Energy consumption and cost analysis of hybrid electric powertrain configurations for two wheelers

Paul D Walker[A]* and Holger M Roser[B]
[A] School of Electrical, Mechanical and Mechatronic Systems, University of Technology, Sydney, 15 Broadway, Ultimo, NSW, Australia, 2007; E-Mail: Paul.Walker@uts.edu.au
[B] School of Electrical, Mechanical and Mechatronic Systems, University of Technology, Sydney, 15 Broadway, Ultimo, NSW, Australia, 2007; E-Mail: Holger.Roser@uts.edu.au

*Corresponding Author
Phone: +61-2-9514-2412,
Fax: +61-2-9514-2567,
Address: PO Box 123 Ultimo, NSW, Australia 2007

Abstract:

The development of hybrid electric two wheelers in recent years has targeted the reduction of on road emissions produced by these vehicles. However, added cost and complexity have resulted in the failure of these systems to meet consumer expectations. This paper presents a comparative study of the energy economy and essential costs of alternative forms of small two wheelers such as scooters or low capacity motorcycles. This includes conventional, hybrid, plug-in hybrid and electric variants. Through simulations of vehicle driving range using two popular driving cycles it is demonstrated that there is considerable benefit in fuel economy realised by hybridising such vehicles. However, the added costs associated with electrification, i.e. motor/generator, power electronics, and energy storage provide a significant cost obstacle to the purchase of such vehicles. Only the pure electric configuration is demonstrated to be cost effective over its life in comparison to conventional two wheelers. Both the hybrid electric and plug-in equivalents must overcome significant upfront costs to be cost competitive with conventional vehicles. This is demonstrated to be achieved if the annual driving range of the vehicle is increased substantially from the assumed mean. Given the shorter distances travelled by most two wheeler drivers it can therefore be concluded that the development of similar hybrid electric vehicles are unlikely to achieve the desired acceptance that pure electric or conventional equivalents currently achieve.

Keywords:

Electric Vehicle; Hybrid Electric Vehicle; Plug-in Hybrid Electric Vehicle; Life Cycle Cost; Scooter; Two wheeler

1. Introduction

The convenience of motorcycles, scooters and mopeds in metropolitan areas combined with low operating costs present commuters an attractive alternative to motorcars and public transport. In Australia nationwide sales of two-wheelers continue to grow, for instance, scooter sales increasing by 8.9% in 2011 and 12.6% for 2012 [1]. In Australia, at least, it is suggested in [2] that this is driven by reduced costs and convenience in comparison to passenger cars and public transport, environmental concerns were not a primary factor in scooter and moped uptake. Furthermore, in Yang [3], the main driving force behind uptake of electrified two wheelers in China is identified as legislated bans on the use of engine powered equivalents in many cities. Furthermore, it is suggested that cost based subsidies were also shown to fail in promoting uptake, particularly as technology failed to meet the expectations set by the existing platforms [3]. A study of multiple forms of transport, ranging from electrified bicycles and scooters through to busses in [4] demonstrates a substantial benefit of this form of transport in terms of emission in comparison to conventional scooters or passenger vehicles.

Perhaps the most significant consideration in the development of hybridized and electrified scooters is the need to do so. Whilst the main driving force behind larger passenger vehicle hybridization is the need for high efficiency and significantly lower fuel consumption, balanced by a reasonable increase in vehicle cost, anecdotally two-wheelers are generally not expensive to operate in terms of fuel consumption. Government legislation, on the other, has had a significant influence on limiting the use of these vehicles, generally as a consequence impact on traffic congestion and/or low quality exhaust emissions [3]. However, it is shown in [5] that the day-to-day operational costs of a simple electric scooter are significantly less than those of a comparable conventional motorcycle or passenger car. In an evaluation of common two wheeler forms of transportation in various cities of China Weinert, et al, [6] depicts the major limitation of conventional and electric two wheelers. Discussion indicates that whilst electric two wheelers are significantly more efficient in terms of energy storage (battery vs fuel tank) to wheels, these vehicles are limited in terms of both top speed and overall range. Conventional scooters possess five times the range of electric equivalents and twice the top speed, and are therefore considerably more flexible in terms of day-to-day use.

