to note that as the overall quality of the vehicle increases, the demand for the number of gears also increases. For example, the 49-tonne electric heavy-duty trucks has up to 8 speeds.

The above study shows that there are significant differences in powertrain topology for different types of commercial logistics. For example, due to the small load capacity, the electric van logistics vehicles mainly adopt the single motor with rear axle integrated drive system, with the increase of load capacity, the corresponding powertrain topology of each model will be different; for electric heavy truck, almost all models adopt the single motor with gearbox drive system, and the larger the load capacity, the larger the corresponding gearbox is, the larger the gear ratio is also large.

IV. RESULT AND DISCUSSION

According to the above research, we can see that different powertrain topology are used in different models of ELVs. The single motor with rear axle drive system emerges as the dominant choice for electric vans. Conversely, the single motor with gearbox drive system is the most common application in heavy-duty trucks. The transmission speed ratios of this drive systems are related to the total vehicle mass, and heavier vehicles require multiple transmissions to effectively manage their operational requirements. However, why different topologies are used for different ELV models and how the different topologies of the powertrain economic benefits for ELVs. To date, the available articles on the subject do not give a detailed explanation.

To answer this question, this section aims to extend the analysis by examining the economic implications of different powertrain topologies within the ELV. By focusing on the variance in parameters and topological structures required for distinct vehicle types, the research highlights the intrinsic advantages of each powertrain configuration [65], [66]. These advantages are scrutinized from two critical perspectives: the application scenarios of the vehicles, which dictate the operational efficiency and suitability of the powertrains, and the vehicle development costs [67], [68]. Through this comprehensive evaluation, the study seeks to provide valuable insights into the economic viability of various powertrain.

A. APPLICATION SCENARIOS FOR VARIOUS ELVS

The application scenario largely determines the powertrain parameters of each vehicle, and the research results show that electric vans and light trucks are very suitable for short-distance logistics distribution or freight transport in cities [67], [68]. Accordingly, we can see that the maximum gradeability of these vehicles is generally 25%, the acceleration from 0-50km/h is generally 10s-15s, and the top speed is generally 90km/h. To delve deeper into the powertrain performance requirements of various ELV types, we conducted a detailed assessment of motor output power and torque across a spectrum of operational loads. This evaluation was carried out by integrating the parameters delineated in Table 1 with the calculations derived from Equations (1) and (2). The resultant data, graphically represented in Figures 4 and 5, provide insightful revelations on the dynamic power and torque output needs of electric powertrains under varying load conditions.

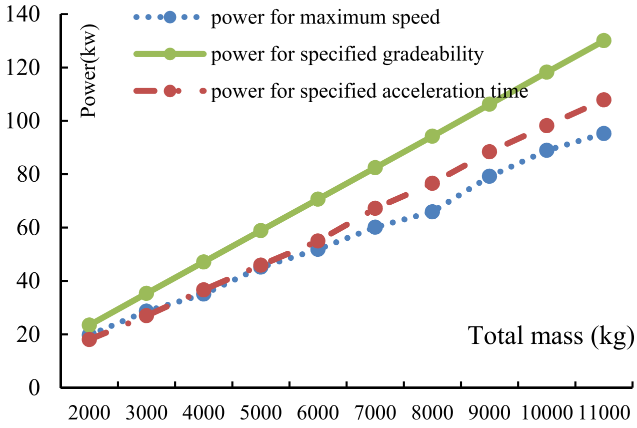


FIGURE 4. Power requirements.

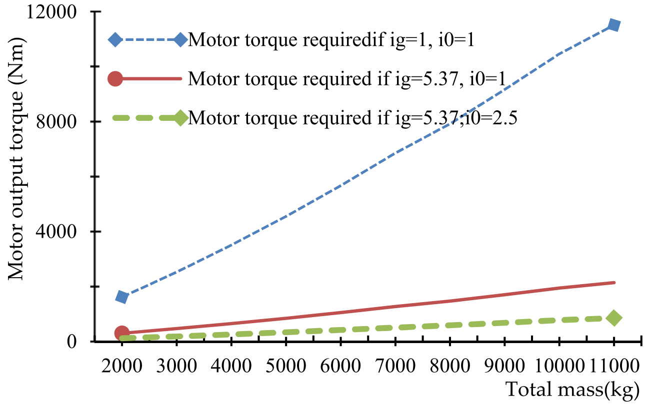


FIGURE 5. Torque requirements.

