An investigation of hybrid energy storage system in multi-speed electric vehicle

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Abstract

Thanks to the lower overall emission of Electric Vehicles, the promising transportation has attracted numerous attentions from industry and academy. However, as a consequence of lower energy density in widely adopted electrochemical energy source-battery, the driving range per charge presents a major barrier for electric vehicle's large-scale commercialization. Additionally, the limited battery life and extra costs associated with its replacement are other negative factors that hinder the development of electric vehicle. Currently, the one-speed gearbox is dominant in electric vehicles' market though it is only a trade-off between manufacturing cost and vehicle performance. Therefore, multi-speed electrified powertrains have been proposed and investigated in this paper to pursue the improvement of energy efficiency and dynamic performance without increasing battery size. In addition, supercapacitor, as the supplementary to battery, is combined with multi-speed transmissions to improve driving range and battery life. The combination of two advanced technologies are investigated in both B and E-class electric vehicle. Results demonstrate that considerable benefits attained for both small and large passenger vehicles through the application of multi-speed transmissions. The effectiveness of hybrid energy storage system in protecting battery from damage is verified. The relationship of hybrid energy storage system and multi-speed transmission is reported.

Key Words: Electric Vehicle, Hybrid energy storage system, Supercapacitor, Transmission

1. Introduction

Despite the long-term benefits of Battery Electric Vehicles (BEVs) to customers and environment [1], the initial cost and unsatisfactory driving range per charge present significant barriers for large-scale commercialization. It is necessary to pursue every possible avenue to improve powertrain efficiency, especially when electrochemical battery is not comparable with fossil fuel in energy density. Therefore, regenerative braking [2], SuperCapacitor (SC) [3] and multi-speed transmission [4] are considered as three of the most promising options to fill the gap between increasing driving capabilities and battery technology development.

The application of multi-speed transmissions to Electric Vehicle (EV) seeks to improve the operating efficiency of motor and enhance driving performance [5]. A infinitely variable transmission was proposed by Bottiglione to reduce energy consumption for EV [6]. An optimized two-speed automatic transmission was integrated into an electric commercial van [7] to improve dynamic and economic performance. The effects of adding a four-speed eDCT to an EV was tested by a UK company [8]. These make up a handful of the available literature that has evaluated the improved economy of adding multispeed transmissions to BEVs. Considering the main difficulties in achieving this are the development of very efficient transmission systems and integrating this design with the vehicle powertrain development, whilst simultaneously maintaining the smooth driving experience of EV, a comparative study of energy consumption and costs of alternative BEV transmissions demonstrated that both two-speed DCT and simplified CVT can improve the overall powertrain efficiency (7%-15% subjecting to cycles), save battery energy (2.6%-14.4% subjecting to cycles) and reduce customer costs ($1815 and $1134 respectively) [9]. Ren.et.al. [10] showed a brief comparison of 1-4 speeds EV, which adopted several subjective ratios and unrealistic shifting algorithm. In summary, the aforementioned studies analysed the complicated relationship of gear numbers design, gear ratios selection, shifting schedules design and related cost and benefits for BEVs. Specifically, following points were missed in the most of previous multi-speed BEV related papers:

1. Structure analysis of selected transmission;
2. Ratios design for multi-speed transmission on BEV based on the specified motor characteristics and target vehicle performance;
3. Shifting schedules design based on selected gear ratios for various speeds BEV;
4. Detailed comparison of potential cost (efficiency loss and weight increasing) and benefit (driving range extend and energy consumption reducing)

Based on state-of-art battery technology, battery design has to carry out the trade-off among specific energy, specific power, and cycle life. The desire for achieving higher specific energy, power density and cycle life has led to some proposals that the energy storage system on BEV and Hybrid Electric Vehicle (HEV) should be a hybridization of an energy source and a power source [11]. Supercapacitors are characterized by a much higher specific power but a much lower specific energy compared to traditional batteries. The merits of SC arise from their high power capability based on ultra-low internal resistance, wide operating temperature range, minimal maintenance, relatively high abuse tolerance to over-charging and over temperature, high cycling capability and reasonable price. Although the energy specific cost of the SC is high relative to batteries due to its modest specific energy density, the specific cost of power is just the reverse, regardless of type. Combining both energy storage (battery and SC) technologies together in an appropriate proportion [12] results in affordable Hybrid Energy Storage System (HESS) with high energy availability combined with high power and high efficiency. A similar result was achieved in a bus HESS by using Sliding-mode and Lyapunov function[11]. The application of HESS by Pay [13] where SC supplement the conventional battery pack to both maximize the recovery of brake energy, and to improve battery life span with the capability of high C rate discharging and charging, provides an important addition to hybrid electric vehicles in general and electric vehicles in particular. However, the large storage capacity of battery EVs, typically greater than 20kWh, may reduce the impact of SC in comparison to hybrid vehicles which have a lower battery capacity. For instance, Toyota Prius, as the most successful hybrid vehicle in the world, only has a 1.2 kWh lithium-ion battery [14]. Ali Castaings et al. [15] proposed two real-time energy management strategies which gave more consideration in system operation safety in comparison to efficiency.

Although aforementioned papers have shown the novel, optimized and well-developed approaches structures and models, few of them undertake a comprehensive investigation of vehicle performance after integrating all these beneficial factors, i.e. HESS, regenerative braking and multi-speed transmission together. It is worth investigating whether these new technologies cooperate well with each other and if they are mutually beneficial. There have been some studies investigating the application of multi-speed EV platforms for studying the vehicle performance [4], optimal selection of gear ratios [16] and shift schedule [17] for two-speed BEV, and demonstrate the dependency of the designed vehicle on driving cycle during analysis. This paper expands this research into evaluation of four-speed EVs and the application of these transmissions to alternative vehicle classes.

The purpose of this paper is to therefore present the findings of an evaluation study into the application of a number of variables associated with the development of modern electric vehicles. In addition to the comparison of the two alternative vehicle platforms, B-class and E-class, this paper will investigate a number of alternative considerations, including:

1. Application of single and different multi-speed transmissions
2. Application of hybrid energy storage devices in multi-speed BEV

The intention of this paper is to cover a wide range of configurations for BEVs considering both transmission arrangements and various forms of energy storage. To achieve this the remainder of the papers is divided into the following chapters: 1) the alternative transmission configurations are introduced and the impact of gear ratio selection is discussed, 2) the EV performance are summarized based on various powertrain architectures 3) different energy storage system configurations are discussed and presented, simulation results are presented and compared, and 4) the paper is summarized and conclusions are drawn based on the results.

2. Alternative transmission configurations

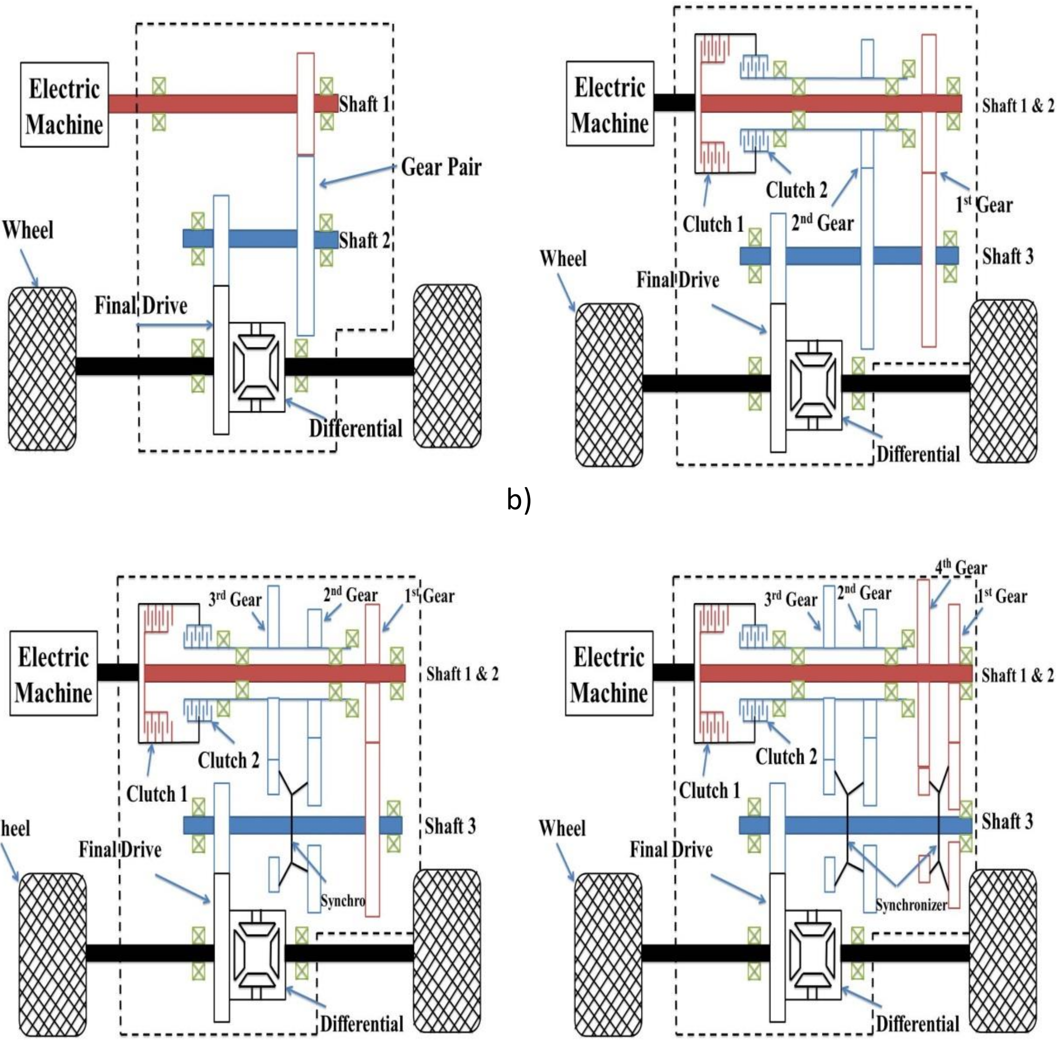
Simulations are carried out to compare the alternative platforms, this section summarizes the simulation parameters each configuration. For the purpose of this paper two extremes of vehicle class are evaluated. At the small end of the size spectrum there is the B-Class platform, often referred to as superminis. The large vehicle platform that will be studied in this paper is the executive sedan or E-Class vehicle. Vehicle characteristics are noted in the following sections.

2.1 electric vehicle configuration

The specification of B-class car, covering the Supermini/Subcompact/City/Small car segment and E-class car, covering the Executive/Large/Full size car segment are presented in Table 1A in appendix, based on [14], which includes an additional 200 kg weight to [18] to simulate a full load circumstance. Also note that SC should be added to the vehicle mass, depending on the configuration being studied.