In recent years the automotive industry has introduced different hybrid electric vehicles (HEV) and electric vehicles (EV) to meet these needs. This has also extended into two wheeled vehicles, including motorcycles, scooters, and electrified bicycles [6]. These vehicles are designed to reduce emissions at the exhaust pipe through a combination of methods, including (1) operation of the engine in more fuel efficient regions, (2) the use of on-board stored electricity, and (3) energy recovery through regenerative braking [7]. The development of hybrid electric and pure electric two wheeled vehicles, such as scooters and motorcycles, has been under development for over ten years now, with a range of electric and parallel hybrid electric configurations developed [6, 8-11]. Whilst electric two wheelers provide a compact efficient configuration, they are severely limited by range, with limited storage capacity for on-board energy storage [6, 12, 13], thus battery sizing and integration are crucial for a balanced vehicle platform. Parallel hybrid scooters overcome this with combined engine and motor/generator configurations for increased range with lower efficiencies. However, these configurations are limited by complex mechanical subsystems to manage energy distribution [10-13], which are referred to as a source of customer complaints in [3].

Several hybrid scooter and motorcycle designs have been developed to overcome limitations of conventional and electric two wheeler designs; these are dominated by parallel designs where electric motor and engine are connected to the wheels for independent or combined driving [7-12], see examples in Figure 1. Nevertheless, limitations exist in parallel hybrid electric two wheeled vehicles. Assessment of a range of hybrid electric two wheeler designs in literature indicates that mechanical power splitting required in these configurations add to vehicle complexity, contributing to higher development, purchasing and ongoing maintenance costs. Thus conventional, electric and even parallel hybrid electric configurations are not ideal for the development of compact, green energy two wheeled vehicles that meet the needs of consumers. This project proposes a simple series hybrid electric powertrain configuration for achieving a combination of high efficiency and driving range through the optimal application of motor, engine/generator, and on-board energy storage, including batteries and fuel.

The purpose of this paper is to develop and analyse a series of alternative powertrain configurations for two-wheelers and study the comparative costs of each. In the next section different powertrain configurations for hybrid vehicles are discussed, this is followed by detailing the alternative configurations being studied for this paper. Statistical analysis of driving cycles are then used to investigate needs for powertrain power and stored energy requirements. This is followed by a simulation based analysis of the different configurations to determine energy consumption for alternative driving cycles. To complete the analysis alternative configurations and lifecycle costs are evaluated for (1) capital component costs, (2) maintenance costs, and (3) energy consumption costs. These are used to evaluate the consumer benefits of each configuration in terms of financial requirements and vehicle driving range.

2. Powertrain configurations and Modelling

In conducting this study several alternate powertrain configurations have been identified as suitable to the development of a compact HEV. Two factors are considered in the selection of initial configuration, powertrain layout and application of energy sources. These are detailed below, beginning with a summary of different powertrain layouts. There are three conventional hybrid vehicle powertrain layouts, series, parallel, and series-parallel, each with specific advantages and weaknesses. The series HEV uses an engine-generator to provide power to a traction motor to drive the wheels, see Figure 1(a). The parallel HEV utilizes a single motor/generator in conjunction with an engine and power-splitting transmission to drive the wheels with the engine or motor, or both, Figure 1(b). The series-parallel HEV utilizes two motor/generators and a power-splitting transmission to achieve a combination of both series and parallel operating configurations depending on driving requirements, Figure 1(c). The benefits and weaknesses of each of these configurations have been discussed at length in numerous HEV studies [6-13].

For a compact HEV powertrain, where efficiency, capital costs and ongoing maintenance costs are all considered as important factors in selection of a particular configuration, it is considered that the series configuration not requiring a power-splitting transmission but needing a larger traction motor outweighs other benefits of other HEV configurations. This can be realized in [8] where series-parallel powertrains are developed for hybrid scooters. One may consider the complexity introduced in these parallel type powertrains, and how this will impact on upfront and maintenance costs. Alternatively, a series type configuration, whilst requiring a larger motor, and potentially generator, benefits from greatly reduced mechanical complexity, overcoming some issues raised in [3]. Thus, making it suitable to compact and cost effective powertrains.

The other major consideration, and the main theme of this paper, is the alternative options available for energy storage in the vehicle. An electric vehicle is restricted in range through the selection of battery size. In a hybrid vehicle the battery pack stored energy is complemented by stored fuel converted to electricity with the generator. Variations on these two considerations lead to several alternative configurations for developing HEV powertrains. These are shown in Figure 2.

