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Comparison of powertrain system configurations for electric passenger vehicles

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Abstract

Electric vehicles (EV) are considered a practical alternative to conventional and hybrid electric passenger vehicles, with higher overall powertrain efficiencies by omitting the internal combustion engine. As a consequence of lower energy density in the battery energy storage as compared to fossil fuels powered vehicles, EVs have limited driving range, leading to a range phobia and limited consumer acceptance. Particularly for larger luxury EVs, electric motors with a single reduction gear typically do not achieve the diverse range of function needs that are present in multi-speed conventional vehicles, most notably acceleration performance and top speed requirements. Subsequently, multi-speed EV powertrains have been suggested for these applications. Through the utilization of multiple gear ratios a more diverse range of functional needs can be realized without increasing the practical size of the electric motor. The major limitation of multi-speed EV powertrains is that the increased transmission complexity introduces additional losses to the vehicle. Through a number of simulations this paper studies the integration of multispeed transmission with EV platforms. Particularly, it investigates the performance improvements of both B and E class vehicle platforms realized through utilization of two and three speed transmissions. Also the potential application of hybrid energy storage systems (i.e. batteries combined with super-capacitors) is studied. Results demonstrate that there can be significant benefits attained for both small and large passenger vehicles through the application of multi-speed transmissions. However, optimization of these ratios must be considered in the analysis.

Introduction

The application of multi-speed transmissions to electric vehicle applications seeks to improve the operating efficiency of the vehicle and enhance driving performance. However, one of the main difficulties in achieving this is the development of very efficient transmission systems and integrating this design with the vehicle powertrain development. Specifically, the transmission ratios and shift schedule can be optimized to maximize vehicle performance and driving efficiency. There are, of course, a number of existing EVs such as the BMW i3, Mitsubishi iMIEV, or Nissan Leaf that use a single reduction gear coupled to the motor that results in a trade-off between both the range and performance characteristics of the vehicle.

Furthermore, the application of hybrid energy storage systems (hESS) where super-capacitors 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 EVs, typically greater than 20kWh, may reduce the impact of super-capacitors in comparison to hybrid vehicles, with lower battery capacity.

Previous research has investigated the modeling of EV platforms for studying the vehicle performance [1], this has been extended into optimal selection of gear ratios [2] and shift schedule [3], and demonstrate the dependency of the designed vehicle on driving cycle during analysis. This paper builds on this research by expanding the study into evaluation of three speed EVs and the application of these transmissions to alternative vehicle classes.

In [1] an extensive comparison of a two and single speed EV was undertaken, investigating the impact of gear ratio on driving range and performance. Salisa, *et al*, [5] undertakes a comparative analysis of alternative hybrid electric vehicles including a novel transmission design, demonstrating the benefits of relying on larger electrical energy storage for reducing greenhouse gas emissions. Whilst, [6] analyses alternative configurations from conventional against many alternative hybrid configuration to evaluate the possible benefits of using different configurations, particularly in terms of cost.

The purpose of this paper is to 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 platforms, B-class and E-class, this paper will investigate a number of alternative considerations, including:

1. Application of single and different multispeed transmissions
2. Hybrid energy storage devices, and
3. Implementation of range extenders to the EV platform

The intention of this paper is to cover a wide range of configurations for EVs 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 discussed, 2) different energy storage system configurations are discussed and presented, 3) the required performance characteristics are then 4) the basic parameters for each vehicle class is detailed, 5) simulation results are presented and compared, and 6) the paper is summarized and conclusions are drawn based on the results.

Alternative powertrain configurations

Single speed EV powertrain

Single speed EVs (SSEV) (Figure 1) are the convention in current vehicles on the market, including the BMW i3, Mitsubishi iMIEV, and Nissan Leaf. 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.

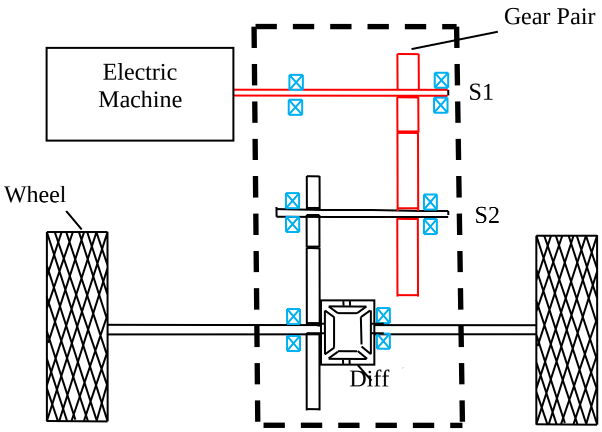

Figure 1: Single speed electric vehicle schematic.

