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Impact of real world driving pattern and all-electric range on battery sizing and cost of plug-in hybrid electric two-wheeler

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ABSTRACT

This study addresses the impact of an actual drive pattern on the sizing and cost of a battery pack for a plug-in hybrid electric two-wheeler. To estimate the daily average travel distance in fixing the all-electric range of two wheelers, a study conducted in Coimbatore city is presented. A MATLAB simulation model developed for estimating the energy and power requirements in an all-electric strategy using an Indian driving cycle (IDC) and a real-world driving pattern are discussed. The simulation results reveal the impact of the real-world driving pattern on energy consumption and also the influence of all-electric range in sizing the battery pack. To validate the results, a plug-in hybrid electric two-wheeler developed by modifying a standard two-wheeler has been tested on the road with the help of the IDC simulator kit. An annual battery cost comparison shows that nickel–metal-hydride batteries are more economical and suitable for in plug-in hybrid electric two-wheelers.

1. Introduction

Mopeds, motorcycles and scooters – known as power two-wheelers or simply two-wheelers – are popular means of transportation, in Asia. Two-wheelers play a very important role in providing personal transportation in most cities in Asia. Because of their small size and easy maneuverability, two-wheelers help to alleviate traffic congestion and reduce energy consumption for the transportation of one or two passengers, compared with passenger cars. In India, two-wheelers serve as a primary transportation option that account for nearly two-third of the total vehicle population and consume more than 50% of gasoline used [1]. Statistics show that the two-wheeler population in India has grown very rapidly in the last decade and has tripled during this period [2]. At present, India has the second highest two-wheeler density in the world. It is also expected that the Indian two-wheeler population will exceed that of China sometime between 2010 and 2020, and will have the largest two-wheeler fleet in the world [3]. The expected high fuel consumption and emissions of two-wheelers in urban areas need to receive more attention to improve the near-term sustainability of energy and urban air quality.

Hybridization is one approach to achieve better fuel economy in automobiles. The advent of hybrid electric drive-trains offers the capacity to improve fuel economy using an electric motor to reduce the fluctuating energy requirements of the internal-combustion engine. Hybrid electric vehicle (HEV) technology has the potential to reduce urban emissions and overall petroleum consumption if it can use grid electricity. A plug-in hybrid electric vehicle (PHEV) has the facility to plug-in to a standard electric outlet, and thereby has the potential to displace a significant portion of transportation petroleum consumption using electricity for portions of trips. A key benefit of plug-in hybrid technology is that the vehicle no longer depends on a single fuel source. A unique advantage of plug-in hybrid vehicles is their capability to integrate the transportation and the electric power generation sectors to improve the efficiency, fuel economy, and reliability of both systems [4]. There is, however, no compact plug-in hybrid electric two-wheeler of any form in today's consumer market.

Another important issue that influences fuel/energy consumption is the driving cycle. For any country, the driving cycle is the probable plot of vehicle speed from starting the engine to the end of a prescribed period of travel. The data are available as a plot of vehicle-speed in km h^{-1} against time in seconds and is called the urban or highway driving cycle of the given country. The information is acquired by averaging the extensive data when the vehicle is driven under actual service conditions on designated urban routes or on highways where the traffic density and driving pattern is representative of the prevailing working day pattern of the country. A typical driving profile consists of a complicated series of accelerations, decelerations and frequent stops, and it is simulated by driving cycles on a laboratory chassis dynamometer [5].

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The Indian driving cycle (IDC) was formulated around late 1985 following extensive road tests by scientists at the Automotive Research Association of India, Pune. Since the IDC involves too many transients because of haphazard traffic situations in India, this is now followed only for two and three wheelers, which are common modes of transportation in Indian cities [6]. The IDC adopted for certification of two and three wheelers in India consists of six cycles with a total distance of 3.948 km, each cycle lasts for about 108 s with an average speed of 21.9 km h^{-1} and the maximum acceleration and deceleration are 0.65 m s^{-2} and 0.63 m s^{-2}, respectively [7]. The IDC is unsuitable for evaluating fuel consumption due to its gentle acceleration, braking and long periods spent in stationary mode. Nesamani and Subramanian [8] found that the IDC does not replicate real-world driving, which is a serious concern. Therefore, many research efforts are targeted to develop drive cycles using recorded real world driving tests (complex transient) as well as the steady-state (cruise) conditions encountered in road driving.