2.1.1 Single speed electric vehicle configuration

Single speed EVs (Fig.1 (a)) is the convention in current vehicles on the market, including the BMW i3, Mitsubishi iMIEV, Nissan Leaf and all Tesla models. Generally speaking, the reasoning behind this is a combination of the capability to meet a wide range of driving operating conditions using the electric machine and the desire for maximum powertrain efficiency. Depending on the motor design and the desired performance of the vehicle, the transmission will typically include one fixed ratio and one final drive gear ratio.



a) b)

c) d)

Figure 1: One-speed (a) and two (b), three (c), four (d)-speed DCT electric vehicle schematic

2.1.2 Two, three and four speeds electric vehicle configuration

A two-speed BEV, shown in Fig.1 (b), or even multi-speed BEVs, shown in Fig.1 (c,d), decouple the launch, top speed, and economic driving requirements for the vehicle from the motor speed and torque range through the application of multiple gear ratios likely improve the overall operating performance of the vehicle. The benefits of using two or more speeds are:

1. Improved motor efficiency over the vehicle driving range
2. Decoupled top speed and acceleration capabilities

The disadvantages include:

1. Increased weight from additional components
2. Poorer transmission efficiency
3. Higher manufacturing costs

The two, three and four speeds transmissions include two sets of parallel gears coupled with a common clutch to the electric machine. Regarding two-speed transmission, no synchroniser is used and shifting is performed between clutches. In terms of three speed transmission, a synchroniser pair is used for first and third gears to select alternative ratios, while the four-speed structure have two synchroniser pairs.

Whilst multi-speed transmissions allow for independent optimization of performance characteristics, the most significant impact is the application of multispeed transmissions increases the losses present through clutches, gear mesh and so on. Impact of efficiency can be viewed in terms of different components [19], for the driveline there are several component losses that can be approximated for rapid assessment of variation of transmission loss:

- Differential ∼5%
- Single gear ratio friction loss 1% (only the gear pair under load)
- Single gear ratio viscous loss 1% (each gear pair spinning in lubricant)
- Wet clutch losses 2∼3%
- Synchronizer mechanism 1∼2%

The implication of such estimation is the changing from a single to two-speed design will increase losses by up to 4∼5% (less if dry clutches are used) but further additions will only increase losses by 2∼3% per gear. Furthermore, if electromechanical actuators are used then minimal parasitic losses for the transmission control unit will be incurred [20]. The overall efficiencies of multi-speed gearbox are summarised in the Table.1

Table 1: Multi-Speed dual clutch transmission efficiency summary

Transmission Type	One-Speed	Two-Speed	Three-Speed	Four-Speed
Efficiency	0.93	0.86	0.83	0.80

2.2 Motor power rating

The acceleration time, top speed, and grade ability have large effect on the vehicle driving performance. In EV drivetrain design, proper motor power rating and transmission parameters are the primary considerations to meet the performance specification. The design of all these parameters depends mostly on the speed–power (torque) characteristics of the traction motor. This characteristic is represented by a speed ratio x, also known as extended-speed range defined as the ratio of its maximum speed to its base speed.

For passenger cars, acceleration performance is more important than maximum cruising speed and grade ability, since it is the acceleration requirement rather than the maximum cruising speed or the gradeability that dictate the power rating of the motor drive. The total tractive power for accelerating the vehicle from zero to speed V_f in $t_a = 10$ seconds can be finally obtained as ([21],Eq.4.12):

$$P_t = \frac{({V_f}^2+{V_b}^2)\delta M}{2t_a} + \frac{2Mgf_rV_f}{3} + \frac{\rho_a C_D A_f {V_f}^3}{5} \tag{1}$$

V_b is the initial velocity; δM stands for equivalent mass including rotating parts; g is the gravity acceleration; f_r represents the coefficient of rolling resistance; ρ_a is air density; C_D represents aerodynamic drag coefficient; A_f is vehicle frontal area. Substituting the specifications of B-class and E-class EV in Table.1A to Eq. (1), the required motor rating power, to accelerate the vehicle from 0 to 100km/h, are estimated to be around P_{t_B}= 59 kw and P_{t_E}= 111 kw respectively. Although a greater speed ratio will significantly lower the motor power rating requirement [22] and improve vehicular dynamic performance [23], especially for initial accelerating, they are set 2.5 and 3 respectively for selected motors (Table.A2) in this study to achieve a trade-off of vehicular dynamic performance and motor shape, which is mainly determined by motor type and control strategy [24].

2.3 Transmission ratio design

Although the transmission design for PEV still need to follow the basic rules in mechanism, the characteristics of EM determines the ratio range of PEV transmission is not necessary as wide as traditional vehicles. The greatest traction requirement is well-known to determine the ratio of the gear with the largest torque multiplication. The capability to climb inclines is important for entering and leaving steep driveways and parking structures [25]. The largest overall gear ratio required for the powertrain is set based on this need for passenger vehicles, it uses the ratio of rolling resistance and incline load for a specified grade divided by the maximum motor torque multiplied by the overall powertrain efficiency, given in Eq.(2):

$$\gamma_{Max} = r_t(MgC_R \cos\varphi + Mg \sin\varphi + \rho C_D A v^2/2)/(T_{EM}\eta_{PT}) \tag{2}$$

A climbing performance of φ_{max} greater than 50% is normally required for an unloaded passenger car. This ensures that a trailer can be towed and steep ramps overcome with ease [26].

The maximum speed achieved in the vehicle can then be used to determine the lowest possible ratio:

$$\gamma_{speed} \leq 3.6\pi r_t N_{max}/(30V_{max}) \tag{3}$$

This ratio can be checked against the capability of the motor to supply torque at this speed by dividing the rolling resistance and aerodynamic drag by the maximum motor torque at its maximum speed.

$$\gamma_{min,torque} \geq r_t(C_R M_V g cos\varphi + M_V g sin\varphi + C_D \rho A_V V^2)/(\eta_{PT} T_{@maxRPM}) \tag{4}$$

Substitute vehicle specifications of Table.1A to Eqs. (2-4), the gear ratio range of B-Class and E-Class vehicle can be determined as:

$$\text{B-Class:} \begin{cases} \gamma_{Max} \geq 9.5 \\ \gamma_{min,speed} \leq 5.1 \\ \gamma_{min,torque} \geq 2.6 \end{cases} \qquad (5)$$

$$\text{E-Class:} \begin{cases} \gamma_{Max} \geq 11.3 \\ \gamma_{min,speed} \leq 5.4 \\ \gamma_{min,torque} \geq 4.5 \end{cases} \qquad (6)$$

The ratio requirement for top speed is in conflict with that for grade in single speed ratio design, which means an inevitable dynamic performance trade-off for single speed transmission. There is no doubt that both of speed and grade requirements can be covered though applying a more powerful motor. However, it will significantly increase the powertrain cost. One of the primary goals in this study is evaluating whether the combination of multi-speed transmission, SC and rated motor can achieve a similar or better performance, comparing to the available EVs on the market, in terms of cost/performance. Therefore, the ratios of single speed transmission is set to cover the speed limit of most countries around the world [27], meanwhile, providing torque as much as possible:

$$\begin{cases} \gamma_{\mathrm{B}} = 1.56, \ \gamma_{\mathrm{Final}} = 3.19 \\ \gamma_{\mathrm{B}} = 2.15, \ \gamma_{\mathrm{Final}} = 4.09 \end{cases} \qquad (7)$$

For a two-speed DCT, 1st gear is selected for accelerating and climbing, meets requirement in Eq.(2). The 2nd gear is used to cruise at high speed, meeting requirement in equation Eq.(3) and (4). A greater 2nd ratio and a lower 1st ratio will prevent motor operating at extreme conditions, e.g. maximum torque output, maximum speed output, and help motor achieve a higher average efficiency. Furthermore, aiming at future experimental validation and commercialization, the maximum and minimum gear ratios selected in this study is closing to the real DCT products on market (B-Class: [28], E-Class: [29]), in the meanwhile, sitting in the above defined range:

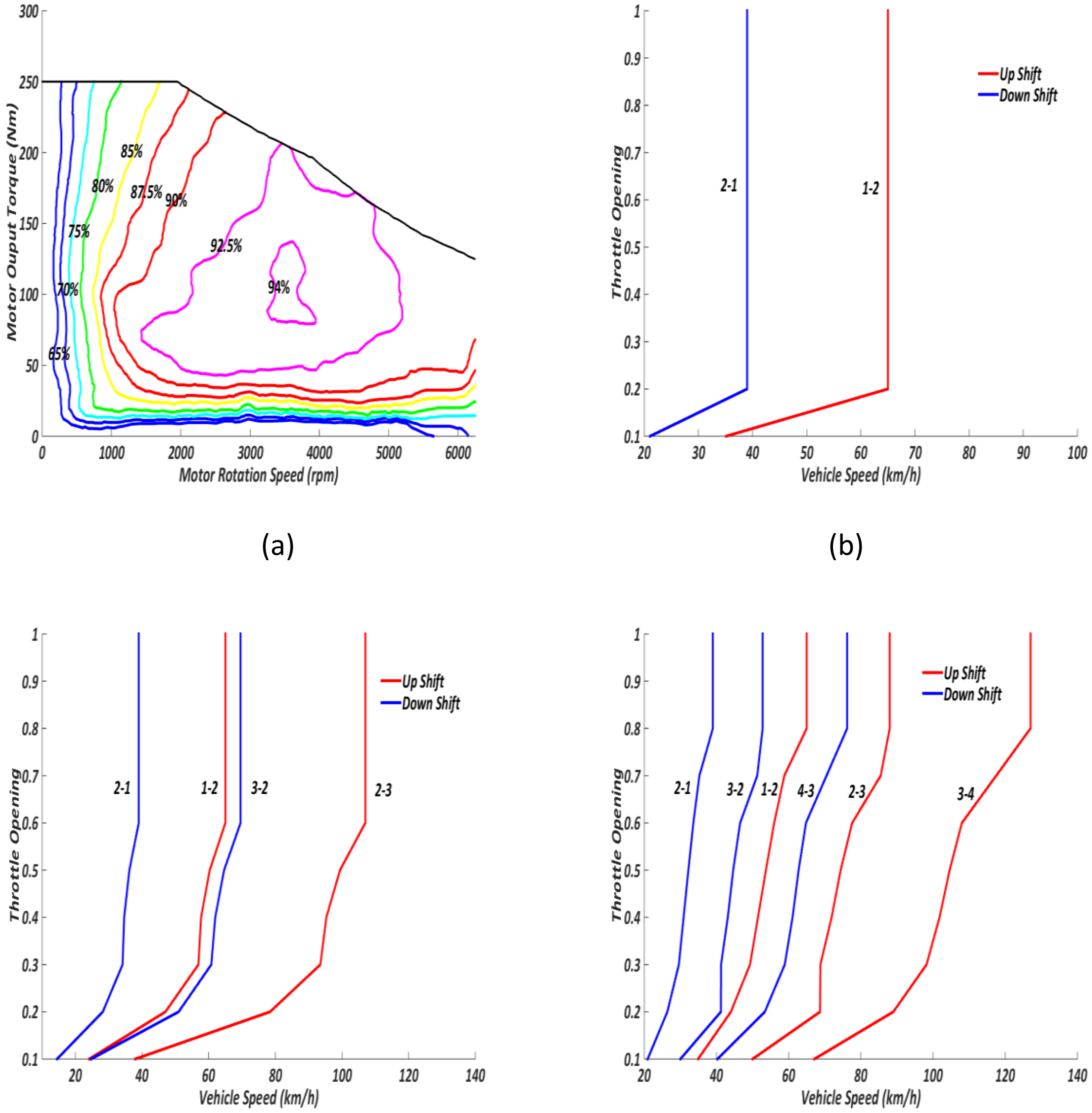
Table 2: Gear ratios of transmission systems for B-Class (E-Class) vehicle

Single Speed	Two-speed DCT	Three-speed DCT	Four-speed DCT
Transmission Ratio: 1.25 (2.15) Final Ratio: 4 (4.09)	Transmission Ratio: 1st : 4.46 (3.69) 2nd : 1.14 (1.03) Final Ratio: 3.19 (4.09)	Transmission Ratio: 1st : 4.46 (3.69) 2nd : 1.56 (1.41) 3rd : 1.14 (1.03) Final Ratio: 3.19 (4.09)	Transmission Ratio: 1st : 4.46 (3.69) 2nd : 2.51 (2.15) 3rd : 1.56 (1.41) 4th : 1.14 (1.03) Final Ratio: 3.19 (4.09)

To make this paper in an appropriate length, only full simulations are presented for B Class EV in the following sections, the results of all other simulations are summarized in table forms.