Two and three speed EV powertrain

A two speed EV (2SEV), shown in Figure 2, or even multispeed EVs (MSEV), shown in Figure 3, 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 that are likely to 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 and three speed transmissions shown in Figures 2 and 3 include two sets of parallel gears coupled with a common clutch to the electric machine. The clutches are denoted with C1 and C2. For the two speed transmission no synchroniser is used and shifting is performed between clutches with fixed ratios. For the three speed transmission a synchroniser is used for first and third gears to select alternative ratios.

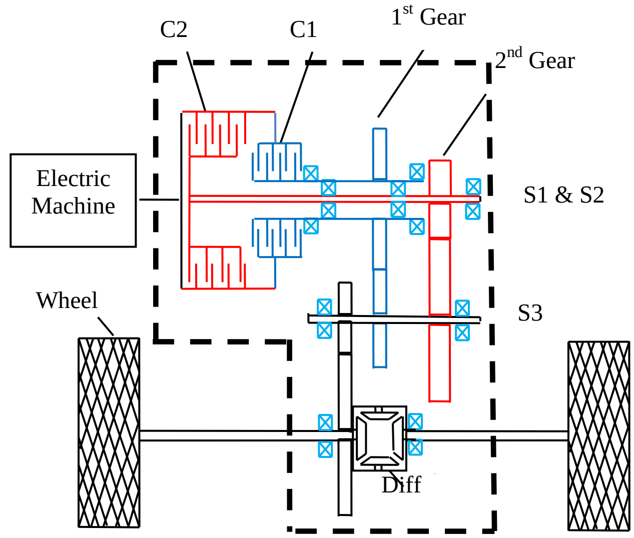

Figure 2: Two speed dual clutch transmission electric vehicle schematic.

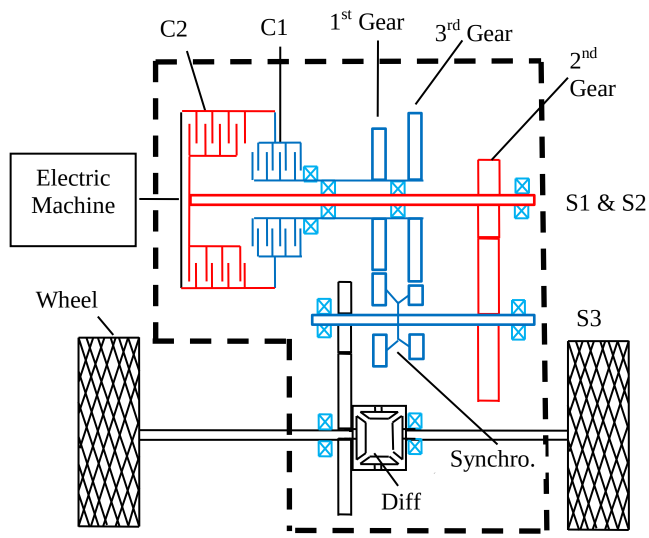

Figure 3: Three speed dual clutch transmission electric vehicle schematic.

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 [4], for the driveline there are several component losses that can be approximated:

- 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 an 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 [7].

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 is defined using the maximum motor power as follows:

$$F_T = \eta_{PT} P_{max}/V \quad (1)$$

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:

$$F_A = C_W \mu_S g M_v \quad (2)$$

Figure 4 shows the traction curve of all three configurations that are part of this study. 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.