The main focus of this investigation is to evaluate the total energy requirements and initial cost of the battery pack for daily average travel needs of plug-in hybrid electric two-wheelers in India. A study conducted in Coimbatore city has helped in estimating the daily average travel range. The MATLAB simulation is used to investigate the battery energy, mass and initial cost. This work also addresses the impact of a real-world driving pattern on the energy and power requirements of a converted plug-in hybrid electric two-wheeler. A comparison between the actual driving pattern and the Indian driving cycle reveals the influence of these factors.

2. Prototype model

A prototype was developed by modifying an existing two-wheeler to a plug-in hybrid electric two-wheeler by retrofitting a wheel hub motor on the front wheel with the battery pack placed at the foot rest (Fig. 1). The hub motor drives the front wheel, whereas the rear wheel is driven by an internal-combustion (IC) engine through a continuously variable transmission as in the existing vehicle. The control system utilizes a real time strategy depending on two inputs, viz., vehicle speed and battery state-of-charge. Switching from electric to hybrid mode, and vice versa, is facilitated by a micro-controller which is provided with the above two inputs. The control system developed has three modes of operation that can be selected by the driver. The three modes of operation are named as electric mode, hybrid mode and engine mode.

- In *'electric mode'*, the plug-in hybrid converted two-wheeler will act as an electric vehicle. The all-electric range (AER) strategy emphasizes all-electric vehicle operation over a desired distance during which the battery discharges to a minimum threshold. So, this mode has all the advantages of an electric vehicle.
- In *'hybrid mode'*, the energy management strategy is formulated in such a way that the existing engine idling and low power modes are eliminated to a great extent. For starting the vehicle and at low speed-high torque region, the battery pack supplies the power to the hub motor fitted in the front wheel. When the speed of the vehicle goes beyond the set speed and is maintained for 5 s, the engine will switch on and power the rear wheel to drive the vehicle. As the engine switches on, the battery power will be cut off to the hub motor. When the speed of the vehicle falls below the set speed and remains in that state continuously for 5 s or more, the engine is switched off followed by power switch on to hub motor. This feature enables the vehicle to offer the best of both electric and engine modes i.e. energy savings and emission reduction.
- In *'engine mode'*, if the state-of-charge level of the battery pack drops below the minimum threshold value, the control system will automatically switch off the electric mode as well as the hybrid mode. Then the vehicle will act as a conventional IC engine powered vehicle. Thus, the range is not limited unlike that of electric two-wheelers.

3. Daily average travel distance

One of the most critical issues for plug-in hybrid two-wheelers is the distance they can run on a single battery charge. For estimating the energy-storage requirements and sizing of battery pack, the daily travel distance by a vehicle plays a vital factor [9]. An earlier study in India estimated that, nationally, the average daily travel distance by two-wheelers is close to 24 km per day. The daily average travel distance for two-wheelers in major Indian cities is illustrated in Fig. 2 [10]. Whereas, the daily average travel distance varies from city to city and hence so do the battery energy requirements.

To observe the daily travel distance of two-wheelers, a study has been conducted in Coimbatore, which is one of the top ten fastest growing cities of India and is the second largest city in the south Indian state of Tamil Nadu. A total of 500 two-wheelers with different categories and capacities has been studied. It is found that

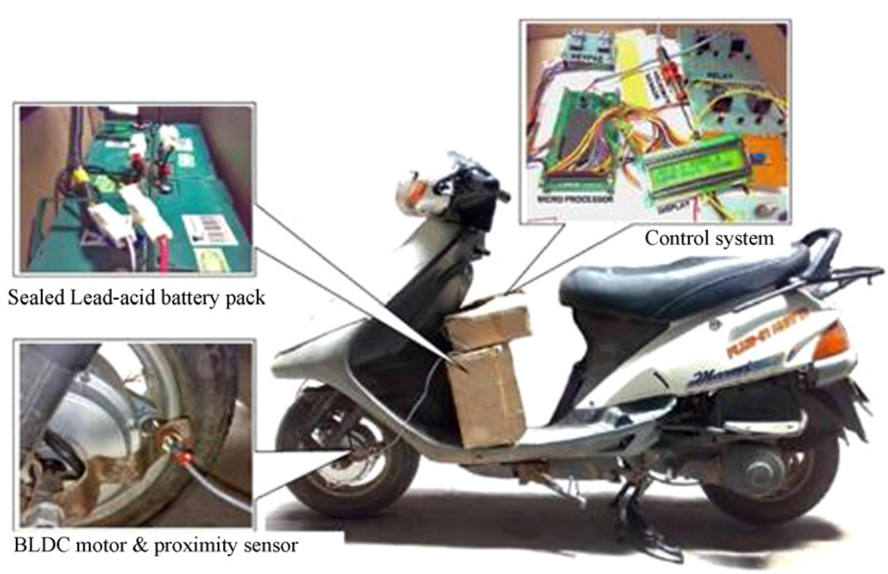

Fig. 1. Converted plug-in hybrid electric two-wheeler.

