CHAPTER 4

MODELING, SIMULATION AND SELECTION OF POWERTRAIN COMPONENTS

4.1 INTRODUCTION

The purpose of modeling is to convert input parameters (performance measurements like desired range, driving cycle that must be sustained and types of power and storage components) into the output parameters of curb weight, battery pack capacity and cost. The derivations of parameters that influence the vehicle tractive efforts are based on Newton’s second law of motion. This chapter describes the power and energy requirements of plug-in hybrid electric two-wheelers. The various operating modes that the vehicle is subjected to throughout a mission profile are presented in order to analyse the instantaneous tractive power requirements and net energy expenditure. This chapter also discusses the simulation methodology followed by selection for powertrain elements for the plug-in hybrid electric two-wheeler.

4.2 MODELING OF POWERTRAIN COMPONENTS

In order to properly simulate the performance of a plug-in hybrid electric two-wheeler, a computer model is created based on the physical properties of a two-wheeler. This model calculates the instantaneous power required as it travels through various driving patterns and derives various numerical performance characteristics like fuel/energy consumed per kilometre of travel, maximum power during the driving cycle and average power during
the driving cycle. There are several different physical forces to consider: air resistance (drag); the rolling resistance of the wheels; the force of gravity, which is not necessarily perpendicular to the velocity if the vehicle is traveling uphill or downhill; and the normal force of the ground acting upon the vehicle. Figure 4.1 shows the free-body diagram of a two-wheeler.

![Free-body diagram of a two-wheeler](image)

**Figure 4.1 Free-body diagram of a two-wheeler**

The propulsion unit of plug-in hybrid electric two-wheeler consists of electrical and mechanical powertrain elements such as, wheel hub motor, internal combustion engine, energy storage device and associated power electronics. Vehicle specifications like weight, friction force, nominal velocity, acceleration and gradability affect this choice. A simple vehicle dynamics model followed by Thomas (1992), Wong et al (2006) and Ismail et al (2010) was used for modeling of the plug-in hybrid electric two-wheeler.

The effort to overcome the resisting forces by transmitting power via the vehicle drive wheels and tyres to the ground is known as the total tractive effort or total tractive force \( F_{tr} \). The selected power plant must be able to supply the tractive force to overcome the aerodynamic resistance force \( F_{aero} \),
rolling resistance force \( (F_{\text{roll}}) \), linear acceleration force \((F_{\text{la}})\) and gradient resistance force \((F_{\text{grad}})\) and this force is expressed as,

\[
F_{\text{tr}} = F_{\text{aero}} + F_{\text{roll}} + F_{\text{la}} + F_{\text{grad}} \tag{4.1}
\]

Rolling resistance force \((F_{\text{roll}})\) is produced by the hysteresis of the tyre at the contact surface with the roadway. When the tyre rolls, the centroid of vertical forces on the wheels move forward from beneath the axle towards the direction of motion of the vehicle. The weight acting on the wheel and the road normal forces are misaligned and thus exert a retarding torque. This force opposes the rotation of the wheel and is expressed as,

\[
F_{\text{roll}} = C_{\text{rr}} mg \tag{4.2}
\]

where \( m \) is the vehicle mass, \( g \) is the gravitational acceleration and \( C_{\text{rr}} \) is the coefficient of rolling resistance.

As a vehicle is propelled, it generates friction with the atmosphere while traveling through. This friction is referred to as the aerodynamic drag. The force opposes the motion of the vehicle and is influenced by the frontal area, shape and protrusions of the vehicle shell design. As there are multiple factors that contribute to this resistive force, it is commonly approximated using a prismatic vehicle body with a frontal area. Aerodynamic effect is considered in this work, even though vehicle is moving at speeds below 50 km/h. The aerodynamic resistance force \((F_{\text{aero}})\) is expressed as,

\[
F_{\text{aero}} = 0.5AC_d v^2 \tag{4.3}
\]

where \( \rho \) is the mass of air density, \( A \) is the vehicle frontal area, \( C_d \) is the aerodynamic drag resistance and \( v \) is the vehicle velocity.
The third component of tractive effort is the linear acceleration force (inertial force). The linear acceleration force is the load due to the acceleration of the mass of vehicle and follows the Newton’s second law. The linear acceleration force \( F_{la} \) is expressed as,

\[
F_{la} = m \frac{dv}{dt}
\]  

(4.4)

The fourth component of tractive effort is the force due to gradient. The gravitational force depends on the slope angle \( \alpha \) of the road in respect to the horizon. This force is induced by gravity when the vehicle travels on a non-horizontal plane. A climbing mission of the vehicle results in a positive force while a descending mission results in a negative force. This gradient resistance force is expressed as,

\[
F_{\text{grad}} = mg\sin(\alpha)
\]  