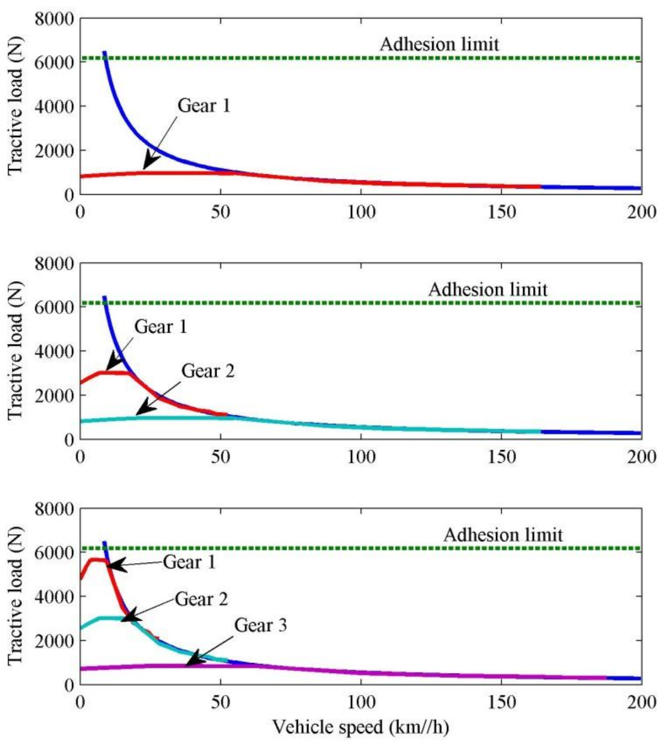

Figure 4: Traction curves of (top) one speed, (middle) two speed, and (bottom) three speed EV. Note that the blue curve represents the maximum traction load at the wheel, based on motor deliverable power.

Ratio design for grade and acceleration

The design of gear ratios for the capability to climb inclines is considered important for entering and leaving steep driveways and parking structures. The largest overall gear ratio required for the powertrain is set based on this need for conventional 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 Equation 3 [8]. For low speeds the aerodynamic drag is assumed to be zero.

$$\gamma_{max} = r_t m_V g(C_R cos\Phi + sin\Phi)/(T_{EM}\eta_{PT}) \quad (3)$$

While conventional ICE powered vehicles have limited torque available at low speeds, electrical drives has peak torque from zero speed. Given the additional ratio spread available with a three speed transmission, a designed ratio using this method is likely to be inappropriate for maximising vehicle efficiency and acceleration, and will ultimately lead to an underperforming transmission. The alternative is to use the tractive load limits to determine the maximum first gear ratio, in conjunction with the need to drive the vehicle from start at a 20% grade (i.e. parked on a steep hill).

The maximum traction load delivered to the wheels is defined as:

$$F_T = \frac{\gamma_{max}\eta_{PT}T_{EM}}{r_T} \quad (4)$$

At the adhesion limit, Equation 2 defined the maximum traction load, and can be combined with Equations 3 and 4 to yield:

$$\gamma_{max} = \frac{r_t M_V g(C_R cos\Phi + sin\Phi) + R_T C_W \mu_S g M_v}{\eta_{PT} T_{EM}} \quad (5)$$

For both methods, i.e. Equations 3 and 5, the maximum gear ratios for both vehicle classes are determined as follows.

Ratio design for speed

Vehicle top speed varies significantly depending on application and is reasonably important for consumer acceptance. The maximum speed achieved in the vehicle can then be used to determine the lowest possible ratio. It must consider the motor characteristics in terms of maximum rotating speed (rad/s) and the ability of the motor torque to reach this top speed. The minimum ratio is defined by the maximum motor speed [9], converted to km/h divided by the maximum vehicle speed.

$$\gamma_{min,speed} = 3.6\pi N_m r_t/(30V_{max}) \quad (6)$$

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.

$$\gamma_{min,torque} = \left(C_R M_v g cos\emptyset + \tfrac{1}{2}C_D \rho A_V V^2\right) \times r_t/\left(\eta_{PT} T_{EM,@maxRPM}\right) \quad (7)$$

Selection of intermediate gear ratio

There are two generally accepted methods for determining intermediate gear ratios. These include (1) geometric and (2) progressive [3]. From these methods it will be possible to determine some available options for the selection of the intermediate ratio of the three speed transmission.

Geometric design of intermediate ratios has the advantage of utilising the motor at similar operating speeds across the vast majority of driving speeds for the vehicle. Therefore the minimum and maximum motor speeds for each ratio is identical. However, this method for selection is generally applied to heavy vehicles rather than passenger vehicles. It is calculated as follows:

$$\frac{\gamma_1}{\gamma_2} = \frac{\gamma_2}{\gamma_3} = C \qquad (8)$$

Where:

$$C = \sqrt{\frac{\gamma_1}{\gamma_3}} \qquad (9)$$

Progressive ratio design is where the span of vehicle speed between gear changes is kept constant. The next ratio is determined using:

$$\gamma_3 = \frac{\gamma_2\gamma_1}{2\gamma_1 - \gamma_2} \qquad (10)$$

Or by re-arranging for the intermediate gear:

$$\gamma_2 = \frac{2\gamma_1\gamma_3}{\gamma_1 + \gamma_3} \qquad (11)$$

The gear shift schedule is based on a previous paper [3] that utilizes the mapped efficiency of the electric machine (and transmission if available) to maximize the driving efficiency of the powertrain depending on the selected gear ratio.