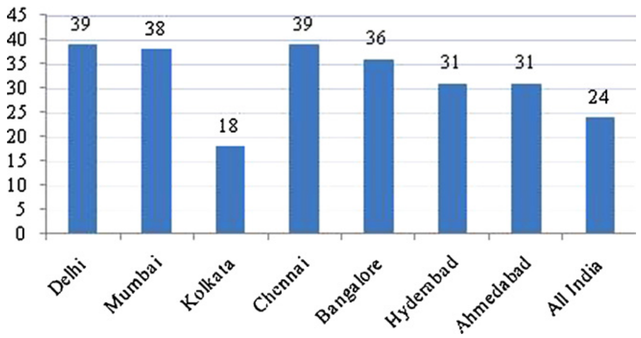

Fig. 2. Daily average travel distance (km) of two-wheelers in major Indian cities.

Table 1
Specifications of converted plug-in hybrid electric two-wheeler.

Specifications	Converted plug-in hybrid electric two-wheeler
Engine	2-stroke (SI)
Engine displacement	98 cc
Max. power	5.7 kW @ 5500 rpm
Max. torque	9.8 N m @4500 rpm
Kerb weight	128 kg
Maximum speed	95 km h^{-1}
All-electric range	26 km
Electric motor	800 W, 48 V BLDC Hub motor, 33 N m @ 150 rpm
Battery	20 Ah, 12 V VRLA traction battery – 4 Nos.

the average travel distance travelled by two-wheeler commuters in Coimbatore city is 25 km per day. The distribution of the distance covered during daily driving is shown in Fig. 3, and it is observed that nearly 61% of riders drive less than 25 km per day. Only 7% of the riders travel more than 50 km per day, and about 32% travel between 25 and 50 km per day.

Since short trips represent the majority of driving in cities, the result would be a dramatic decrease in fuel/energy consumption and urban pollution. This study helps in sizing the battery packs for plug-in hybrid electric two-wheelers to meet the daily travel needs of two-wheeler riders in India. The specifications of a converted plug-in hybrid electric two-wheeler are given in Table 1.

4. Real-world driving pattern in Coimbatore city

Given that driving patterns vary from city to city and from area to area, the available drive cycles obtained for certain cities or countries are not usually applicable for other cities. Therefore they are unable to represent the actual driving conditions. Real-world driving cycles are derived from the movement of a test vehicle on the road under real traffic conditions. Such drive cycles have not been developed for the city of Coimbatore and for the present the IDC is used for simulation and test.

Table 2
Summary of Indian driving cycle and real-world driving cycle.

Characteristics	Indian driving cycle	Real-world driving cycle (Coimbatore)
Distance (km)	3.948	3.68
Duration (s)	648	590
Average speed (km h^{-1})	21.93	22.46
Maximum speed (km h^{-1})	42	50
Maximum acceleration (m s^{-1})	0.65	1.22
Maximum deceleration (m s^{-1})	0.63	1.11

A road test was conducted in Coimbatore city with a converted plug-in hybrid two-wheeler to study and observe the real-world driving pattern. A predetermined urban route was taken for the vehicle on-road driving in this study. The prototype was instrumented and the speed was recorded on a second-by-second basis. The study was conducted during the peak hours of weekdays and it was ensured that there were no abnormal activities in the study corridor. Finally, the data was downloaded to a computer for further analysis. The real-world driving pattern has top speed of 50 km h^{-1} with average speed of 22.65 km h^{-1} and the maximum acceleration and deceleration are 1.22 m s^{-2} and 0.78 m s^{-2}, respectively. The parameters of both the Indian driving cycle and the real-world driving cycle are summarized in Table 2.