Mathematical modelling of the configurations in Figure 2 has been presented in previous literature; see Walker and Roser [14]. Each configuration is modelled using a top down strategy, where the driver input is defined using a proportional-integral-derivative (PID) controller, with the input being the difference between required and actual speed. The output is equivalent to the demand power. The power flow trhough each configuration is then mediated against efficiency of each component (i.e. motor, engine or batteries) to determine the actual power demand for the energy source (batteries or engine). Thus the overall consumption through each driving cycle is determined. In terms of energy management for the different configurations, both the PEV and CV are direct drive and there is no requirement for higher level energy mediation during driving. For the BHEV and PHEV configurations a charge sustaining approach is adopted [15], given the series hybrid configuration of these platforms. This method aims to maximise the efficiency of the engine-generator whilst maintaining the battery pack in a predefined SOC range.

The main characteristics of each of these configurations are detailed as follows:

1. The pure electric vehicle (PEV) is shown in Figure 2 (a); it is charged of the electricity grid and uses battery power to drive the wheel via a fixed ratio belt drive.
2. The battery hybrid series electric vehicle (BHEV), shown in Figure 2 (b), uses a combined engine-generator to generate power to drive the vehicle with excess power stored in the battery pack.
3. The plug-in hybrid series electric vehicle (PHEV) is shown in Figure 2 (c); it has a similar configuration to the BHEV only it utilises a larger battery back that can be charged off the grid.
4. The conventional vehicle (CV) is shown in Figure 2 (d); it drives the wheels using a typical engine in conjunction with a belt continuously variable transmission and centrifugal clutch. The limitation of the CVT is shown in Zhu, et al. [16], where experimental efficiency studies are as low as 40% under specific speed and torque conditions, rising to about 70% peak efficiency.

3. Powertrain Design to Driving Cycle

For estimation of required component sizes two driving cycles are analysed and the torque and power demands analysed. For a typical platform the desired vehicle specifications some basic vehicle data for a conventional powertrain are assumed, shown in Table 1. These are the basic specifications for a mid-sized electric scooter. The primary variation will be in the vehicle mass when other platform configurations and sizes are considered in Section 4 of this study. For the PEV, BHEV and PHEV the powertrain efficiency (i.e. belt drive) is listed in Table 1, For the CV typical CVT belt drive efficiency, based on [16], is also shown.

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 the torque at the wheels; if brake torque is ignored, the motor torque (multiplied by any driving ratio) can be considered the torque required to accelerate the vehicle. The wheel torque equation can therefore be written as [14]:

$$T_W = \left(M_V \frac{dV_v}{dt} + C_R M_V g \cos\phi + M_V g \sin\phi + 0.5\rho C_D A_V V_V^2 \right) r_t \tag{1}$$

where T_W is the wheel torque, C_R is rolling resistance, g is gravity, $\emptyset$ is road incline angle, C_D is drag coefficient, ρ is air density, A_V is frontal area, V_V is linear vehicle speed.

The first consideration here is that the vehicle mass will vary significantly between configurations. For the drive cycle itself, vehicle top speed has the same problem. To illustrate this problem consider Figures 3 and 4. Part (a) of each figure is the actual driving cycle. In Part (b) Equation 1 is solved using the provided speeds in driving cycle and a dt of 1s, thus the acceleration is calculated for the specified driving cycle and from this the instantaneous torque at the wheel is determined. In Part (c) the wheel torque and angular speed are multiplied to determine power required at the wheel (i.e. Power = Torque x angular speed). Finally, in (d) a frequency histogram of the wheel power is presented for evaluation of power demand requirements.

The European ECE driving cycle is a strictly urban cycle that does not include a high speed component, with a top speed of approximately 50km/h. The Urban Dynamometer Driving Schedule (UDDS) achieves a top speed of about 100km/h, thus the designed powertrain will achieve a higher degree of flexibility, at additional cost.

Table 2 provides some statistics for the power and torque of the vehicle. Included in these statistics are both the mean torque from the cycle and the mean driving torque, i.e. those torques above zero. This data provides insight into the requirements for motor power and torque requirements for the powertrain. A 5kW continuous (8kW peak) power permanent magnet direct current (PMDC) motor is selected based on the data in Table 2. For the series hybrid and electric vehicle configurations a reduction ratio of 4:1 is chosen to match the motor torque and speed characteristics to the requirements of the driving cycles studied. However, the conventional scooter relies on the use of a belt CVT and final drive gearing to provide a variable reduction between engine and wheels. Converting the vehicle speed and wheel torque in Figures 3 and 4 with the reduction ratio, the cycle instantaneous motor efficiencies are shown in Figure 5.