Alternative energy storage system configurations

Complementing the application of alternative multi-speed transmissions it the evaluation of by conventional battery energy storage systems to hybrid super-capacitor-battery ESS. The two configurations are discussed below. Further the application of range extenders is also included in the study. Figure 5 provides the general power flow of the EV platforms to be studied, including provision for supercapacitors in the system. In cases with the application of range extenders, a third input is added that the power converter to simulate the range extender.

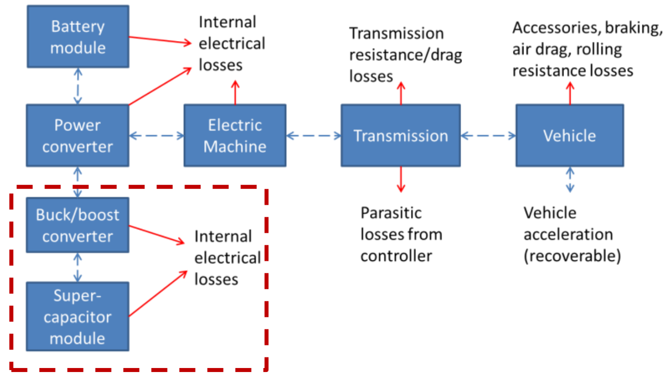

Figure 5: Power flow of vehicle powertrains, including losses, and provision for super-capacitors for hybrid energy storage system.

Conventional battery energy storage system

Conventionally, energy storage systems rely on the use of large battery banks in EVs. These are a significant weight addition to an EV as there is a low energy density of batteries in comparison to fuel. Furthermore, both range anxiety and the cost of replacing the battery have always been a hindrance to the acceptance of EVs in general.

Hybrid battery-super-capacitor energy storage systems

Hybrid battery-super-capacitor energy storage systems (hESS) utilize the addition of a super-capacitor bank to maximize energy captured during braking and also absorb peak power demands to and from the battery pack. There is not a significant addition of vehicle range as SCs do not store a significant quantity of energy, in comparison to batteries. SCs are considered to be power dense, in so far as that they can repeatedly supply very high currents without degradation as can be expected for long term use of a conventional battery. The main limitation of super-capacitors is that it is a variable voltage component and requires a DC/DC converter to maintain bus voltage during charge and discharge. Its state of charge (SoC) is defined from its change in voltage, rather than the change in current as is the convention for batteries. Consequently some power loss must be expected during voltage conversion.

Implementation of range extenders to EV platforms

The integration of range extenders to EV applications typically falls under two alternative control configurations that are compatible to rule based control of an EV. These include (1) charge sustaining and (2) charge depleting configurations. In a charge sustaining range extender mode power is supplied in short bursts to maintain a specified SOC region, thus the battery is cycled in a 15~20% relative SOC region. For charge depleting modes the range extender runs continuously at a moderate power to supply a ‘baseline’ load that extends the duration of complete discharge of the (h)ESS. Typically, one would expect that a charge sustaining range extender will have a larger requirement than a depleting range extender to be able to recharge batteries whilst driving. Different modes are demonstrated in Figure 6.

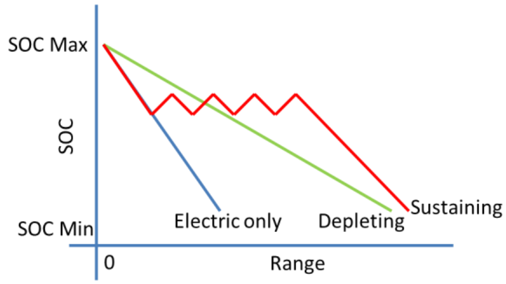

Figure 6: Influence of different range extenders on driving range

Summary of vehicle 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.

B-Class EV configuration

The B-class car covers the Supermini/Subcompact/City/Small car segment of the automotive passenger vehicle market. They comprise of approximately 30% of vehicle sales in Australia ([10] FCIA 2014) depending on where the exact divisions are made between classes. It should be noted that the nominal vehicle mass is shown below, variations for additional transmission ratios and different energy storage considerations are not included in the summary, but are included in simulations.