2.4 Shifting strategy

The gear shifting schedules of two, three and four speeds DCT, shown in Fig.2 , are based on a previous paper [9] that utilizes the mapped efficiency of the electric machine to maximize the driving efficiency of the powertrain depending on the selected gear ratio. It is worth noting that the vertical part of each shifting curve is the result of speed limitation by certain gear ratio.



(a) (b)

(c) (d)

Figure 2: Shifting Schedules of B-Class EV, (a) Motor Efficiency (b) Two-speed shifting schedule (c) Three-speed shifting schedule (d) Four-speed shifting schedule

Application of different ratios is required to meet or improve on a number of vehicle requirements, including acceleration, top speed, and average motor efficiency. These can be viewed in terms of the vehicle traction curve. The traction load F_T is defined using the maximum motor power as follows:

$$F_T = \eta_{PT} P_{max} / V \qquad (8)$$

P_{max} is the maximum power of motor; η_{PT} is the overall powertrain efficiency. The adhesion limit is the force required for the wheels to transit from rolling to sliding, and for a front wheel drive it is a function of (C_W) weight distribution, and (μ_S) tire static friction coefficient:

$$F_A = C_W \mu_S g M_v \qquad (9)$$

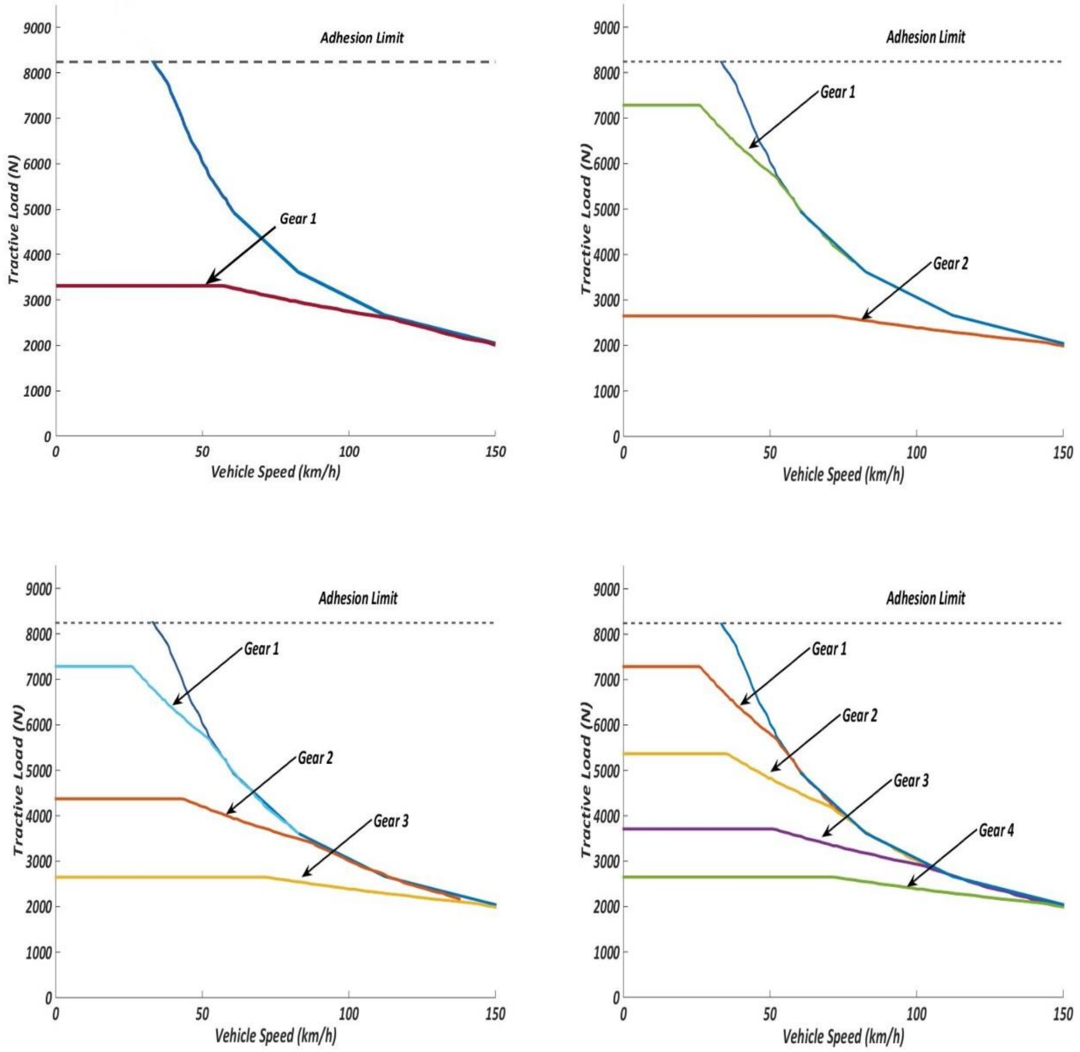


Figure 3: Traction curves of one, two, three, four speeds B-Class EV

Fig.3 shows the traction curve of all four configurations that are part of this study, which is a extension of previous work [30]. The dark blue curves in all four figures are the maximum traction load at the wheel, based on motor deliverable power. The clear benefit of the EV is that the constant power region of the motor matches well with the traction available, unlike conditions present in conventional vehicles. Thus it becomes beneficial to use fewer gears in comparison between ICE and electric vehicles.

3. Conventional energy storage system with multi-speed transmission

Considering the computational efficiency, a Matlab/Simulink® backward-facing model for energy efficiency simulation with different driving schedules is used in this study, which is shown in Fig.4. The model derives the required energy and torque from battery and motor according to driving patterns and vehicle dynamics, starting from speed profile of selected testing cycle. Then, the motor generated torque goes to wheel to propel vehicle through transmission and shafts. Given the selected transmission, corresponding ratios, shifting schedules and mechanical efficiency are applied automatically as in Fig.5.

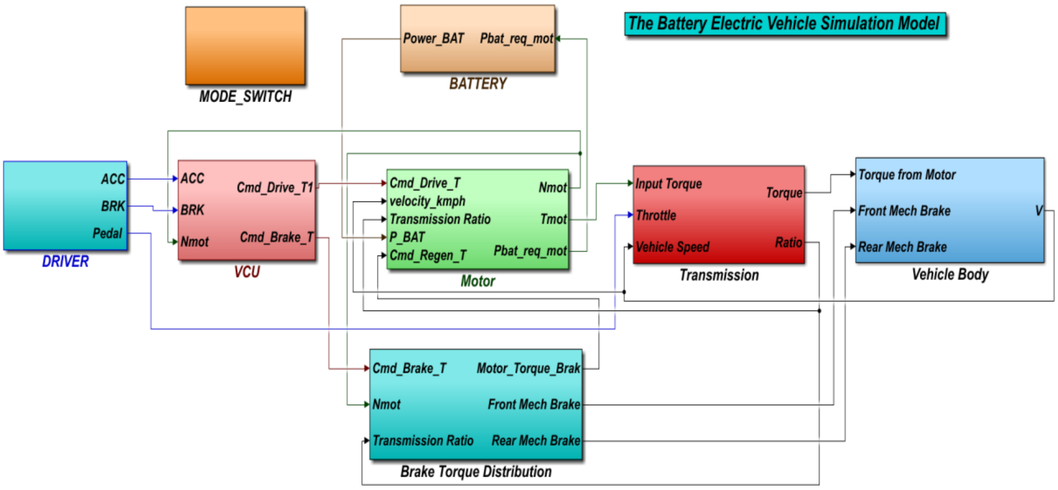


Figure 4: General view of vehicle Matlab/Simulation® model

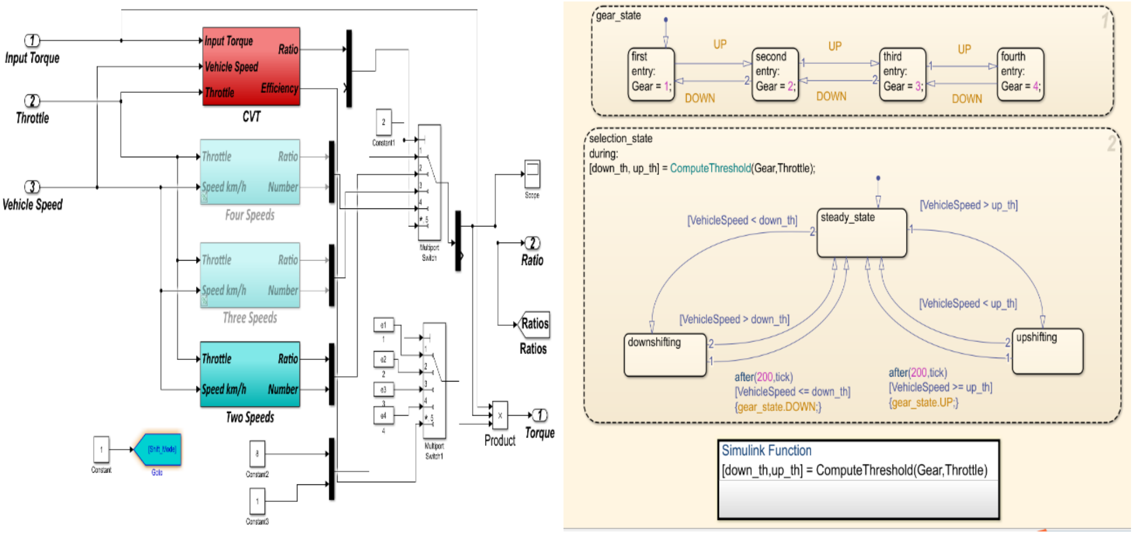


Figure 5: Alternative transmission model (left) and shifting strategy Stateflow® (right)

Conventionally, energy storage systems rely on the use of large electrochemical battery banks in EVs, which convert electrical energy into potential chemical energy during charging, and convert chemical energy into electric energy during discharging. Simulation results are presented for the conventional battery based alternative transmission configurations detailed in this section. Analysing will be based on a combined fuel economy testing cycle, which is calculated by averaging the city and highway (FTP75 and HWFET) fuel economies with weightings of 43 per cent and 57 per cent, respectively, through Eq. (10). An approximation of the 5-cycle fuel economy values can be calculated directly from the "unadjusted" FTP75 and HWFET fuel economy values by Eqs. (11) and (12) [31].

$$Combine_{KPK} = \frac{1}{\left(\frac{0.43}{[5-cycke\ City_{KPK}]} + \frac{0.57}{[5-cycke\ Highway_{KPK}]}\right)} \quad (10)$$

$$Highway_{KPK} = \frac{1}{\left(0.001376 + \frac{1.3466}{HWFET_{KPK}}\right)} \quad (11)$$

$$City_{KPK} = \frac{1}{\left(0.003259 + \frac{1.1805}{FET75_{KPK}}\right)} \quad (12)$$

KPK is the abbreviation of kWh per kilometre. Substitute simulation results into Eqs. (17- 19), the consumed electricity of BEV with various gear number in cycles are summarized in the Table.3 and 4.