5. Simulation using MATLAB

Several computer programs have been developed to describe the operation of hybrid electric powertrains for four wheelers. But, there is no specific software for the simulation of two-wheelers available commercially. Using simulation, the influence of driving cycle and all-electric range on battery characteristics with different types of batteries can be quickly modelled and studied. In this particular work, a MATLAB simulation code has been developed to estimate the energy and power requirements of the plug-in hybrid electric two-wheeler for different all-electric range operations. The simulation software predicts the power demand and energy request, taking into account the driving cycle and all-electric

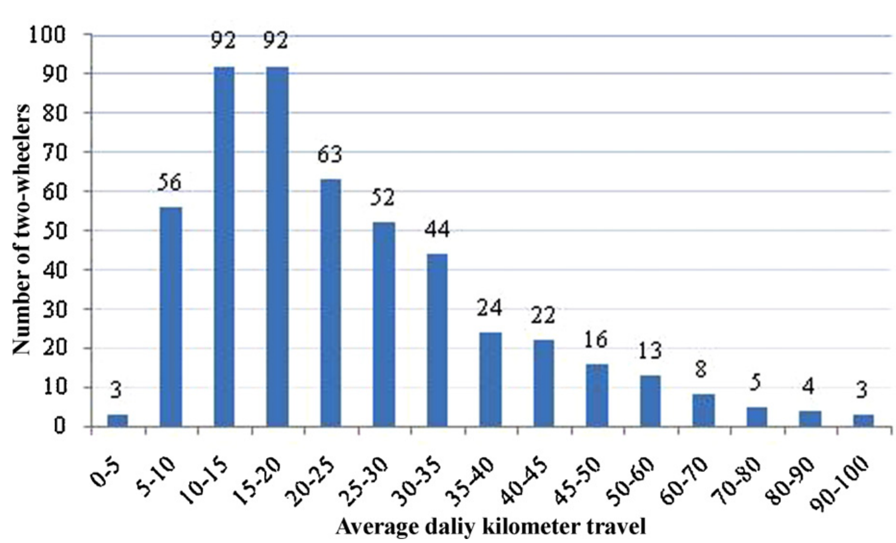

Fig. 3. Distribution of daily travel distance.

range. A simple vehicle dynamics model is followed for simulation modelling of a plug-in hybrid electric two-wheeler [11,12].

The key advantage of a plug-in hybrid electric two-wheeler is the all-electric range (AER), during which the battery discharges to a minimum threshold. Maximum battery energy storage is the core part of the plug-in hybrid electric two-wheeler system design [13] and it is calculated as,

$$E_{\text{battery}} = \frac{f_{\text{electric}}\, r_{\text{electric}}}{0.8} \qquad (1)$$

where E_{battery} is the maximum battery energy storage in kW h; f_{electric} is the electric fuel consumption of all electric operations in kWh km^{-1}; r_{electric} is the all-electric range in km. Batteries in PHEVs will only be discharged to 80% degree-of-discharge (DoD), which is the highest permitted limit to safeguard good battery cycle life. The maximum battery power is calculated as:

$$P_{\text{battery}} = E_{\text{battery}}\, R_{\text{p-e}} \qquad (2)$$

where P_{battery} is the maximum battery power in kW; $R_{\text{p-e}}$ is the ratio of specific power to the specific energy of the battery.

The cost of the battery is calculated as:

$$C_{\text{battery}} = E_{\text{battery}}\, \rho_{\text{battery}} \qquad (3)$$

where C_{battery} is the cost of battery; ρ_{battery} is the cost of battery per kWh.

As mentioned earlier, the key factors that influence the deployment of plug-in hybrid electric two-wheelers for the desired all-electric range are the driving cycle and energy storage device. The influence of other drive-line components on the vehicle performance and cost are not considered in the simulation. The battery energy capacity, mass and initial cost are varied according to corresponding AER and type of battery in each iteration. Therefore, the additional battery energy capacity, mass and cost are considered automatically during the simulation process.

5.1. Simulation methodology

The important steps in the simulation process are as follows:

- The required inputs for the simulation are taken from the user and available driving cycle data.
- A loop is initialized and iterated for driving cycle data values of aerodynamic resistance, rolling resistance, acceleration resistance, gradient resistance, tractive force, and power demand.
- The usable energy required at every instant is calculated by multiplying the integral of power values with the corresponding difference in time.
- An array with 11 values of all-electric range is initialized.
- The 11 initial values of usable energy required, battery energy capacity and hence the final battery mass are calculated using the formulae.
- Now, using the final mass of the battery a loop is again initialized.
- The new energy required is calculated, using the time integral of power demand for all the driving cycle data values.
- The 11 values of final energy required, capacity and battery mass are calculated.
- The final cost of the battery is calculated using the formula.
- Graphs and comparative curves are plotted.