E-Class EV configuration

The E-class car covers the Executive/Large/Full size car segment of automotive passenger vehicles. They comprise of approximately 6% of vehicle sales in Australia [10]). These are significantly larger than B-class vehicles and may represent the other end of passenger vehicle market in terms of vehicles size. Vehicles are summarized in Table 1. Vehicle specifications are chosen as typical values and are similar to published literature, such as [5, 6]. Also note that supercapacitor and range extender masses should be added to the vehicle mass, depending on the configuration being studied.

Table 1. B-class and E-class vehicle design and performance parameters.

	Units	B Class	E Class
Single speed ratio	-	4.9	7.06
Two speed ratios (1st, 2nd)	-	7.13, 2.67	10.66, 3.46
Three speed ratios (1st, 2nd, 3rd)	-	7.13, 3.89, 2.67	10.66, 5.23, 3.46
Motor Power (Torque)	kW (Nm)	58 (400)	100 (550)
Battery capacity	kWh (Ah)	28 (200)	36 (150)
Super capacitor capacity	MJ	0.6	0.6
Super capacitor mass	kg	70	70
Range extender power	kW	15	23
Range extender mass	kg	80	80
Range extender tank	l	20	20
Vehicle mass (Nominal only)	kg	1400	2200
Fontal area	m^2	2.47	2.68
Rolling radius	m	0.302	0.334
Rolling resistance coefficient	-	0.013	0.013
Drag coefficient	-	0.28	0.3
Desired all electric range	km	160	160

Design analysis of EV platforms

To analyze the proposed platform and determine the desired vehicle specifications, begin with some basic vehicle data, shown in Table 1 and Table 2. These are the basic specifications for two alternative EV platforms. The primary variation will be in the vehicle mass when other energy storage and transmission configurations are considered in this study. The instantaneous torque at the wheel and the power demand at the wheel are studied in this section to provide evaluation of the requirements for vehicle power consumption and torque for the driving motor. This analysis is then extended into the energy storage requirements for the battery pack. Consider Equation 12, if brake torque is ignored, the motor torque (multiplied by any driving ratio and efficiency losses) can be considered the torque required to accelerate the vehicle at the wheel. Therefore:

$$T_W = \left(M_V \frac{dV_v}{dt} + C_R M_V g \cos\phi + M_V g \sin\phi + 0.5 \rho C_D A_V V_V^2 \right) r_t \quad (12)$$

Both the operating mass and aerodynamic characteristics can vary significantly between platforms. Thus there are two alternative results for the same driving cycle shown below. By numerically differentiating the velocity at a fixed time step the wheel torque is determined (part b of both Figure 7 and 8), and then by multiplying by the wheel rotational speed the instantaneous power is calculated (part c of Figures 7 and 8). Finally, frequency histograms are shown to demonstrate the range of required power for each configuration. Note that regenerative braking is denoted as having negative power so as to discriminate between regen and driving power.

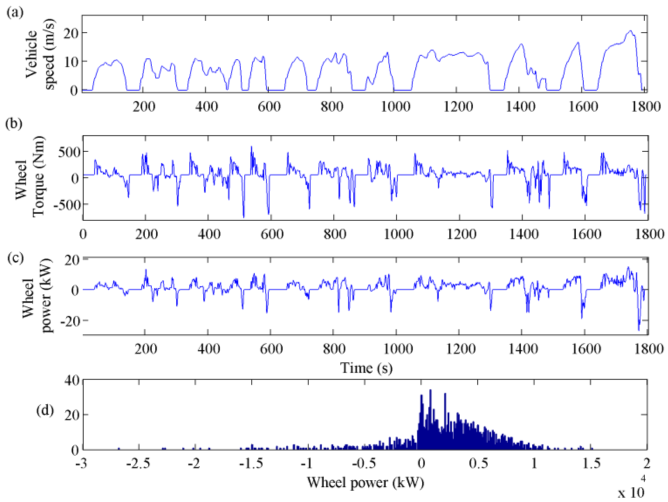

Figure 7: B class vehicle cycle instantaneous (a) speed, (b) torque at the wheel, (c) power at the wheel, and (d) frequency histogram of power