The analytical results depicted in Figures 4 and 5 elucidate a direct correlation between the total mass of the vehicle and the output power of the motor system. To facilitate comprehension, this study provides a detailed examination of the powertrain's output torque requirements. For instance, considering a vehicle climbing gradient of 25%, we compute the torque demands for commercial vehicles with total masses ranging from 2000 kg to 18000 kg, as shown in Figure 4. Notably, at a vehicle mass of 7000 kg, the total torque input to the wheel is calculated at 7925 Nm, escalating to 20946 Nm for a vehicle mass of 20000 kg. This indicates a progressive increase in torque requirements with escalating vehicle mass. For vehicles with substantial mass, the hub drive system, characterized by drive ratios of 1 (i.e., $i_g = 1$, $i_0 = 1$), proves inadequate for satisfying gradient requirements. Conversely, utilizing a single motor direct drive system (i.e., $i_g = 1$) with a vehicle rear axle speed ratio of $i_0 = 5.37$, the required input torque to the wheel for a vehicle mass of 7000 kg is considerably lower, at 1278 Nm. This comparison underscores the efficiency of the motor direct drive system in reducing output torque. Moreover, when employing a single motor with gear drive system (typically $i_{01} = 2.7$, $i_{02} = 1$, $i_g = 5.37$), the drive motor's output torque can be further mitigated, as depicted in Figure 5. In summary, vans and light trucks, with the relatively lighter total mass, benefit significantly from the motor direct drive system due to lower driveline output torque requirements. As vehicle mass increases, the advantages of the transmission drive system become increasingly pronounced. For heavy trucks, the single-motor direct drive system may fall short in fulfilling the normal operational torque demands of the vehicle.

B. DEVELOPMENT COSTS AND ECONOMIC BENEFITS

The comprehensive value of vehicle ownership encompasses various costs including the initial purchase price, the powertrain, battery expenses, and operational costs. However, this analysis is confined to the examination of powertrain-related expenses (i.e., drive motor, gear box).

Take the motor with gearbox drive system as example, this type of powertrain can significantly reduce the need for motor output torque, thereby reducing the amount of permanent magnet materials and copper wire used in the drive motors [56], [69], [70]. In addition, the reduction in motor torque can also reduce operation current of drive motor to a certain extent, which can also reduce motor housing, bearing, shaft and the power electronic device cost of motor controller. At the same time, this drive solution requires additional gearbox costs. It is assumed that the total material cost saving by the motor with gearbox drive system is T_{total}, and the corresponding calculation equations are as follow.

$$\begin{cases} T_m = k_1 C_1 \\ T_C = k_2 C_2 \\ T_0 = C_{01} + C_{02} + C_{03} \ldots + C_{others} \\ T_{total} = T_m + T_C + T_0 - T_{box} \end{cases} \tag{3}$$

where, T_m is the cost savings on ferromagnetic materials; T_C is the cost savings on copper wire; k_1 is the ratio factor of the output torque of the motor to the amount of magnetic steel that is required; C_1 is the unit price of the ferromagnetic materials; k_2 is the ratio factor of the output torque of the motor to the required copper wire. C_{01}, C_{02}, C_{03}, …, C_{others} are the total cost of motor shell, shaft, power electronic device and other materials reduced after the output torque of the motor is reduced, respectively. T_{box} is the cost of gearbox.

Statistical analysis reveals two pivotal ratio factors that directly correlate with the material costs of ELV powertrains: the ratio of the motor's output torque to the required magnetic steel (k_1) and the ratio of the motor's output torque to the required copper wire (k_2). Specifically, k_1 is determined to be approximately 150 Nm/kg, indicating that an additional kilogram of magnetic steel is necessitated for each increment of 150 Nm in output torque [60], [61]. Similarly, k_2 is 75 Nm/kg, it means for an extra kilogram of copper for every 75 Nm increase in torque. Current market evaluations price magnetic steel at around 420 yuan/kg and copper wire at 78 yuan/kg. Furthermore, the pricing of gearboxes, based on their input torque capacity, has been assessed. For a gearbox capable of handling an input torque of 320 Nm, the cost is approximately 2,500 yuan per unit. This price escalates to around 3,200 yuan per unit for gearboxes which its input torques ranging from 500 to 800 Nm, and further to about 3,800 yuan per set for those suited to 1,000 to 1,300 Nm. It is assumed that the cost savings resulting from the reduction in motor output torque are negligible ($C_{others} = 0$). By integrating these financial and technical parameters, a comprehensive analysis is presented in Fig. 6.