The mean ECE motor efficiency is determined to be 53.7%, excluding zero speed data, and for UDDS it is determined to be 65.6%. The energy consumed driving the vehicle is also derived from the driving cycles; it is however not as direct. For energy consumed, only the power driving the vehicle is consuming energy. Negative power in Figures 3(c) and 4(c) is actually the energy generated from braking, not a component of energy consumed, particularly as regenerative braking is not included in the evaluation of battery size.

$$E_W = \int \frac{T_W}{r_t} ds \tag{2}$$

Given that V = ds/dt, and that these consumption calculations are performed at a constant time step dt (= 1s), equation 2 can be written as:

$$E_W = \sum_{i=1}^{n} \frac{T_W}{r_t} V \Delta t \tag{3}$$

This results in the calculation of estimated energy consumption at the wheel of 0.270kWh for the UDDS driving cycle and 0.0186kWh for the ECE driving cycle. This is, of course, the energy consumed at the wheel to drive the vehicle. It does not include the consideration of efficiency losses which will substantially increase the energy consumed. Given the markedly different range of each of the two cycles, these two sets of results are divided by the driving distance. For the UDDS this is 0.0224kWh/km and for the ECE cycle 0.0183kWh/km. This is not dissimilar estimates in [17] for 30Wh/km and [18] of 51.5Wh/km when the efficiency losses of the scooter powertrain are taken into consideration, but at the lower end of other estimates, such as [19], which can be between 57wh/km and 100wh/km, based on physical tests.

The combined efficiencies of the powertrain, (average) motor and power converter, estimated consumption per kilometre, and by using a nominal battery voltage of 48V (i.e. 16S1P pack configuration) and a 70% depth of discharge, it is now possible to determine the battery stored charge requirements for different all electric ranges under both driving cycles. These results are summarized in Table 3 along with the variation of vehicle mass that results from the change in size of the battery pack. The all electric range is chosen based on single trip data provided by Blackman [2]. By repeating the previously described procedure for each of the alternative vehicle masses, stored charge for UDDS and ECE cycles is estimated. The reason behind the identical results can be surmised from the variation in consumption and average motor efficiencies of the powertrain, whilst the ECE cycle has lower consumption at the wheel, there is also poorer driving efficiency that degrades the operating performance.

4. Vehicle Simulations

Modelling of the alternative vehicle architectures was under taken in [14]; these models are used in this section for a comparative study of vehicle driving range. For the purpose of this paper the depth of discharge for each pack is 70%, furthermore a constant tank size of 5l is used for all vehicle configurations, and the PHEV tests are based on starting with a high SOC, whilst the BHEV is set to 50% SOC. The battery model utilized in these simulations has a nominal stored charge of 7Ah per cell; the actual pack size is based on a multiple of this value. Additionally, simulations of driving range in this section will include the use of regenerative braking to further enhance driving range.

Results presented in Table 4 suggest that the method for estimating vehicle range presented in the previous section consistently underestimates the range achieved by the vehicle, primarily due to the lack of analysis of regenerative braking in the analysis. There are particular differences between the estimation strategy and simulation method for developing appropriate configurations, notably the load dependent characteristics of batteries and motor. It is also important to note that the ECE driving cycle produced a lower average driving efficiency than the UDDS cycle. This results in a poorer range estimation in Table 3, when comparing ECE and UDDS cycles. The plug-in HEV is designed to maximize benefits of both PHEVs and BHEVs. To this end the battery capacity selected for these simulations is 100Ah. Complementing this is the selection of an appropriate generator. Revisiting Figures 3(d) and 4(d) the minimum possible size of the generator should be 2~4kW. For the ECE cycle this is more than sufficient to meet most, if not all requirements. However, for the UDDS cycle this size will only meet approximately 60% of power requirements. Therefore PHEV and BHEV simulations will be extended to consider alternative power ratings for the generator.

The following conclusions can be drawn from the results presented in Table 4:

1. The PHEV has the poorest fuel efficiency of all configurations in the UDDS cycle as it is heavily penalised by the additional mass of the large battery pack in the more demanding driving cycle.
2. Results for the BHEV and PHEV suggest there is an optimal size of the engine/generator that is notionally in the region around 4kW.
3. Furthermore, the balance between battery size and generator can also benefit the optimal design of such hybrid vehicles.
4. The low reported efficiency of the CVT has a strong negative influence on the overall performance of the conventional vehicle; improvement in CVT efficiency will strongly improve its performance.