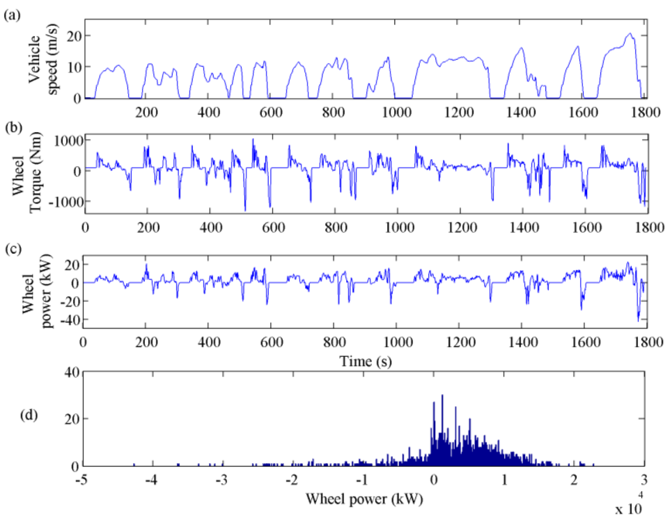

Figure 8: E class vehicle cycle instantaneous (a) speed, (b) torque at the wheel, (c) power at the wheel, and (d) frequency histogram of power.

Simulation

Simulations in this paper are performed with an extension of the model presented in [1]. Alternative configurations are provided for the inclusion of supercapacitors and range extender to the two EV platforms chosen for this investigation.

Simulation results are presented for the alternative configurations detailed in the previous sections. This includes two vehicle platforms, three transmission options, and three ESS variants; totaling 18 alternative options for the vehicle simulations. To balance these results only full simulations are presented for B Class one speed EV, the results of all other simulations are summarized in table form.

Simulations will be conducted using a Chinese City Cycle, shown in Figure 9 (a).

Figures 9 and 10 show the speed profile, instantaneous hESS power and instantaneous hESS current drawn over one particular driving cycle iteration. The main differences between Figure 10 and 11 is the inclusion of the super-capacitor component in the hESS model. Simulation results demonstrate that the conventional battery pack has a range of 176 km, slightly longer than the desired 160km, though this can be modified with optimization of the battery size. The hybrid ESS provides a range of 179 km using the same driving cycle, an increase of 3 km with the inclusion of the super capacitor module, see figure 10. The hESS has initial super-capacitor charge of 100% of usable SOC. The results in figure 9 show that the battery EV rarely exceeds the single C rating of the battery pack under the zero grade driving conditions. This indicates that there is little opportunity to improve the battery life by minimizing the high C discharge and charge events. However, this is not likely to be the case when driving under graded road conditions. Furthermore, the use of the hESS has a minor improvement on the driving range of the EV being capable of capturing a greater portion of the regenerative brake energy.

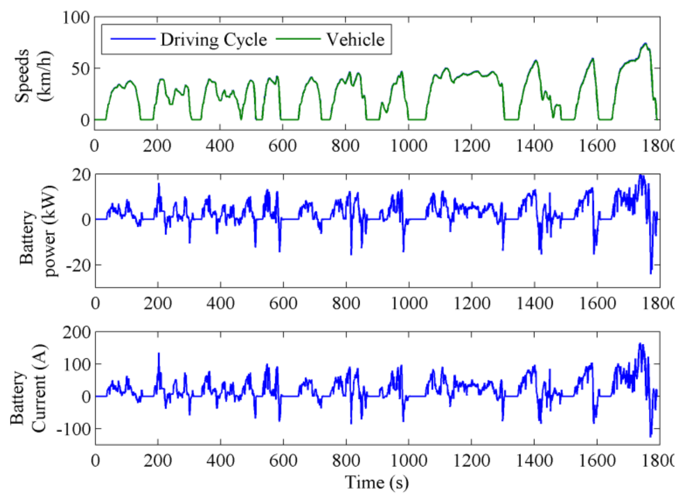

Figure 9: Single iteration of the driving cycle for conventional battery only ESS. (top) speed profile, (middle) battery power, and (bottom) battery current.

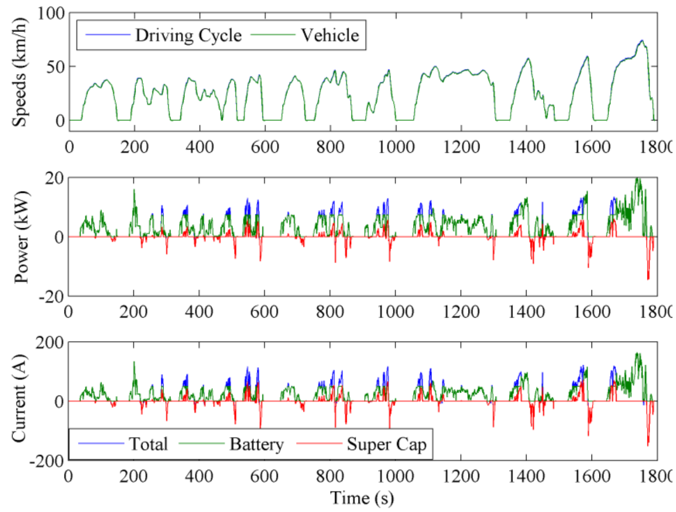

Figure 10: Single iteration of the driving cycle for hybrid battery and super-capacitor ESS. (top) speed profile, (middle) battery, capacitor and total power, and (bottom) battery, capacitor and total current.