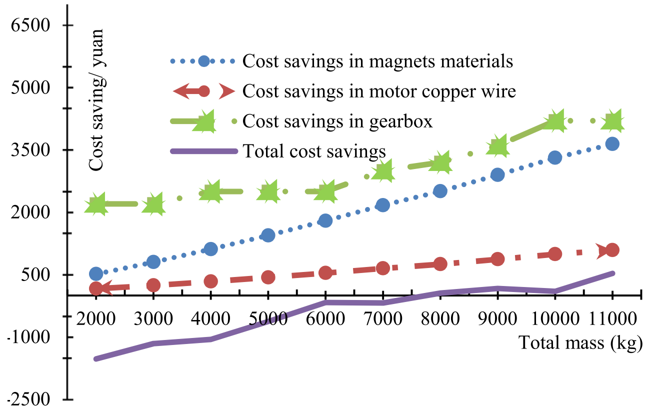


FIGURE 6. **Cost saving comparison of different drive systems.**

From Fig. 6, it can be seen that the single-motor direct drive system has a good cost advantage for ELVs with a lower total mass, and as the total mass of the vehicle gradually increases, the cost saving advantage of the motor with gearbox drive system becomes more and more obvious. In this paper, we can roughly conclude that when the total vehicle mass is about below 7500 kg, the motor direct drive system has more advantages in terms of material costs. If the total mass exceeds this value, the motor with gear drive system has more advantages in terms of material costs. The greater the total mass, the greater the cost saving advantage. This is why the single-motor, rear-axle integrated drive system is popular in electric vans, while large tonnage vehicles such as trucks, especially heavy trucks, are driven by a motor-gearbox system. It is important to note that the optimal balance between the direct drive and gear drive configurations will vary over time due to fluctuations in the cost of magnets, copper wires, and gearboxes. The equilibrium between the configurations of the direct drive system and the gear drive system will vary.

V. CONCLUSION

To understand the economic benefits and adaptability of different ELV powertrain topologies. The paper carries out theoretical calculations and comparative analyses of the powertrain of ELVs conjunction with the actual application, the advantages of different type powertrains on ELVs are explained from the application scenarios, development costs, driving feeling, et al. From the research results the following conclusions can be drawn. The topology of powertrain depends mainly on the total mass of the vehicle, the motor direct drive system is economically optimal for ELVs with a light payload, and as the payload mass increases the motor with gearbox drive system has a more pronounced cost advantage. In addition, from the perspective of material costs, the design of the powertrain motor necessitates the use of greater quantities of ferromagnetic material and copper wire in order to achieve a higher output torque. This results in increased costs, which is the primary rationale behind the preference of heavy-duty ELVs for motors with a gearbox drive system. These research results will not only contribute to a deeper understanding of current technological preferences but also guide future innovation and optimization efforts in the development of electric vehicles, ultimately fostering a more sustainable and cost-effective transportation ecosystem

The paper primarily examines and assesses the powertrain topology of ELV models across diverse operational contexts, with a focus on the associated costs of powertrain development. Given the extensive range of ELV specifications analysed in this paper, the parameter differences are considerable, and no complex simulation analysis of different powertrain systems is conducted. In the future, we intend to conduct a comprehensive and integrated simulation study for a specific ELV model.

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KEXIANG WEI received the Ph.D. degree in mechanical engineering from Shanghai Jiao Tong University, in 2006. From 2010 to 2011, he was invited to The University of Sydney, Australia, as a Visiting Scholar. In the following two years, he held a position as a Postdoctoral Researcher with Shanghai Jiao Tong University. He is currently a Professor of mechanical engineering with Hunan Institute of Engineering. His research interests include machinery dynamics, vibration control, condition monitoring, and fault diagnosis.

HONGGUANG ZHOU was born in Hunan, China, in 1997. He received the bachelor's degree from Hunan Institute of Technology, in 2019, and the master's degree in mechanical engineering from Xiangtan University, in 2023. His research interests include condition monitoring for electric vehicles.

XIONG SHU received the B.S. degree in mechanical engineering from Hunan Institute of Science and Technology, Hunan, China, in 2011, the M.S. degree in mechanical engineering from Changsha University of Science and Technology, and the Ph.D. degree from Hunan University of Science and Technology. Since 2012, he has been engaged in research on electric vehicles. His research interests include signal processing, fault diagnosis, and reliability analysis techniques of power train systems of electric vehicles.

SONGLIN XIE was born in Hunan, China, in 1995. He received the bachelor's and master's degrees in power engineering from Hunan Institute of Engineering, in 2017 and 2023, respectively. His research interests include condition monitoring of electric transmission systems.

KONLAYUTT PUNYAWUDHO received the Ph.D. degree in chemical engineering from the University of South Carolina, in 2010. He is currently a Professor of mechanical engineering with Chiang Mai University. His research interests include machinery dynamics, electric vehicle powertrains, condition monitoring, and electrochemical processes in battery and fuel cells.

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