5.2. Simulation validation

Validation plays an important role in the software development, as it provides users with the degree of accuracy of the software. Modelling tools could be validated using the data sources of the vehicle testing. In this particular work, the validation of simulation was undertaken by comparing the energy consumption levels using road test. For this purpose, a simple IDC simulator kit is developed which displays the time and speed on the LCD screen in decrement format. The circuit consists of a PIC (programmable interface controller) microcontroller and a LCD (liquid crystal display) unit powered by battery. The developed IDC simulator kit was fitted on the dash board that displays the speed of the vehicle to be maintained as per IDC driving cycle time. The rider has to follow the vehicle speeds as it is displayed.

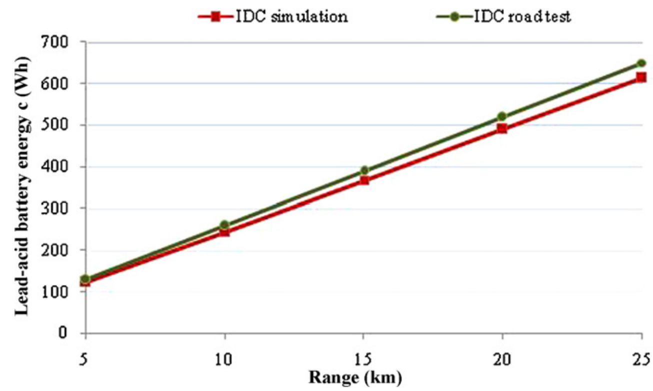

Fig. 4. Variation between simulation and road test.

A road test was conducted in a traffic free zone on a prototype vehicle and the state-of-charge and distance travelled values were recorded manually at different intervals. The prototype was driven in an electric mode for a range of 25 km with a lead–acid battery pack. From the road test, it is observed that the total energy consumed by the prototype vehicle on the road using the IDC simulator is 650 Wh, whereas using MATLAB simulation, the total energy consumed by the prototype for AER of 25 km is only 613 Wh. The variations between the road test and simulation at different AERs are shown in Fig. 4. There is about 6% difference in energy consumption between road test and simulation. This may be because of the assumptions made in the simulation process and human errors that occurred in following the vehicle speed manually during the test. Based on this test, it is assumed that the simulation results are on par with actual results and the similar simulation process can be continued for further analysis.

6. Results and discussion

To optimize the fuel economy of any propulsion system, a representative driving cycle must be known. In this work, the simulation process has been started with a lead–acid battery using the IDC. During the simulation, the peak power is evaluated by feeding the velocity values from the IDC data sheet. For the developed prototype model, the peak power demand at IDC is found to be 2.25 kW, as shown in Fig. 5. The negative values shown in the plot are regions of deceleration. The average power demand, however, is much lower comparatively. The usable energy requested by the IDC cycle can be calculated by taking the time integral of the power request. The energy requirement of the prototype model is about 16.8 Wh for the travel distance of 0.658 km in one cycle that lasts for 108 s. From the usable energy required and the distance travelled, the maximum energy storage capacity of the battery can be calculated using Eqs. (1) and (2). The battery mass is estimated using the specific energy and the battery initial cost is calculated by Eq. (3).

The simulation process was repeated for different all-electric ranges using the IDC. The initial battery mass is assumed to be zero and during the simulation process it varies according to corresponding AER and type of battery in each iteration. The process is repeated again for nickel–metal-hydride (Ni–MH) and lithium-ion

Table 3
Typical characteristics of traction batteries.

Type of battery	Specific energy[a] (Wh kg^{-1})	Energy density[a] (Wh L^{-1})	Specific power[b] (W kg^{-1})	Cycle life (cycles)	Projected cost (US$ kWh^{-1})	Projected cost[c] (INR Rs. kWh^{-1})
VRLA	30–50	60–100	200–400	400–600	120–150	5504–6880
Ni–MH	50–70	100–140	150–400	800–2000	150–200	6880–9174
Li-ion	120–140	240–280	700–950	1200	150–180	6880–8256

[a] At 80% depth-of-discharge.
[b] At 3-h discharge rate.
[c] At 1 US$ = INR ì 45.87.

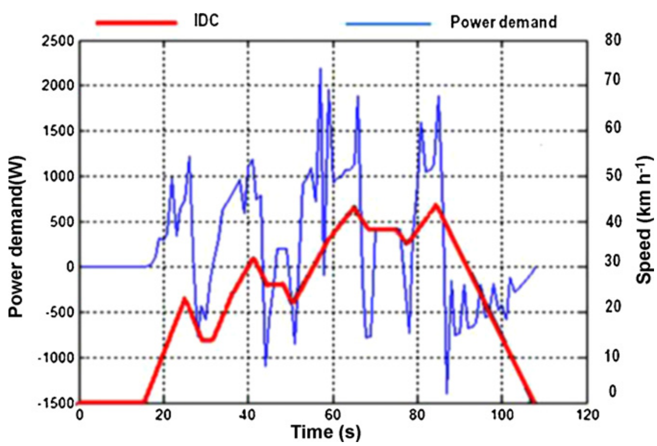

Fig. 5. Power demand by motor and battery at IDC.