5. Economic Analysis of Alternative Powertrain Configurations

In this section the comparative costs of ownership of the different vehicle configurations is studied. This includes the costs associated with (1) energy consumption, (2) capital costs for the different powertrains, and (3) ongoing maintenance of the vehicles.

5.1. Energy Consumption Costs of Alternative Powertrains

To properly evaluate the proposed configurations and provide a uniform basis for comparison, the operational costs for each of the provided powertrains are studied. The cost values below are taken as being typical of the current market, and are reflected in [20], for example.

The evaluation of energy consumption costs is conducted using the following strategy, with results summarised in Table 5:

1. For each variant studied take the average of UDDS and ECE cycle range.
2. Apply a cost of \$1.50 per liter of fuel to PHEV and BHEV configuration.
3. Assume a charging efficiency of 85%.
4. Apply a cost of \$0.20 per kWh for charging from the grid for PEV and PHEV configurations.
5. Calculate total costs and dollars per 100 km by dividing the average driving range into the total cost to refuel/recharge.

The results demonstrate that the PEV configuration is the cheapest to refuel/recharge of the three proposed variants. Additionally, the BHEV is the most expensive. This is the result of not being capable of benefiting from the cheaper cost of electrical charging. Furthermore, these two configurations have a comparable maximum range, thus demonstrating the cost effectiveness of the PEV. However, if we are to consider the need to maximize driving range, the PHEV provides the highest range option; it is also cheaper to run than the BHEV configurations.

5.2. Capital Costs of Alternative Powertrains

To properly evaluate the proposed configurations and provide a uniform basis for comparison, the capital costs for each of the provided powertrains are studied, based on the capital costs of the vehicle a retail margin is added to more accurately reflect purchaser cost.

Relying on the cost estimates from [16], Table 6 summarizes assumptions made with respect to the relative cost analysis of each configuration. Probably the most significant consideration is the treatment of battery costs. In each of the electrified platforms the battery pack is the most significant cost addition to the platform, see Table 7. In [16] an average cost of \$800/kWh was utilized based on recent Australian studies [17]. Other studies, including [18, 19] place a significantly lower cost on these units at between \$150 and \$280 USD for the batteries. To mediate such a significant difference a mid-range value of \$500 is chosen. Scooter usage data was taken from a recent study into driving patterns for two-wheelers (scooters and mopeds) in the city of Brisbane, Australia [2].

5.3. Maintenance Costs of Alternative Powertrains

The third major cost contribution to each of the two wheeler powertrain configurations shown is the inclusion of vehicle maintenance costs. These will include regular maintenance items, such as general servicing of powertrain (lubricants, filters, belts) and vehicle systems (electrical, brakes), as well as irregular maintenance items (tire and battery replacements).

Maintenance frequencies and labour times have been derived from [23], a typical OEM maintenance schedule for conventional two wheelers, and extrapolated across all variants as outlined in Table 8 (labour rate is assumed at \$80/hr and parts costs have been taken from typical conventional two wheelers). In the absence of reliable hybrid two wheeler maintenance data, and given that CV, BHEV and PHEV configurations only differ significantly in terms of engine size, it is assumed that the variation in powertrain service costs does not differ substantially between engines. The conventional vehicle is also inhibited by the variation. Nonetheless, expected maintenance costs for the BHEV and PHEV types are likely to be lower as a result of reduced engine operating periods. The PEV type adheres to similar service intervals for electrical system, brake, and tire maintenance.

The other major consideration for the electrified platforms is the life of the traction batteries. Generally this is considered a function of environmental degradation when not in use (i.e. storage loss) and discharge related degradation. Brooker [24] revises much of the current literature and, with correlation to published expectations, produces a description of the life expectancy of batteries as a function of the depth of discharge (DoD). This is defined as [25]:

$$D = 86L^{-0.68} \tag{4}$$

where L is the usable lifespan of the battery in cycles and D is the depth of discharge as a percentage. The common depth of discharge selected for this paper is 70% across all electrified vehicles in this study, and by rearranging equation (4) the number of cycles can be determined accordingly. For the sake of consistency across all platforms in this study it is then assumed that the vehicle is driven through the full DoD before recharging. The frequency of recharging is then linked to the vehicle driving range and consequently how often it must be recharged by the user.