The current average driving range per driver per day is between 40-50km in US [32], UK [33], Australia [34], Singapore [35] and China [36] major cities. However, this range is far more away from the requirement of average daily driving mileage for home-use personal vehicle. A short trip capability for EV is still an important factor for potential customers' willingness of purchasing. According to the study [37], the percentage of days in a whole year, when daily driving range does not exceeds 160 km, is over 95%. Considering a 32 km 'range buffer' for passenger vehicle [37], 200 km one-charge range is regarded as an appropriate range for most consumers who would charge once per day only, typically at home over night.

Table 3: Consumed electricity per 100km of multi-speed B-Class BEVs

kWh / 100 km	1-speed	2-speed	3-speed	4-speed
FTP75	13.05	11.31	11.8	12.83
HWFET	14.92	11.72	13.32	14.16
Combined Cycle	14.05	11.54	12.62	13.79
Energy Utilizing Rate Improvement	---	17.86%	10.18%	1.85%
Required battery capacity of 200km range*	36 kWh	29 kWh	32 kWh	35kWh

Table 4: Consumed electricity per 100km of multi-speed E-Class BEVs

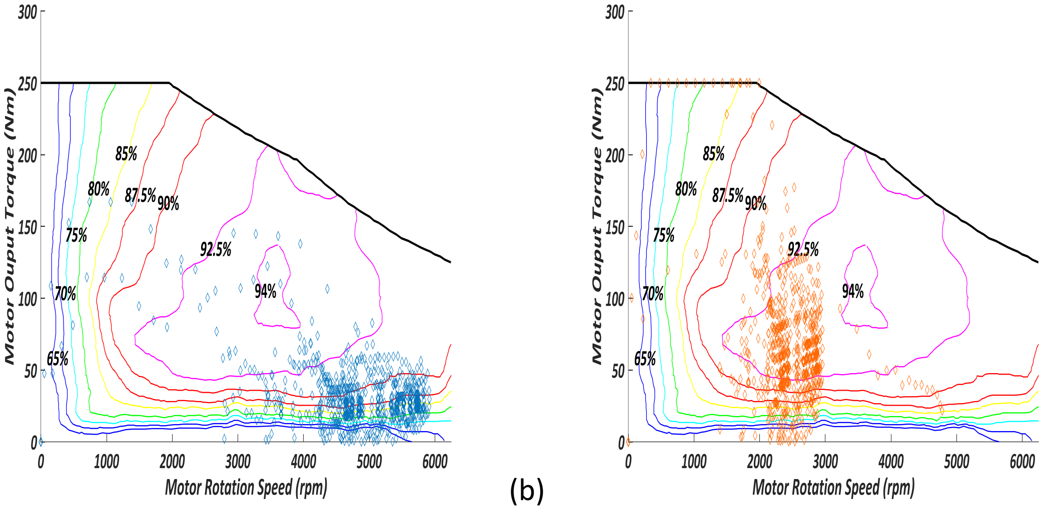
kWh / 100 km	1-speed	2-speed	3-speed	4-speed
FTP75	23.1	20.17	20.72	22.3
HWFET	22.45	19.08	20.56	21.84
Combined Cycle	22.73	19.54	20.63	22.04
Energy Utilizing Rate Improvement	0	14.03%	9.24%	3.04%
Required battery capacity for 200km range*	57 kWh	49 kWh	52 kWh	55 kWh

* The actual operating life of the battery is affected by the charging and discharging rates, Depth of Discharge (DOD), and other conditions such as temperature. Additionally, a normal 80% DOD is preferred in automobile application to effectively extend battery life cycle. Therefore, a 20% battery capacity design redundancy is included in this study. The required battery capacity, consequently, can be achieved.

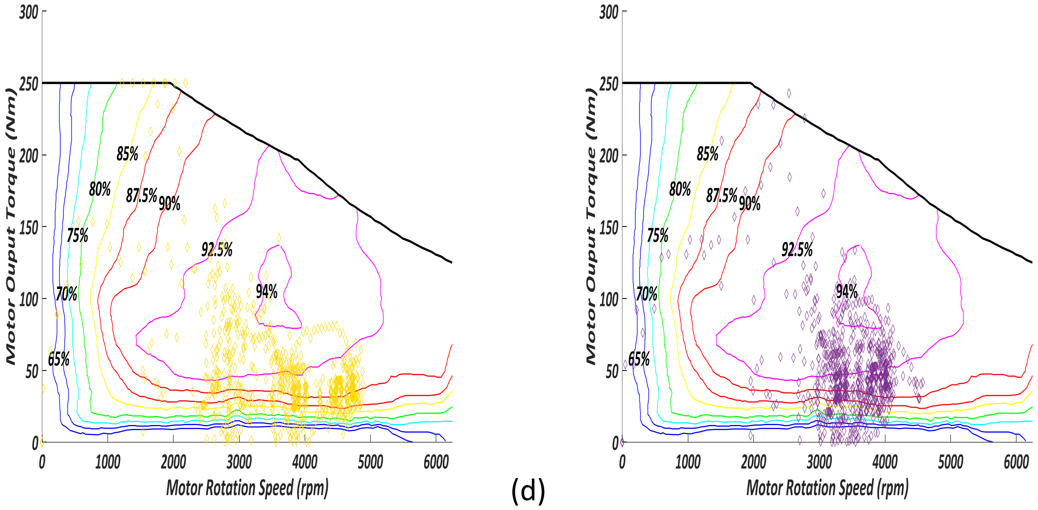
As shown in above tables, comparing to fixed ratio one gear BEV, one additional gear significantly improve energy utilizing efficiency by 17.86% in B-Class and 14.03% in E-Class respectively. Additionally, another gear does continuously improve the efficiency of B-Class BEV, but not as much as the first added one due to the increased energy loss in transmission. When the gear number goes to four, the benefit of energy saving by increasing motor efficiency is almost offset by the loss in transmission. Although the circumstance is similar in E-Class BEV, greater battery capacity reduction is recorded in all alternative powertrains comparing to B-Class vehicle.

Figures 6 and 7 demonstrate the motor operating traces with alternative multi-speed transmissions in driving cycles. Due to the trade-off ratio design in single speed transmission, motor has to work in the relatively low efficiency area large portions of the driving cycle, which outputs high speed and low torque. This is more prominent for high-speed cruising cycle (HWFET), in which motor operates at extremely high speed zones for most of time. With the help of additional gears in lower ratio, operating tracks move to more efficient operating regions. Comparing 2, 3, 4 speeds BEVs' motor efficiency, the intermediate gears help motor avoiding the low speed-high torque area in city cycle, which has higher speed, higher acceleration, and fewer stops per km and less idle time. In summary, the more gears transmissions have the fewer motor operating tracks in low efficiency area.

Specifically, two-speed transmission help motor avoid high-speed & low torque area, comparing to single speed powertrain in HWFET. Three-speed transmission improve average motor operating efficiency slightly higher through more evenly spread gear ratios. Four-speed transmission show the ability to narrow the motor operation range by providing more available ratios to find the most appropriate one. Speaking to FTP75 city driving cycle, all multi-speed powertrains avoid high speed motor operating, which occurs to single speed one. The difference of operating tracks in alternative powertrains is not as distinct as that in HWFET.

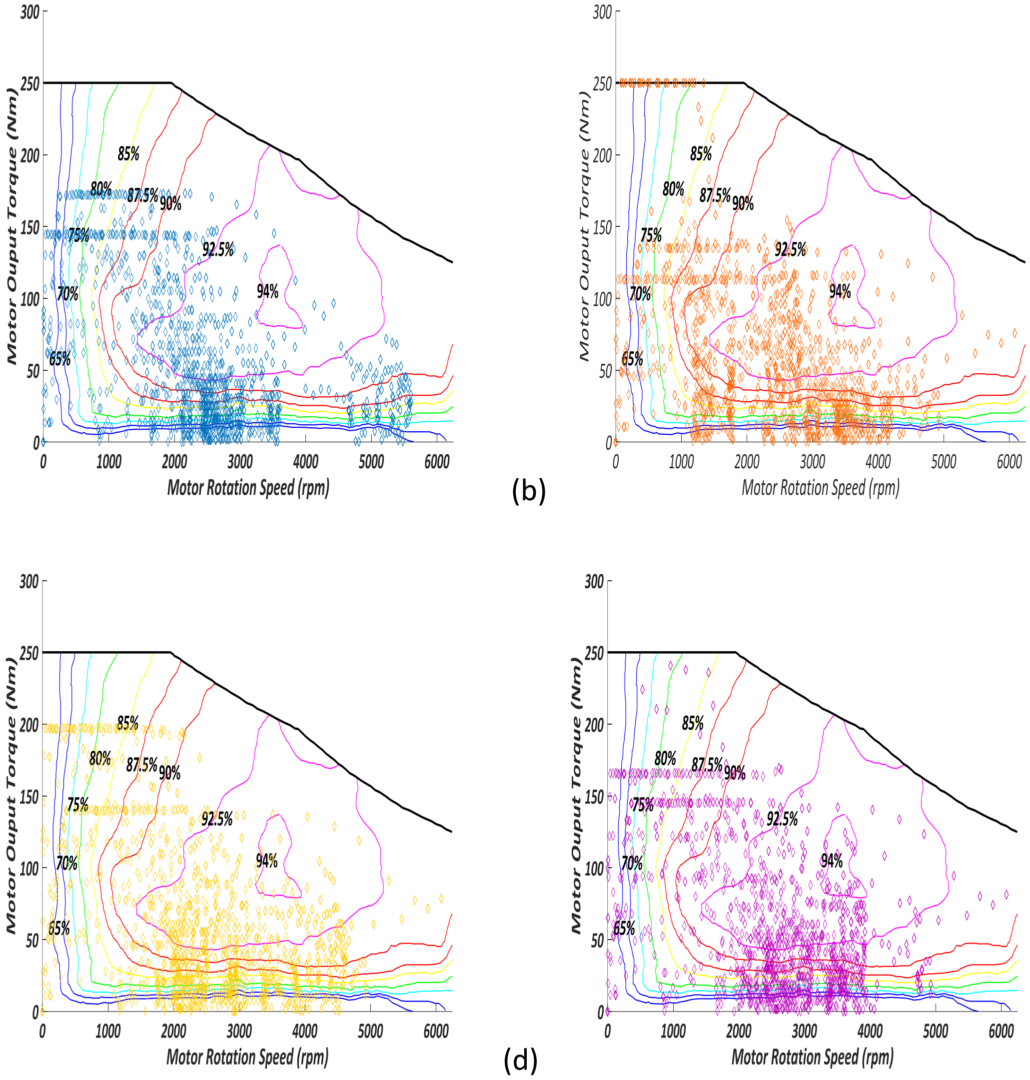


(a) (b)