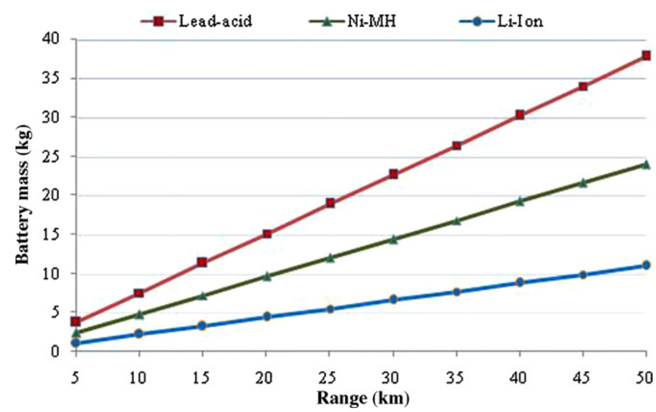

Fig. 7. Variations in the estimated battery mass at IDC.

(Li-ion) batteries using the IDC. The typical characteristics of these batteries are listed in Table 3 [13].

The variation in estimated energy capacity and mass of these batteries for different travel ranges is shown in Figs. 6 and 7, respectively. For a given range, lead–acid batteries are heavier compared with the other two common types of batteries, because of their lower specific energy. Moreover, lead–acid batteries occupy more space compared with the other two types, because of their lower energy density. The increase in mass of the battery makes the vehicle heavier which, in turn, increases the battery energy capacity proportionately. For the desired all-electric range of 25 km, lead–acid battery weighs 19 kg, whereas, Ni–MH and Li-ion batteries weigh only 12 and 5.5 kg, respectively. For an AER of 25 km, lead–acid batteries need 766 Wh of battery energy capacity, whereas Ni–MH and Li-ion batteries require only 728 and 691 Wh, respectively. Because of the higher specific energy of Li-ion batteries, they weigh lighter which in turn reduces the energy consumption. Thus, the required battery energy capacity is also low for the desired AER. The mass and energy capacity for the Ni–MH batteries falls between the Li-ion and lead–acid batteries, because of its moderate specific energy.

It is observed that, the battery energy capacity (Wh) varies linearly with the AER, whose slope is a function of battery mass. Among the three battery types listed in Table 3, the lead–acid battery packs have the highest mass. The battery pack weight also increases with the AER. The electricity consumption is also assumed to increase linearly with the vehicle mass.

In general, initial cost for Li-ion batteries is the highest on a per Wh basis, but their specific energy (Wh kg^{-1}) is higher than other two type of batteries so that for the desired AER, the initial cost of Ni–MH batteries appear to be higher and lead–acid batteries look cheaper. The initial cost of these batteries for different AERs with reference to the IDC is presented in Fig. 8. For example, for AER of 25 km, the initial cost of lead–acid battery is about Indian rupees (INR) Rs. 4220 and for Ni–MH and Li-ion batteries it is about Rs. 5344

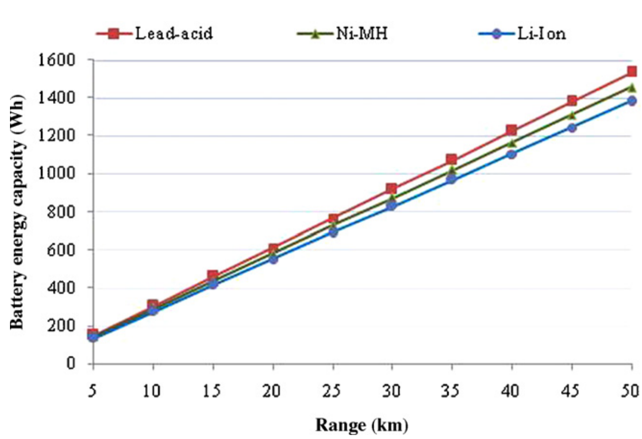

Fig. 6. Comparison of battery energy capacity requirements at IDC.