(4.5)

With the tractive force, the instantaneous tractive power \( P_{tr} \) can be expressed as,

\[
P_{tr} = v(F_{\text{aero}} + F_{\text{roll}} + F_{la} + F_{\text{grad}})
\]  

(4.6)

Depending on the value of tractive power, it is possible to classify the various operating modes of the vehicle as

- For \( P_{tr} > 0 \), the vehicle is in traction mode with a positive tractive effort.
- For \( P_{tr} < 0 \), the vehicle is in braking mode with a negative tractive effort
- For \( P_{tr} = 0 \), two possibilities occur in this condition. The first is when the vehicle is costing with the resistive force losses
exactly equal to the decrease in kinetic energy (coast mode).

The second indicating the vehicle is at rest (dwell mode).

The torque at wheels \( T_w \) can be obtained by multiplying the tractive force with wheel radius \( R_w \) and it can be expressed as,

\[
T_w = F_{tr} R_w \tag{4.7}
\]

The acceleration time is defined as the time required to reach a certain speed on a flat road. By applying the Newton’s second law of motion, the equation for the acceleration performance of a vehicle on a flat road, can be written as,

\[
F_{tr} = F_{aero} + F_{roll} + F_{ia} \tag{4.8}
\]

In the more explicit form, the acceleration time for initial velocity \( v_1 \) to the final velocity \( v_2 \) can be written as,

\[
t_{v_1 \rightarrow v_2} = \int_{v_1}^{v_2} \frac{\lambda m}{F_{tr}(v) - F_{roll} - F_{aero}} \, dv \tag{4.9}
\]

The gradability of a vehicle is defined as the road grade angle at which the vehicle can keep moving at constant speed. From the equation of motion of a vehicle climbing a hill with a grade angle \( \alpha \), the tractive force required to overcome a grade starting from standstill can be written as,

\[
\sin(\alpha) = \frac{F_{tr} - (F_{aero} + F_{roll} + F_{ia})}{mg} \tag{4.10}
\]

The main driving performance criteria for a road vehicle are its acceleration performance, gradability and maximum cruise speed. The
maximum cruise speed is defined as the maximum speed that the vehicle can achieve on a flat road and is written as,

\[ v = \sqrt{\frac{(F_{tr} - F_{roll})}{0.5 \rho C_d A}} \]  
(4.11)

Sizing of onboard energy storage system in plug-in hybrid electric two-wheeler is based on both the instantaneous power demand and as well as on the energy demand. The rate of change of energy is defined by the tractive power and is given by,

\[ \frac{dE_{tr}}{dt} = P_{tr} \]  
(4.12)

where \( E_{tr} \) is the instantaneous tractive energy. Following this, the energy required by the propulsion load over an interval is obtained by integration of the instantaneous power equation. The energy demand (\( E_d \)) can be arrived by using time integral of tractive power with time (s) and is written as,

\[ E_d = \Delta E_{tr} = \int_{t=0}^{t=f} P_{tr} dt \]  
(4.13)

The key advantage of plug-in hybrid electric two-wheeler is the all-electric range (AER). The all electric range emphasizes all electric vehicle operation over a desired distance in which the battery discharges to a minimum threshold. Battery will only be discharged to 80% degree-of-discharge (DOD), which is the highest DOD permitted in the interest of good battery cycle life (Wong et al 2006). The maximum battery energy storage is the core part of the plug-in hybrid electric two-wheeler system design and it is calculated as,
\[ E_{\text{battery}} = \frac{E_d}{0.8} \]  

(4.14)

Above equation can also be written as,

\[ E_{\text{battery}} = \frac{E_{\text{electric}}}{0.8} \]  

(4.15)

where \( E_{\text{battery}} \) is the maximum battery energy storage in Wh, \( f_{\text{electric}} \) is the electric energy consumption of all electric operations in Wh/km and \( r_{\text{electric}} \) is the all-electric range in kilometre. The maximum battery power is calculated as,

\[ P_{\text{battery}} = E_{\text{battery}} R_{p-e} \]  

(4.16)

where \( P_{\text{battery}} \) is the maximum battery power in W and \( R_{p-e} \) is the ratio of specific power to the specific energy of the battery in W/Wh.