(c) (d)

Figure 6: Motor operating tracks in HWFET of B-Class BEV (a) single speed (b) two-speed (c) three-speed (d) four-speed



(a) (b)

(c) (d)

Figure 7: Motor operating tracks in FTP75 of B-Class BEV (a) single speed (b) two-speed (c) three-speed (d) four-speed

Another significant benefit of multi-speed transmission based BEV is the reduction of battery size. One more gear, compared to single speed, can reduce 4-5 kWh battery capacity requirements. Increasing speeds to three and four does not save much more cost on battery. The increased cost of multi-speed transmissions is taken into consideration in the following section to investigate if the benefits from battery reduction will be offset. It seems necessary to add the 4th gear to E-Class BEV.

According to the method of "design using characteristic value" [38], the transmission relative selling price (RSP) can be related to the input torque T_1, the maximum ratio $i_{G,max}$, and the number of gears z, shown in Eq. (6).

$$RSP = 0.0183 \times (i_{G,max} \times T_1)^{0.512} z^{0.256} \tag{13}$$

Based on the data in Table.A2 and Table.2, the estimated gearbox relative selling prices (RSP) are presented in Table.5. However, a one-speed transmission is more similar to the main reducer, or final drive ratio, in multi-speed transmissions rather an actual transmission. The estimated price for a one-speed transmission using RSP is unrealistic. Therefore, its price is reduced to zero in this study by assuming that the final drive gear is common to all configurations. Allowing evaluation of the multi-speed transmissions capacity to compensate for the cost of the transmission through savings realised in battery energy storage and component manufacturing costs.

Table 5: Estimated gearboxes relative selling price

Type	$T_1 = 350\ Nm$, $z = 6, i_{G,max} = 5.5$	1-speed	2-speed	3-speed	4-speed
RSP (B-Class)	1	0.52	0.62	0.69	0.74
Increased Cost Comparing to Single Speed (B-Class)	N/A	0	+ 62%	+ 11%	+ 7%
RSP (E-Class)	1	0.64	0.77	0.85	0.92
Increased Cost Comparing to Single Speed (E-Class)	N/A	0	+ 20%	+ 10%	+ 8%

According to study [39], the saved cost on electricity and battery manufacturing and increased cost on transmission are shown in Table.6 and 7, which are based on the assumption of 250,000 km vehicle lifespan, \$ 800/kWh Li-ion battery pack price (Battery Management System included) [2], and \$ 0.3/kWh electricity cost [2].

Table 6: Cost saves in manufacturing and ownership by transmission for B-Class BEV

		1-speed	2-speed	3-speed	4-speed
Manufacturing cost save	Battery components	0	-5600(USD)	-3200(USD)	-800(USD)
	Transmission	0	+595(USD)	+ 660(USD)	+ 707(USD)
	Total	0	-5005(USD)	-2540(USD)	-93(USD)

Ownership cost save	Electricity for 250000 km*	0	-1883(USD)	-1073(USD)	-195(USD)
Total			-6888(USD)	-3613(USD)	-288(USD)

Table 7: Cost saves in manufacturing and ownership by transmission for E-Class BEV

		1-speed	2-speed	3-speed	4-speed
Manufacturing cost save	Battery components	0	-6400(USD)	-4000(USD)	-1600(USD)
	Transmission	0	+959(USD)	+1055(USD)	+1139(USD)
	Total	0	-5441(USD)	-2995(USD)	-461(USD)
Ownership cost save	Electricity for 250000 km*	0	-2393(USD)	-1575(USD)	-518(USD)
Total			-7834(USD)	-4570(USD)	-979(USD)

*The charging efficiency with Level 2 standard voltage is 81% [40], as a result of same 90% efficiency for both plug-in charger and lithium-ion battery charge/discharge [41].

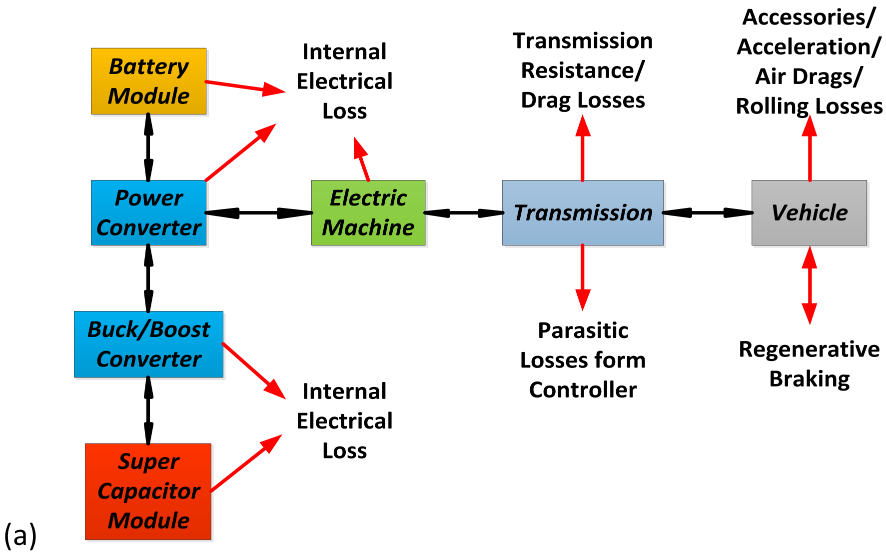
Regarding B-Class BEVs, the two-speed transmission achieves the highest cost saving in the long term, almost double of three-speed. Four-speed DCT platforms offer the least cost savings, although may experience a more comfortable ride as shift performance is directly impacted on by the step size between consecutive gear ratios [26]. In perspective of initial selling price, BEVs equipped with three and four-speed transmissions are more expensive than two-speeds due to the additional components cost. Additionally, the requirement of manufacturing and control of three-speed DCT is much higher than two-speed DCT, which does not require synchronizers and achieves gear change only with the primary clutch. In terms of E-Class BEV, all alternative multi-speed transmission outperform I themselves in B-Class vehicle, though two-speed transmission is still the most promising one to reduce manufacture and ownership cost.

4. Hybrid battery-supercapacitor energy storage systems

The complementary application of hybrid supercapacitor-battery energy storage system to alternative multi-speed transmissions based conventional battery EV is investigated in this section. Figure 8 provides the general power flow of the EV platforms to be studied, including provision for SC in the system.

Energy management systems (EMS) make decisions on charge/discharge rates on the basis of load demands, cell voltage, current, and temperature measurements, and estimated battery SoC, capacity, impedance, etc [42]. Since battery has a longer lifetime if exposed to low frequency charges and discharges with input/output current rate as low as possible [43,44]. The desirable result is that peak currents are mitigated in the battery and the SoC of battery is more stable than without the SC, and that regenerated energy from braking as is maximized.

Considering the battery voltage is relative stable for short durations, the current is then proportion to power, 10 kW threshold (T, Fig.8(b)), namely 0.35C current for a 70 Ah, 438 V battery, is set as the threshold of SC intervention in HESS to relieve the battery stress and extend lifetime cycles [45]. Overall, eight different working states of HESS is determined by the current direction, power level, battery SOC and SC SOC as shown in Fig.8(b). The threshold control method adopted in this article is industry oriented robustness, effective, and easy to realize, providing a fair platform to investigate to performance of the HESS and multi-speed transmission combination, although the results may not as fancy as others in terms of energy flow control.