In summary, the PEV configuration exhibits the lowest annualized maintenance cost across all configurations, predominantly due to the lack of a service intensive IC engine, as shown in Table 8.

5.4. Cost Recovery of Alternative Powertrains

To this point only the single cycle use has been considered, this has enabled the gathering of average fuel and energy consumption and vehicle emissions data. To extend this into the consideration of vehicle emissions consider some average annual driving data for scooter users. Blackman [2] conducts a primary survey of scooter usage in Queensland, Australia. The average annual range of scooter drivers surveyed is 7186 km with a standard deviation of 6993 km; this data was taken from a total of 151 participants to an online survey with location determined via supplied postcode. Figure 9 presents the total cost breakdown of all alternative two wheeler configurations based on the average driving distance.

The main outcomes of the cost analysis are that whilst the PEV has the higher capital costs, cheaper maintenance and ongoing operating costs make it financially viable for longer term use. This is particularly true as the mean trip suggested in [2] is 46km. Overall, it is more desirable to include a larger battery to provide for the larger range requirements, and also the smaller packs were assessed to require more frequent replacement as a result of more frequent charging. The major cost additions to the hybrid type vehicles are (1) the addition of an engine-generator, (2) battery pack, (3) the use of conventional fuel instead of or supplementing electricity. Whilst it may be possible to reduce some of these costs with parallel hybrid type vehicles, such as [8], these will require more complex and costly power splitting transmissions and additional control. These results do suggest that the PHEV could be optimized to achieve a desirable balance between both the on-board stored electricity and costs. This will lead to a functionally balanced (larger driving range between charges) and cost effective configuration. Further evaluation of the costs of $LiPhO_4$ batteries would further strengthen the cost incurred in this study. Also, note that, using the previously detailed method in Section 5.3, it was found not to be necessary to replace traction batteries for any configuration, even for an annual driving range of 10 000 km (see Figure 7).

As there is such a significant variation of the driving range by on road uses according to [2], Figure 6 present the total costs of the CV7, PEV50, PHEV5 and BHEV6 configurations using half the mean, mean and twice the mean driving range. It is important to note that, with the larger driving range of 10 800 km, even the smaller PEV battery does not reach the end of its useful life (using the method of calculating in Equation 4). The general consensus drawn from these results is that the hybridization of this type of passenger vehicle is generally not cost effective unless substantial driving ranges are involved.

7. Conclusions

The purpose of this paper is to develop and evaluate alternative powertrain configurations for serial hybrid two wheelers. This includes conventional, pure electric, plug-in hybrid, and battery hybrid electric vehicle powertrain variants. To achieve this statistical analysis both UDDS and ECE driving cycles were used to determine the requirements for major component parameters, including motor torque and power requirements, battery capacity and minimum generator size. Based on simulations of vehicle driving performance the fuel and energy economy of different variants was assessed and utilised in a cost comparison of all available vehicles. Results demonstrate that while it is possible to achieve improved fuel economy through hybridisation of this type of vehicle the financial benefits were not attained. There are some important considerations that can be drawn from the overall results:

1. Both hybrid vehicles demonstrate the need to achieve an optimal balance between energy storage and generator sizes. This impacts both the fuel economy and overall vehicle costs.
2. The PEV is significantly cheaper than all alternatives; however this needs to be weighed against more frequent charging of the system. Nevertheless, a pack size between 50 and 100 Ah is favourable to achieve most daily drives.

Results of fuel economy and cost analysis have demonstrated that the pure electric vehicle is financially beneficial in comparison to the conventional equivalent. It was further demonstrated that there needs to be significant increases in driving range for the hybrid vehicles studied to be cost competitive to the current state of conventional vehicles. Finally, this research will be extended to include a comprehensive study of the life cycles emissions of the four vehicles.