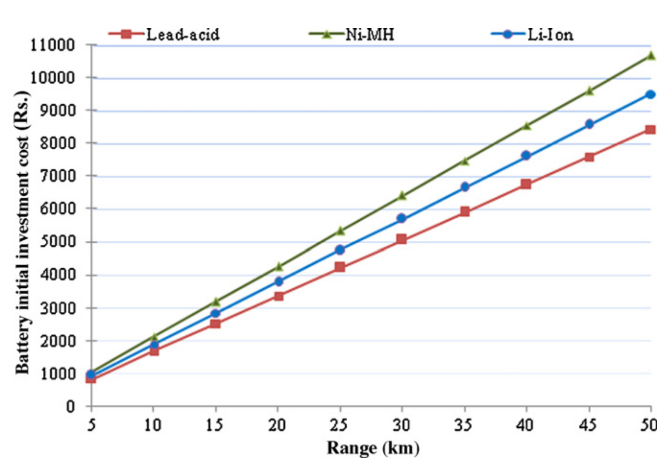

Fig. 8. Variations in the investment cost among three batteries with reference to IDC.

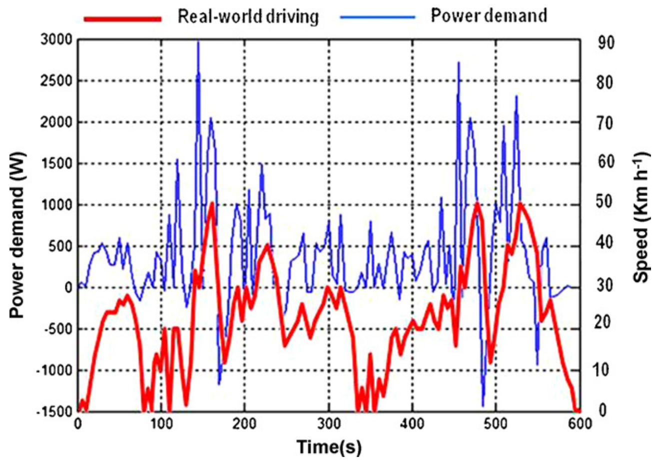

Fig. 9. Power demand by motor and battery at real-world driving.

and Rs. 4758, respectively. As the AER increases, the cost difference becomes wider for these batteries.

6.1. Comparison of real-world driving pattern with the IDC

To study the effect of real-world driving profile on power and energy requirements, similar simulation procedure is repeated for the real-world driving pattern obtained in Coimbatore city. The peak power demand is found to be 2.9 kW, which is about 29% more than the peak power demand observed by the IDC. The reason for this increase in peak power demand is because of higher top speed and high rate of acceleration and decelerations. From the power plot (Fig. 9), it is understood that the power requirements have considerable influence on the actual driving pattern. Taking an AER of 25 km, for example, the maximum energy storage capacity required by lead–acid battery under the IDC is 766 Wh and for real-world driving it is 912 Wh.

The total energy capacity estimated for the lead–acid battery under real-world driving is about 19% more than under the IDC. The variation in estimated energy capacity for batteries between the IDC and real-world driving for different all-electric ranges is illustrated in Fig. 10. The total energy capacity required for the Ni–MH battery under the real-world driving pattern is about 18% more than for the IDC, whereas it is 17% more for Li-ion battery. For an AER of 25 km, the energy capacity of the Ni–MH battery under the IDC is 728 Wh, whereas for real-world driving pattern, it is 861 Wh. Similarly, for the AER of 25 km, the energy capacity requested by the Li-ion battery under the IDC is 691 Wh, whereas for a real-world driving pattern, it is 814 Wh. Hence, today's real-

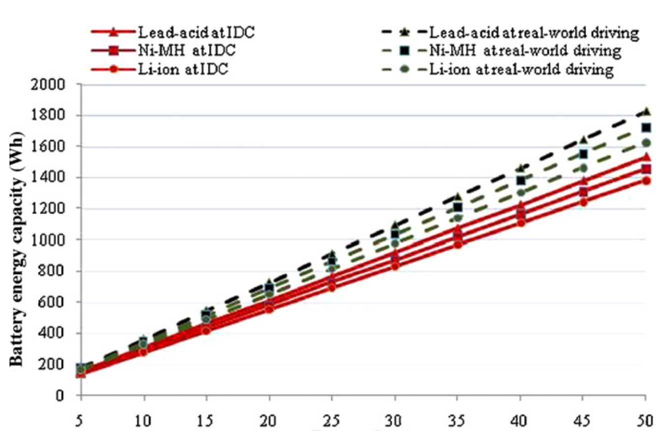

Fig. 10. Variation of battery energy capacity between IDC and real-world driving.