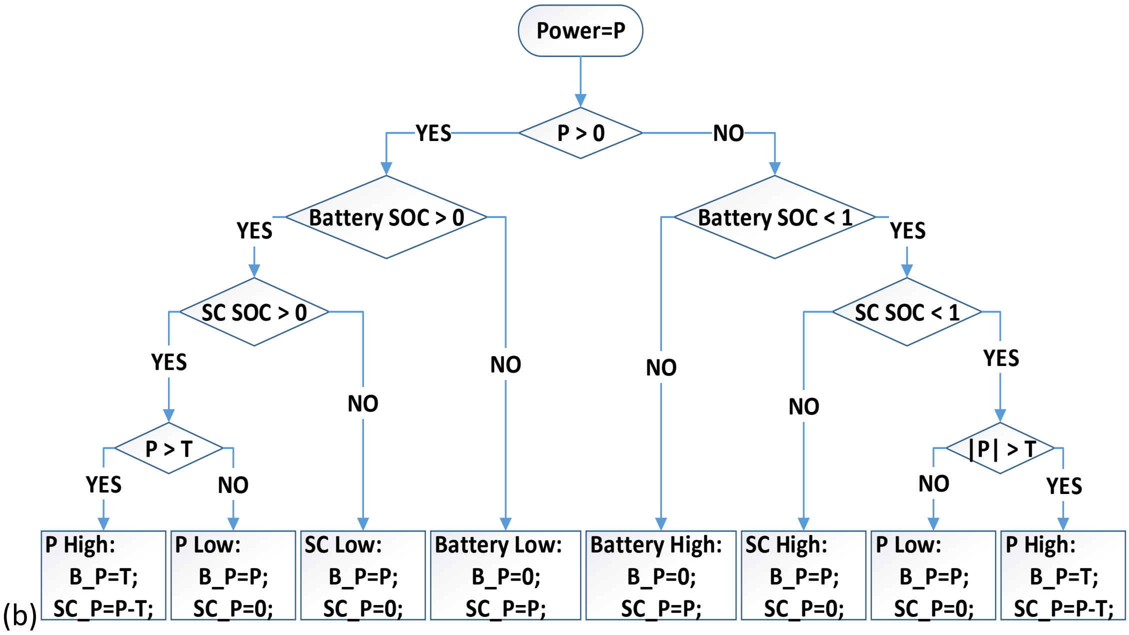
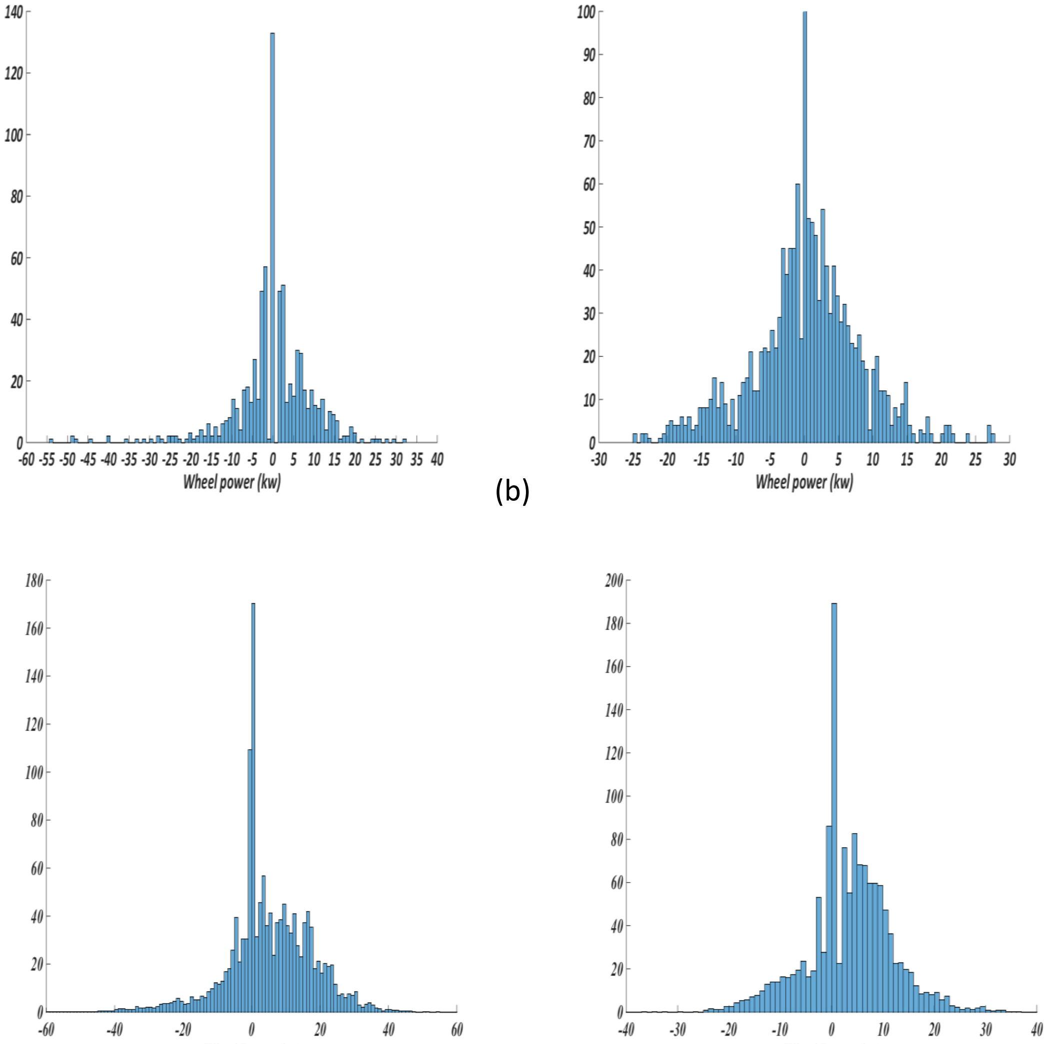


Figure 8: Power flow of vehicle powertrains, (a) including losses, and provision for supercapacitors for hybrid energy storage system (b) energy flow control strategy, T=10kw

The discharging and charging profile of battery is highly varied due to the frequent stop and go events, especially in metropolitan areas. Comparing to the peak power required to accelerate vehicle and climb hills, the average required power is relatively low as shown by the frequency histogram of power in Fig. 9.



(a) (b)

(c) (d)

Figure 9: B-class vehicle frequency histogram of power in HWFET (a), FTP75 (b), LA-92 (c) and UDDS (d)

For daily driving patterns, frequent start-stop cycles are common and most of them are low-power required events, which means they are relatively small current events in constant battery operating voltage. It becomes more obvious in the real-world driving, especially in congested metropolitans. However, the conventional energy storage system-battery still needs to carry sufficient spare power to meet the rare, but vital, high-power requests, typically observed in hard acceleration and high-speed cruising on hills. Consequently, most of spare power in battery is wasted and add unnecessary weight and cost to vehicle. Although, the low energy density excludes the possibility of using commercial available SC as the main power source to improve the DOD or driving range performance of EV, it could reduce power requirement of battery and keep it from the damage by over-discharge/charge.

Considering the high-power required events in typical cycles (high than 20 kW in Fig.9) only take a small proportion, a 0.17 kWh SC is selected in this study as the supplementary power source in the HESS. The combinations of battery with different SC capacities will be discussed and compared in term of cost in the following sections.

Fig.10-11 show the power variation of HESS, battery and SC respectively in FTP75 and HWFET. The charging/discharging power of battery is well controlled and kept lower than the threshold for most of time.

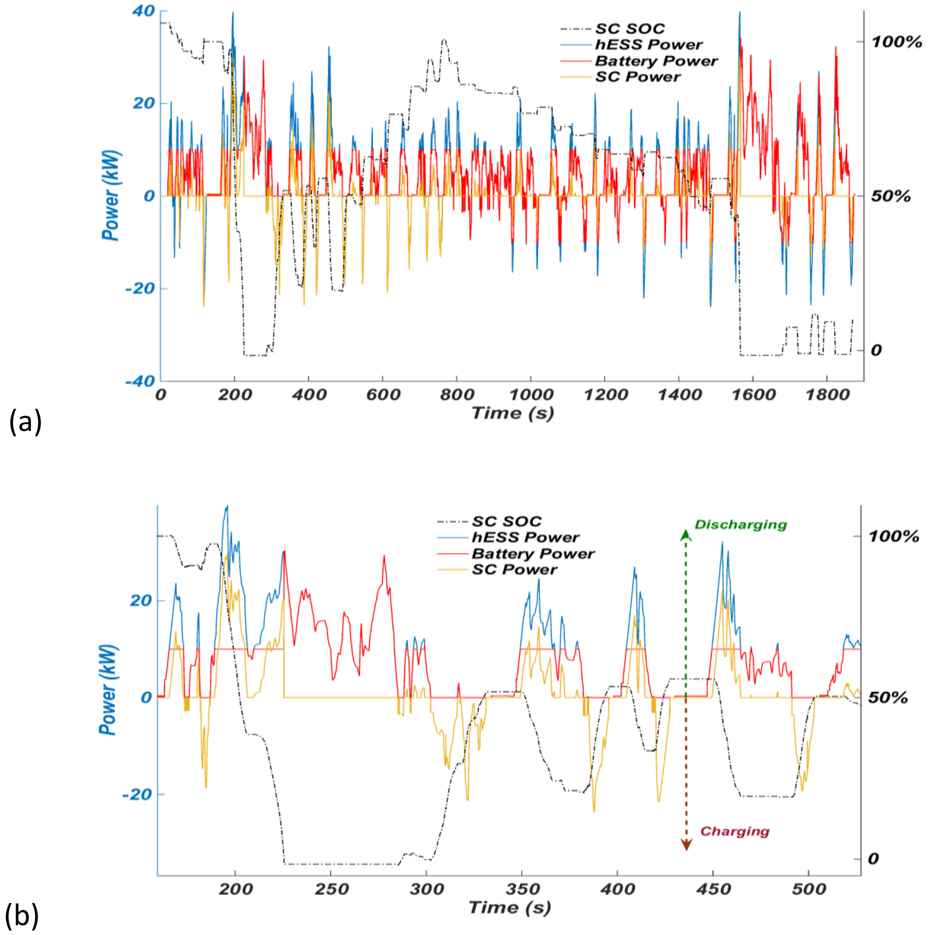
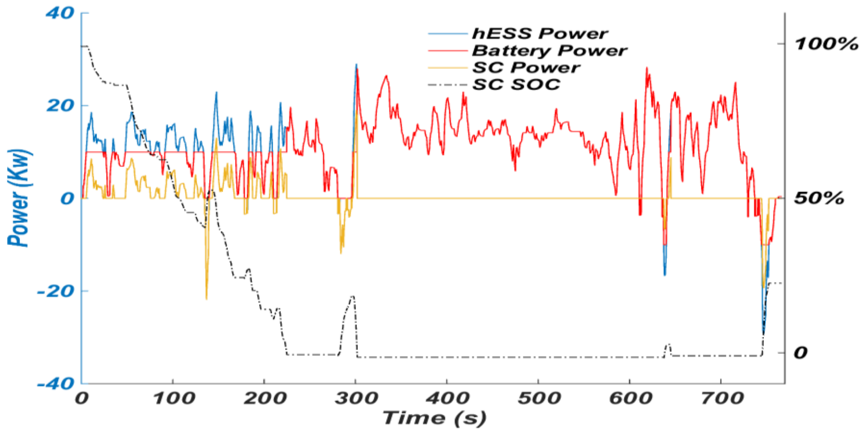


Figure 10: Partial current profiles of HESS, battery and SC in FTP75 (a) full range (b) Partial



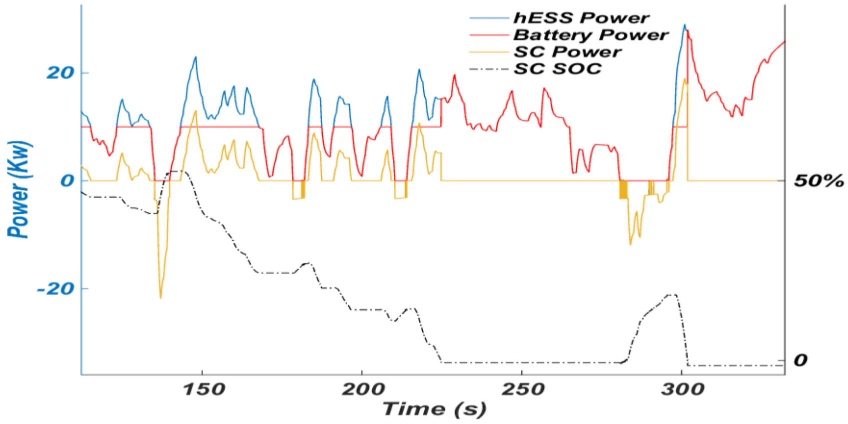


Figure 11: Partial current profiles of HESS, battery and SC in HWFET (a) full range (b) Partial

Fig.10 to Fig.11 clearly show the battery power over the threshold due to SC reaching a low SoC. Increasing SC capacity will reduce the possibility of overshooting power in battery, however, the more than \$10USD/Wh unit price [3] presents a significant barrier. An investigation on the relationship of SC capacity and its economic benefit is carried out in the following section.