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References

1. Federal Chamber of Automotive Industries, 2012, “Motorcycle Group - National Sales Report: Summary”, http://www.fcai.com.au/motorcycles/introduction. Accessed 19 May 2014.
2. Blackman RA, 2012, “The increased popularity of mopeds and motor scooters: exploring usage patterns and safety outcomes”, PhD Thesis, Queensland University of Technology.
3. Yang, CJ, 2010, “Launching strategy for electric vehicles: lessons from China and Taiwan”, Technological Forecasting and Social Change, 77:831-834.
4. Cherry, CR, Weinert, JX, Xinmiao, X, 2009, “Comparative environmental impacts of electric bikes in China”, Transportation Research Part D, 14:281-290.
5. Bishop, JDK, Doucette, RT, Robinson, D, Mills, B & McCulloch, MD, 2011, “Investigating the technical, economic and environmental performance of electric vehicles in the real world: A case study using electric scooters”, Journal of Power Sources, 196:10094-10104.
6. Weinert J, Ogden J, Sperling D, & Burke A, 2008, “The future of electric two-wheelers and electric vehicles in China”, Energy Policy, 36:2544-2555.
7. 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.
8. Sheu, KB, & Hsu, TH, 2006, “Design and implementation of a novel hybrid-electric-motorcycle transmission”, Applied Energy, 83:959-974.
9. Sheu, KB, 2008, “Simulation for the analysis of a hybrid electric scooter powertrain”, Applied Energy, 85:589-606.
10. Tong, CC & Jwo, WS, 2007, “An assist-mode hybrid electric motorcycle”, Journal of Power Sources, 174:61-68.
11. Huang KD and Tzeng SC, 2004“A new parallel-type hybrid electric vehicle”, Applied Energy, 79:51-64.

12. Amjad S, Rudramoorthy R, Neelakrishnan S, Varman KSR, & Arjunan TV, 2011 “Impact of real world driving pattern and all-electric range on battery sizing and cost of plug-in hybrid electric two-wheeler”, Journal of Power Sources, 196:3371-3377.
13. Amjad S, Rudramoorthy R, Neelakrishnan S, Varman KSR & Arjunan TV, 2011 “Evaluation of energy requirements for all-electric range of plug-in hybrid electric two wheeler”, Energy, 36:1623-1629.
14. Walker, PD & Roser, HM, 2014, “Configuration design and energy balancing of compact-hybrid powertrains”, in 12th Biennial Conference on Engineering Systems Design and Analysis (ESDA2014), Copenhagen, Denmark, June 25-27.
15. Wang, X., He, H., Sun, F., Sun, X., and Tent, H. 2013 “Comparative study on different energy management strategies for plug-in hybrid electric vehicles” Energies, 6: 5656-5675.
16. Zhu, C, Liu, H, Tian, J, Xiao, Q & Du, X, 2010, “Experimental investigation on the efficiency of the pulley-drive CVT” International Journal of Automotive Technology, 11(2):257-261.
17. Hwang, JJ, & Chang, WR, 2010, “Life-cycle analysis of greenhouse gas emission and energy efficiency of hydrogen fuel cell scooters”, International Journal of Hydrogen Energy, 35:11947-11956.
18. Hwang, JJ, 2010, “Sustainable transport strategy for promoting zero-emission electric scooters in Taiwan”, Renewable and Sustainable Energy Reviews, 14:1390-1399.
19. Bishop, JDK, Doucette, RT, Robinson, D, Mills, B, & McCulloch, MD, “Investigating the technical, economic and environmental performance of electric vehicles in the real-world: A case study using electric scooters” Journal of Power Sources, 196:10094-10104.
20. 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, 25:238-249.
21. Kinghorn, R., Kua, D., 2011. Forecast Uptake and Economic Evaluation of Electric Vehicles in Victoria. Technical Report 60149263, Department of Transport.
22. Shaik Amjad, R. Rudramoorthy, S. Neelakrishnan, K. Sri Raja Varman, T.V. Arjunan, 2011, Impact of real world driving pattern and all-electric range on battery sizing and cost of plug-in hybrid electric two-wheeler, Journal of Power Sources, 196(6):3371-3377.
23. Piaggio, 2012 “Service Station Manual - MSS Fly 125-150 i.e. (2012)” Piaggio & C. S.p.A., Publication no. 677675 EN, p. 37.
24. Mayer, T, Kreyenberg, D Wind, J, & Braun, F, 2012 Feasibility study of 2020 target costs for PEM fuel cells and lithium-ion batteries: A two-factor experience curve approach, International Journal of Hydrogen Energy, 37(19): 14463-14474.
25. Brooker, A., Thornton, M. and Rugh, J. 2010 “Technology Improvement Pathways to Cost-effective Vehicle Electrification” SAE Technical Paper 2010-01-0824.