Figure 11 shows that variation of usable SOC for the three configurations of ESS (conventional, hybrid, and range extender) during the repetition of the prescribed driving over the complete discharge of all onboard energy storage. The use of a 15 kW range extender has the influence of providing a total driving range of 425 km, an added 255 km in comparison to the hESS EV configuration.

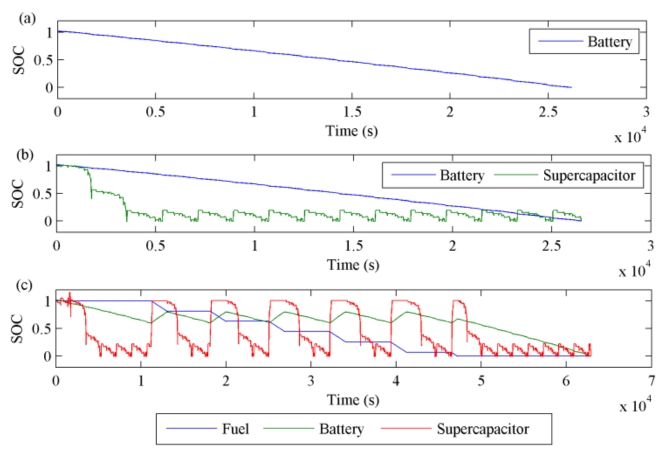

Figure 11: Simulation of relative State of Charge results for continuous simulations for the provided driving cycle. (top) conventional ESS, (middle) battery and super-capacitor ESS (bottom) battery, super-capacitor and fuel for hESS with range extender. Note particularly that the fuel SOC is determined by dividing the maximum tank capacity by the current capacity.

Table two summarizes the results for the different combinations of both transmission and energy storage system. For the given driving conditions it demonstrates that the hESS is capable of improving the energy capture during regenerative braking events, thereby slightly increasing the driving range of the vehicle. However, as was initially expected the large energy storage capacity of the battery has led to fewer high current (aka high C) events. Consequently, the benefits of utilizing super-capacitors are limited for the B-Class electric vehicle in this study. It can also be inferred that if the battery capacity is further reduce (for a hybrid or range extended vehicle, for example) then the use of hESS can be expected to provide larger benefits than is the current case.

Table 2. Summarized B-class vehicle range results (units: km).

	ESS	hESS	RE-hESS
One speed	176	179	425
Two Speed	191	201	448
Three Speed	189	193	456

Results in Table 2 demonstrate a potential for increased performance of between 8 and 12% in driving range for the given driving cycle, depending on energy storage configuration and number of speeds in the transmission, with the addition of supercapacitors alone responsible for an increase of up to 5% in driving range. The range extender is capable of providing significant improvements to driving range. However it is suggested that its addition can be further enhanced by balancing against a smaller battery capacity to reduce vehicle mass.

The main cause of the reduction in three speed performance is the proximity of second and third gear. As these ratios are reasonably close together there is rarely any requirement to select third gear for the driving cycle utilized in this study. As a result of condition the marginally lower efficiency of the three speed EV has a negative effect on the driving range. Of course, the addition of the range extender has a considerable influence on the driving weight of the vehicle. This increases power demand for normal driving and thus gear changes and the operating region of the electric motor. As a result the driving performance is slightly improved. It must be concluded that the opting for a range extended EV may only be necessary for extended driving conditions. However, this consideration may change if smaller battery capacity is utilized in the EV.

Table three presents a similar series of results for the E-Class EV platform. The results demonstrate that, for the given class of vehicle using this particular driving cycle, there were insufficient number of shifts into higher gear ratios for the vehicle to benefit from the application of multi-speed transmissions. A more aggressive driving cycle, such as US06, or higher speed would demonstrate the superior benefit of using the multispeed platforms. However the application of super-capacitors demonstrates a pronounced benefit in enhancing driving range through the capture of more regenerative braking events.