Battery, as the most expensive component of HEV/BEV, its service length plays an important role in vehicle's lifetime maintenance cost. By now, the average battery price in terms of \$/kWh is around \$800 including battery management system [3,9], which accounts for almost half of the manufacturing cost for a general C-Class BEV [9]. The fading rate of lithium-ion battery mainly depends on several factors, named as stress factors, i.e. DOD, SoC, C rate (charging and discharging), temperature. Eq.14, proposed by [46], reveals that, excepting DOD and temperature, the average and deviation of SoC has significant and complicated effects on battery capacity fading rate. Furthermore, the impact of C rate can be represented by temperature variation because it is a result of ohmic heating.

$$\xi(\mathrm{T}, SoC_{avg}, SoC_{dev}, Ah) = \sum_i^E \left(\left(k_1 SoC_{dev,i} e^{(k_2 SoC_{avg,i})} + k_3 e^{k_4 SoC_{dev,i}} \right) e^{\left(-\frac{E_a}{R} \left(\frac{1}{T_i} - \frac{1}{T_{ref}} \right) \right)} \right) Ah_i \tag{14}$$

$$SoC_{avg} = \frac{1}{\Delta Ah_m} \int_{Ah_{m-1}}^{Ah_m} SoC(Ah) dAh \tag{15}$$

$$SoC_{dev} = \sqrt{\frac{3}{\Delta Ah_m} \int_{Ah_{m-1}}^{Ah_m} (SoC(Ah) - SoC_{avg})^2 dAh} \tag{16}$$

ξ is the total battery capacity fade in Ah; SoC_{avg} is the average Soc during a testing event; SoC_{dev} is the normalized standard deviation; Ah_{m-1} is the initial amount of charge (Unit: Ah); Ah_m is the final amount of charge (Unit: Ah); R is the gas constant; E_a is the activation energy (78.06 kmol/J); k1=-4.092e-4; k2=-2.167; k3=1.408e-5; k4=6.13 [46] .

Although a standardized dynamic load profile [47] is likely to present a better performance of lifetime cycles improvement and current reduction, this study focuses on the daily normal driving, which most of the charging/discharging current events spread in 0-0.2C given the , and barely over 1C (2%) [48]. Therefore, typical driving cycles are more closely to aligned reality to investigate the battery capacity fading, rather than the high C rate current profiles. The annual battery capacity fade (Ah) of battery electric vehicle is summarized in Table.8, which is based on a provisional 50 Km drive per day for major cities in the world [32–36,49]. It is clear in the table that one-speed and two-speed HESS achieve similar annual battery fading rate improvement in each cycle, at the same time, their performance are more balanced comparing to three and four-speed HESS. The reason of three and four-speed HESS achieving bigger improvement in FTP75 and less improvement in HWFET is the intermedia gear ratios resulting a relatively big variation of battery SOC, i.e. $\mathrm{SoC_{dev}}$, rather than the average SOC.

Table 8: Battery capacity fade per year for ESS and HESS

Battery Fade per year (Ah, 50 Km per day)	1-speed	2-speed	3-speed	4-speed
ESS FTP75	0.7893	0.7039	0.5757	0.5757
HESS FTP75	0.6614	0.5879	0.4771	0.3975
Improvement (%)	16.2%	16.2%	17.1%	17.4%
ESS HWFET	0.6931	0.5881	0.9085	0.9769
HESS HWFET	0.6931	0.5049	0.7919	0.8485
Improvement (%)	14.0%	14.1%	12.2%	13.1%

According to the definition of state of health (SoH) in Eq.18 [46], a 20% battery capacity fade indicates the end of life of battery. The lifetime SoH deterioration of BEV battery are illustrated in Fig.16 and Fig.17 based on Eq.18 and Table.8.

$$SoH = \left(1 - \frac{\xi}{0.2Q_{nom}}\right) \times 100\% \qquad (17)$$

$\mathrm{Q_{nom}}$ is the nominal capacity of battery. As shown in Fig.12 and Fig.13, additional 0.8-1.3 and 0.4-0.8 calendar year are added to battery service life by introducing supercapacitor in ESS for each powertrain architecture based on FTP 75 and HWFET respectively. It is also clear in Fig.12 that the more speeds BEV powertrain has, the deterioration of battery in FTP75 is slower. Specific to FTP75, the service life of battery in HESS with four-speed transmission is around 2.8 years longer than that with one-speed gearbox, compared to 2.2 years extension achieved by four-speed gearbox in ESS. Considering the positive effect from supercapacitor and multi-speed transmission together, the battery service life is doubled from about 3.5 years to 7 years in FTP75 testing. However, the battery service life does not extend monotonically with the increasing gear number for highway cycles-HWFET. Two-speed powertrain outperformance other competitors with up to 6-7 years valid battery life, as shown in Fig.13. Comparing to one-speed BEV, two-speed transmission gives battery additional 2.2 and 1.9 years' service life in HESS and ESS respectively. The total battery life improvement in HWFET via transmission and HESS is 2.7 years, which almost double the life span as they do in FTP75.

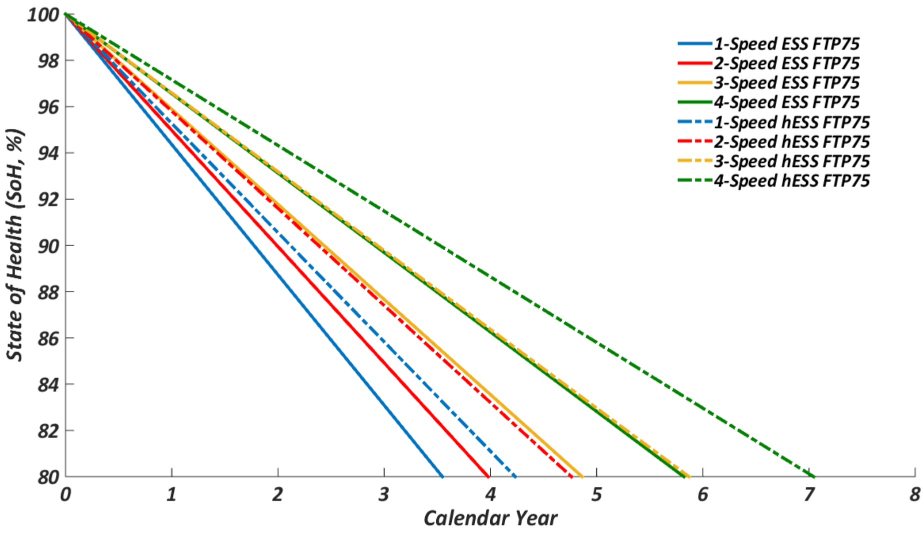


Figure 12: SoH calendar year deterioration on FTP75

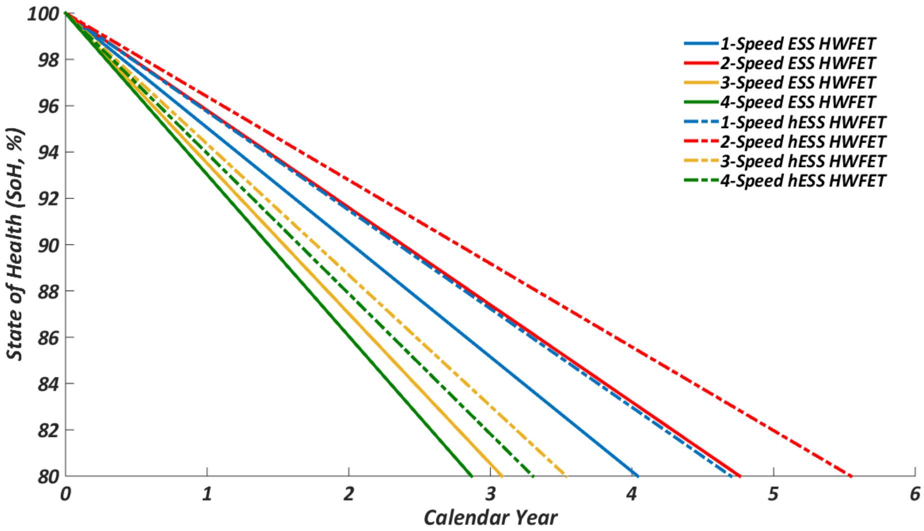


Figure 13: SoH calendar year deterioration on HWFET

Table.9 and Table.10 show another benefit of HESS that the peak/average current reduction, compared to ESS, in different cycles for B-Class and E-Class respectively. A 20%-40% peak charging current reduction is achieved by using SC to relieve the current burden of battery as much as possible. The battery charging current are all well kept under 22A as designed in two driving cycles regardless of the transmission types. On the contrary, the peak discharging current are much higher in all circumstance, which occurs when SC runs out of power in high-current (power) events. This situation happens to other driving cycles as well because the required energy for high-current (power) event is much greater than the capacity of SC, while the charging (regenerative braking) event, which only lasts a few seconds and input a small amount of energy. Therefore, the battery discharging current is still relatively high although reduction is achieved in some extent. The greatest overall current fluctuation reductions including FTP75 and HWFET are obtained in two-speed and four-speed DCT based BEVs in B-Class and E-Class respectively, which happens to match the transmission selection results in terms of energy utilizing rates in previous section. It also can be seen from these two tables that the average current rises with total gear numbers due to the power loss in additional gear pairs and synchronizers.