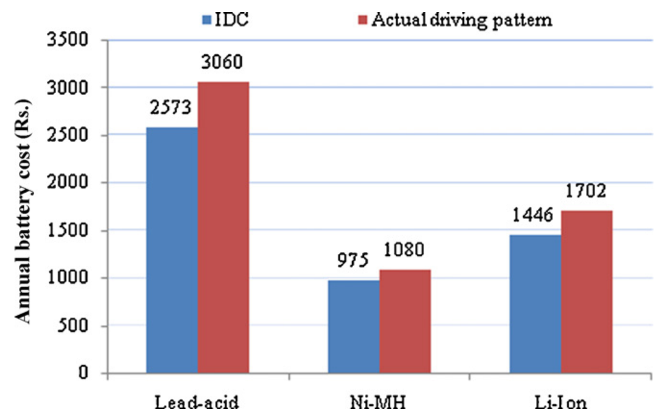

Fig. 11. Comparison of annual battery cost for an AER of 25 km.

world driving pattern has considerable influence on both the peak power demand and the battery energy capacity. Based on this analysis, it is observed that the real-world driving pattern demands 17–19% more energy than the IDC for a given battery type.

6.2. Effect of battery cycle-life on annual cost

The maximum cycle-life of the lead–acid battery is 600 cycles, whereas, for Ni–MH and Li-ion batteries it is 2000 and 1200 cycles, respectively [13]. Based on simulation with a IDC, for an AER of −25 km the initial cost of the lead–acid battery is about Rs. 4220 and for Ni–MH and Li-ion batteries it is about Rs. 5344 and Rs. 4758, respectively. Since the cost of the battery pack varies relatively, the interest factor is neglected in this study when estimating the annual cost. For simple analysis, by neglecting the interest factor and assuming that vehicle is operated for 365 days in a year with an AER of 25 km per day, the annual cost of lead–acid battery is around Rs. 2573 and for Li-ion battery it is Rs. 1446, but for Ni–MH it is only Rs. 975. Fig. 11 shows the annual cost variations between the IDC and actual driving pattern for the three types of batteries with an AER of 25 km. The cycle life has significant effect on annual cost of battery pack and on its selection. The lifetime costs are the highest for lead–acid batteries, even though their initial costs are lower. With reference to the IDC, even though the initial cost of Ni–MH batteries are on the high side for the desired AER, the annual cost of Ni–MH batteries is 62 and 33% lower than that of lead–acid and Li-ion batteries, respectively. So, finally, from the customer point of view, Ni–MH batteries are more economical and most suited for deployment of plug-in hybrid electric two-wheelers in the near future, but it is not stable and is influenced by other factors. If the annual cost is compared between the IDC and real-world driving patterns, the energy required in real-world driving is higher and hence the annual costs are also higher. The lead–acid battery cost is 19% higher, whereas Ni–MH and Li-ion batteries cost about 11 and 18% more, respectively.

7. Conclusions

Two-wheelers contribute two-thirds of the total vehicle population in India and the implementation of a plug-in hybrid concept in these vehicles will lead to a dramatic reduction in petroleum consumption, which helps efforts to achieve national energy security in the near future. A methodology for the development of a MATLAB code and simulation using the Indian driving cycle and the real-world driving cycle for a plug-in hybrid electric two-wheeler are presented for different all-electric ranges with three types of batteries. To validate this simulation code, a simple road test is also conducted using an IDC simulator kit developed for this work. A study conducted in Coimbatore city is helpful in estimating the daily average travel distance and also to develop the real-world driving pattern. A comparison of the real-world driving pattern with the Indian driving cycle (IDC) has revealed a significant influence on peak power and energy demand. The real-world driving pattern has shown a higher peak power demand of 29% and 17–19% of more energy than the IDC based on battery type.

The simulation results also indicate that the estimated battery energy capacity of the prototype model varies linearly with the all-electric range (AER), whose slope is a function of battery mass. For an AER of 25 km, Li-ion batteries weigh only 5.5 kg, which is compared with 12 kg for Ni–MH and 19 kg for lead–acid batteries and hence proportionately consume 5–11% less energy. Battery cycle-life has significant effect on the annual cost of the battery pack and its selection. Even though the initial cost of Ni–MH batteries is seen to be on the higher side for the desired AER, the annual cost is very low compared with Li-ion and lead–acid batteries. The annual cost of Ni–MH batteries is 62% lower than lead–acid and 33% lower than Li-ion batteries. Based on the analysis, it is noted that Ni–MH batteries are more economical and suitable for implementing in plug-in hybrid electric two-wheelers.

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