Table 3. Summarized E-class vehicle range results (units: km).

	ESS	hESS	RE-hESS
One speed	189	199	427
Two Speed	182	193	409
Three Speed	179	189	399

Given that the results in Table 3 reverse the performance improvements achieved in Table 3 for the addition of extra gear ratios it can be concluded that substantial performance improvements may result from the optimization of these gear ratios beyond what is suggested through the application of Equations 3 - 11.

Particularly, one must note that the inclusion of a range extender allows for the reduction in the battery energy storage. This has the further effect of enabling a much higher impact of the supercapacitors as these take a larger portion of high C pulses during acceleration and braking. This therefore becomes a significant consideration for minimizing optimizing the cost against range/emissions.

Summary/Conclusions

The investigation has broadly covered the application and use of alternative transmissions and energy storage systems, including range extenders, to EV applications to two alternative vehicle platforms. Generally speaking results demonstrate several key areas where configuration optimization is likely to lead to further improvement of the vehicle performance:

- Battery-super-capacitor-range extender relative capacity
- Range extender power capacity and optimal control
- Optimal design of vehicle shift schedule and gear ratios to maximize driving efficiency.

Finally, one of the main considerations that must be evaluated in almost all EV design applications is the suitability of the driving cycle chosen. The results of this study are to a fairly specific inner city style cycle. A high speed cycle and/or demanding cycle, such as HWFET or US06, will lead to strongly different range results and must necessarily affect the overall vehicle performance.

References

1. Walker, P. D., Abdul Rahman, S., Zhu, B. and Zhang, N. “Modeling, Simulations, and Optimization of Electric Vehicles for Analysis of Transmission Ratio Selection” Advances in Mechanical Engineering, vol. 2013, Article ID 340435, 13 pages, 2013. doi:10.1155/2013/340435
2. Zhou, X., Walker, P. D., Zhang, N., and Zhu, B., “Performance Improvement of a Two Speed EV through Combined Gear Ratio and Shift Schedule Optimization” SAE Technical paper: 2013-01-1477
3. Zhu, B., Zhang, N., Walker, P. D. Zhou, X., Zhan, W., Wei, Y., and Ke, N., “Gear shift schedule design for multi-speed pure electric vehicles” Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, In Press, 2014. doi:10.1177/0954407014521395
4. Zhou, X., Walker, P. D., Zhang, N., Zhu, B., and Ruan, J., “Numerical and experimental investigation of drag torque in a two-speed dual clutch transmission” Mechanism and Machine Theory 79:46-63,2014.
5. Salisa, AR, Zhang, N, & Zhu, J, 2011, “A comparative study of fuel economy and emissions between a conventional HEV and the UTS PHEV” IEEE Transaction on Vehicular Technology, 60(1):44-54.
6. Sharma, R., Manzie, C., Bessede, M., Brear, M. J., & Crawford, R. H. 2012, “Conventional, Hybrid and Electric Vehicles for Australian Driving Conditions – Part 1: Technical and Financial Analysis”, Transportation Research Part C, 25, pp. 238-249.
7. Berger, R., Meinhard, R., and Bunder, C. 2002, the Parallel Shift Gearbox PSG, 7th LuK Symposium, 11-12 April, Badem Germany pp197-210.
8. Lechner, G., Naunheimer, H. 1999 Automotive transmissions – Fundamentals, Selection, Design and application Springer-Verlag, Berlin, pp. 77-109.
9. Jazar, R. N., (2008) Vehicle Dynamics: Theory and Application, Springer.
10. Federal Chamber of Automotive Industries, http://www.fcai.com.au/sales, Accessed 30/10/2014.

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Definitions/Abbreviations

2SEV	Two speed electric vehicle
DCT	Dual clutch transmission
ESS	Energy storage system
EV	Electric vehicle
hESS	Hybrid energy storage system
ICE	Internal combustion engine
MSEV	Multi-speed electric vehicle
RE	Range extender
A_V	Vehicle frontal area
C_D	Drag coefficient
C_R	Rolling resistance coefficient
C_W	Weight distribution
F_A	Adhesion force (maximum)
F_T	Traction load
M_V	Vehicle mass
N_m	Motor speed
P_{MAX}	Maximum motor power
r_t	Tyre radius
T_{EM}	Motor Torque
V	Vehicle speed
η_{PT}	Powertrain efficiency
μ_S	Static friction limit of tyres
γ	Gear ratio
ϕ	Road grade
ρ	Air density