Table 9: B-Class Peak/average current of discharging/charging for ESS and HESS in cycles

Battery Peak(Average) Discharging/Charging Current (A)	**1-speed**	**2-speed**	**3-speed**	**4-speed**
ESS FTP75	97(17)/47(17)	112(18)/49(18)	117(18)/51(19)	122(19)/53(19)
HESS FTP75	77(14)/22(13)	85(15)/22(14)	94(16)/22(14)	118(16)/22(14)
Peak/Average Current Fluctuation Reduction by SC*	32%/18%	34%/19%	31%/19%	20%/27%
Battery Peak(Average) Discharging/Charging Current (A)	**1-speed**	**2-speed**	**3-speed**	**4-speed**
ESS HWFET	78(32)/61(18)	80(31)/69(19)	83(35)/72(20)	87(36)/74(20)
HESS HWFET	75(30)/22(16)	73(29)/22(15)	79(33)/22(16)	84(33)/22(16)
Peak/Average Current Fluctuation Reduction by SC*	30%/8%	36%/12%	35%/11%	34%/13%

Table 10: E-Class Peak/average current of discharging/charging for ESS and HESS in cycles

Battery Peak(Average) Discharging/Charging Current (A)	**1-speed**	**2-speed**	**3-speed**	**4-speed**
ESS FTP75	167(24)/74(25)	206(25)/76(27)	222(26)/79(28)	245(28)/81(29)
HESS FTP75	153(19)/22(15)	179(21)/22(16)	185(22)/22(17)	190(23)/22(17)
Peak/Average Current Fluctuation Reduction by SC*	27%/31%	29%/29%	31%/28%	35%/30%
Battery Peak(Average) Discharging/Charging Current (A)	**1-speed**	**2-speed**	**3-speed**	**4-speed**
ESS HWFET	121(44)/97(28)	131(40)/102(27)	134(41)/106(28)	144(42)/112(27)
HESS HWFET	118(41)/22(17)	125(36)/22(17)	127(37)/22(17)	140(39)/22(16)
Peak/Average Current Fluctuation Reduction by SC*	23%/19%	37%/21%	38%/22%	37%/20%

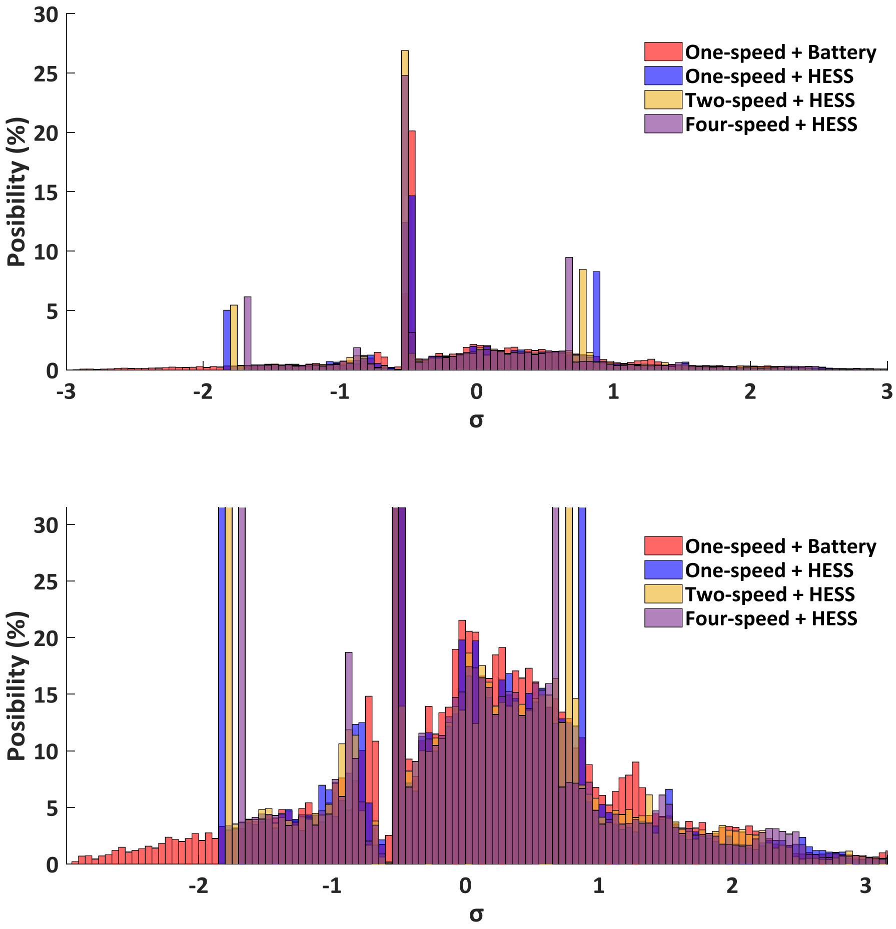
*The current fluctuation reduction is defined as the function of maximum charging and discharging current, i.e.I_{Max_ch} and I_{Max_dis} and expressed as: $Q = \frac{I_{Max_{ch}}(ESS)+I_{Max_{dis}}(ESS)-(I_{Max_{ch}}(hESS)+I_{Max_{dis}}(hESS))}{I_{Max_{ch}}(ESS)+I_{Max_{dis}}(ESS)}$

Standard deviation, defined as Eq.17, is used in this study to quantify the degree of dispersion of battery current in cycles. The difference between the mean and transit battery current are presented in Fig.14 and Fig.15 in term of the amount of standard deviation.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \qquad (18)$$

is the standard deviation of battery current in one cycle; μ stands for the mean of recorded data set; N is amount of recorded data; x_i represents the individual current value.

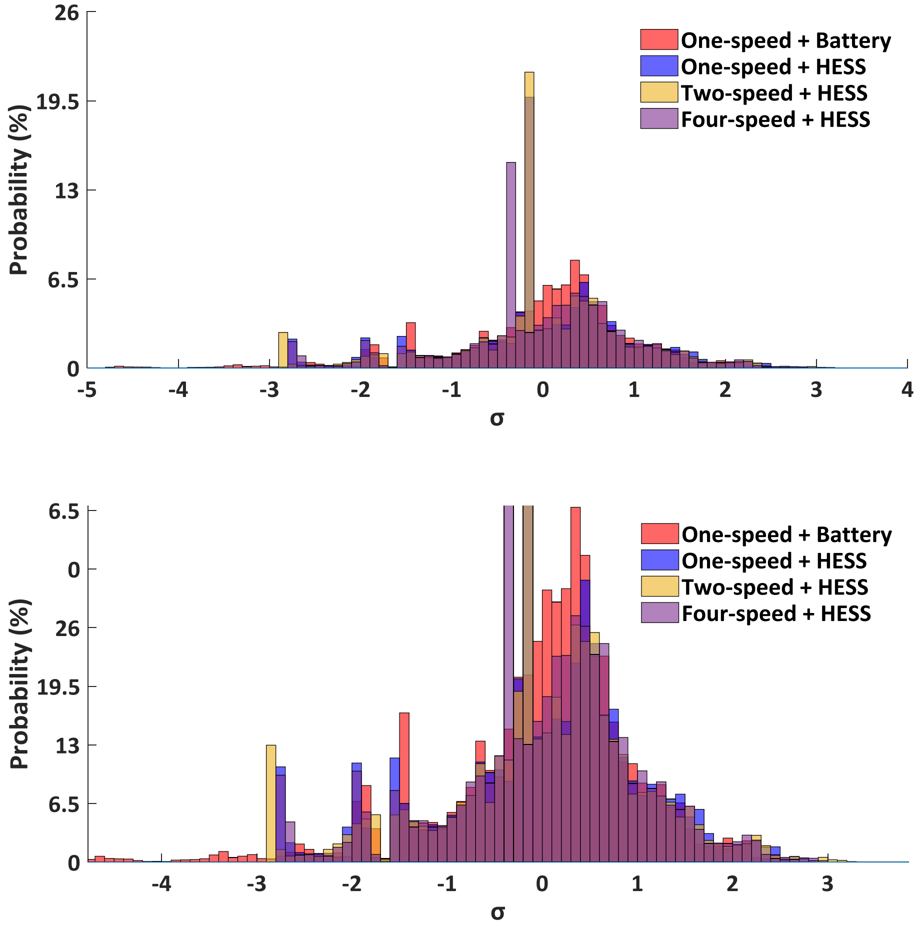
For HWFET, shown in Fig.14, most of battery current deviation are in the range of three times of mean value (zero in the figure). With the help of SC, all HESS equipped powertrains maintain the battery current deviation below three times of standard deviation, while the required current of battery-only one-speed powertrain can reach to almost five times of the standard current deviation shown in Fig.14 (b). Furthermore, HESS perform better in current charging than discharging due to the limited SC energy capacity. Regarding LA92, like HWFET, the powertrain combination of four-speed transmission and HESS outperform other alternative powertrains in both current charging and discharging.



(a)

(b)

Figure 14: Standard deviation of alternative powertrains' battery current in HWFET (a) full range (b) partial



(a)

(b)

Figure 15: Standard deviation of alternative powertrains' battery current in LA92 (a) full range (b) partial

5. Conclusion

This study reports the application of alternative multi-speed DCTs to traditional single reduction BEVs, comparing a range of vehicle and transmission configurations. The mechanism and structure of four transmissions are compared to demonstrate the advantages and disadvantages in manufacturing complexity, efficiency and cost. Following this the appropriate motor power is determined for B-Class and E-Class vehicles respectively by target acceleration time. Based on vehicle dynamic performance target and other widely accepted methods, such as climbing ability, top speed cruising and progressive ratio design algorithm, gear ratios of 2,3 and 4 speeds transmission are determined, and customized shifting schedules are designed for each transmission.

A comparison is carried out among alternative multi-speed powertrains in a hybrid cycle, which combines city cycle, FTP75, and highway cycle, HWFET, with weighting factors. The results demonstrate that 2-speed DCT obtains the most remarkable energy utilizing rates improvement in both B-Class and E-Class BEVs, which are 17.86% and 14.03% higher than the single speed BEV respectively. Three and four-speed powertrains do furtherly increase energy utilizing rate, however, considering the increased cost and complexity in manufacturing and control, extra speeds are not as attractive as 2-speed one.

The impact factors of battery aging and cycle life are analysed before commencing the model simulation. Based on the required power of several typical cycles, which are reported by four frequency histogram figures, the intervention threshold of SC in HESS is determined. An investigation on the battery service life is carried out in terms of battery capacity fade and state of health. The results show that supercapacitos based HESS significantly reduce the battery capacity fade in all powertrain architectures based on both city and highway cycles. Consequently, SoH is improved and longer battery service life is achieved. HESS based BEVs received significant current fluctuation reduction regardless of gear number in simulation, comparing to conventional energy storage system. Specifically, battery charging current are all well kept under 0.1C in two driving cycles regardless of the transmission types. On the contrary, the peak discharging current are much higher in all circumstance due to the limited SC capacity. The most significant current fluctuation reductions are achieved by the combination of two-speed DCT and SC in B-Class BEV, and the combination of four-speed DCT and SC in E-Class BEV. In summary, two-speed DCT and four-speed DCT are the best choice for B-Class and E-Class BEV respectively not only because the powertrain efficiency, also the energy storage system performance.

Appendix

Table A11: Vehicle specifications and target performance[30]

	Parameter	B-Class	E-Class	Unit
Gross Weight	M	1400	2200	kg
Vehicle Front Areas	A	2.47	2.68	m^2
Aero-drag Coefficient	Cd	0.28	0.3	
Tyre Radius	r	0.302	0.344	m
Tyre Rolling Coefficient	Ct	0.013	0.013	
Air Density	ρ	1.127	1.127	kg/m^3
Combined Rotational Inertia Coefficient (Motor, Transmission, Driveshafts, Wheels)	δ	1.1-1.5[50]	1.1-1.5[50]	

Table A2: Selected motor specifications of B-Class and E-Class EV [18]

Parameters	B-Class	E-Class
Motor Type	Permanent Magnetic AC	Permanent Magnetic AC
Motor Peak Power (kw)	65	110
Max Torque (Nm)	250	350
Max Speed (rpm)	6250	9000
Base Speed (rpm)[24]	2500	3000
Speed Ratio (Max/Base Speed)[24]	2.5	3

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Definitions/Abbreviations

BEV	Battery Electric Vehicle
DCT	Dual Clutch Transmission
DOD	Regenerative Brake System
SoC	State of Charge
SoH	State of Health
CPK	Consumed energy per km