An important attribute of electric propulsion systems is the ability to recapture some of the electrical energy via regenerative braking. During regenerative braking, the kinetic energy of the vehicle should be ideally fully converted and recuperated by the energy storage systems via the DC distribution Bus. Practically, only 30% to 50% (Miller 2004) of this energy is recoverable due to conversion losses. The amount of regenerative energy that can be recuperated depends on several factors, primarily the motor, deceleration rate and the receptiveness of the energy storage system. In rapid decelerations events, especially from high velocities, the magnitude of power that the traction motor is required to convert would be very large. To process this high power in a short period would require a traction motor with a significantly large power rating. The kinetic energy that the motor can convert within the required deceleration time then has to be transferred to the energy...
storage system. In India, two-wheelers design for low power applications with slow accelerations and decelerations. The amount of regenerative energy that can be recaptured may be fractional. So, in this work, regenerative braking is not considered and it can be taken as future work. However, the negative tractive energy has been considered as braking loss, which is added to the total energy demand.

The battery mass can be calculated as,

\[ m_b = \frac{E_{\text{battery}}}{S_e} \]  \hspace{1cm} (4.17)

where \( m_b \) is the battery mass in kg and \( S_e \) is the specific energy of the battery in Wh/kg.

The cost of the battery can be calculated as,

\[ C_{\text{battery}} = E_{\text{battery}}p_{\text{battery}} \]  \hspace{1cm} (4.18)

where \( C_{\text{battery}} \) is the battery cost and \( p_{\text{battery}} \) is the battery cost per Wh.

### 4.2.1 Technical Specifications of a Selected Two Wheeler

A prototype is planned to develop by modifying an existing two-wheeler into plug-in hybrid electric two-wheeler by retrofitting with wheel hub motor, battery pack, control system and other accessories. Based on the vehicle modeling, the base vehicle platform selected for this study is a commercially available 98cc, 2-stroke petrol two-wheeler. Because, two-wheelers having less than 125cc engine capacity account for nearly 85% of the total two-wheeler population in India. The technical specifications of the selected base vehicle are shown in Table 4.1.
Table 4.1 Technical specifications of a selected two-wheeler [36]

<table>
<thead>
<tr>
<th>Engine</th>
<th>Two-stroke/petrol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>Automatic</td>
</tr>
<tr>
<td>Engine displacement</td>
<td>98 cc</td>
</tr>
<tr>
<td>Maximum power</td>
<td>7.7 bhp @ 5500 rpm</td>
</tr>
<tr>
<td>Maximum torque</td>
<td>1.0 kgm @ 4500 rpm</td>
</tr>
<tr>
<td>Wheel base</td>
<td>1,215 mm</td>
</tr>
<tr>
<td>Ignition</td>
<td>Electronic</td>
</tr>
<tr>
<td>Dry weight</td>
<td>98 kg</td>
</tr>
<tr>
<td>Fuel tank capacity</td>
<td>6 litres</td>
</tr>
<tr>
<td>Battery</td>
<td>12 V</td>
</tr>
<tr>
<td>F/R suspension</td>
<td>Trading link and tlad drive system</td>
</tr>
<tr>
<td>R/R suspension</td>
<td>Unit swing arm</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>95 km/h</td>
</tr>
<tr>
<td>Front tyre size</td>
<td>3.50 x 10.4 PR</td>
</tr>
<tr>
<td>Rear tyre size</td>
<td>3.50 x 10.4 PR</td>
</tr>
</tbody>
</table>

4.3 DRIVING CYCLE SIMULATION

The essential factors which influence the deployment of plug-in hybrid electric two-wheelers are the battery energy capacity, its mass, cost and cycle life (charging / discharging cycles). In addition, the relative fuel/energy consumption depends greatly on the driving cycle over which the vehicle operates, but more important is the all-electric range (AER). The AER designed for the plug-in hybrid electric two-wheeler should be able to satisfy the daily average travel distance. Since short trips represent the majority of driving in cities, the result would be a dramatic decrease in fuel/energy consumption and urban pollution. Hence, the simulation work is limited to estimate the above mentioned vital factors in all-electric strategy.

System modeling and simulation analysis can reduce the development costs and shorten the development cycle. To properly simulate the performance of a plug-in hybrid electric two-wheeler, a MATLAB v7 based computer model was created based on the physical properties of the vehicle. The simulation of major components was not included in this work.
The simulation model calculates the energy and power requirements of the plug-in hybrid electric two-wheeler based on driving pattern and all-electric driving range. The simulation also helps in estimating the additional energy requirement, added battery mass and initial cost of battery pack. Based on this simulation, one can estimate the additional cost and annual investment cost on battery pack. The various forces acting upon it and this can be calculated by using Equations (4.1) to (4.6). The energy demand can be calculated by taking the time integral of the power request using Equation (4.13). From the energy demand and the distance travelled, the total energy capacity of the battery can be calculated by using Equations (4.14) or (4.15). The battery mass and the battery initial cost are calculated by using Equations (4.17) and (4.18).

As mentioned earlier, the key factors that influence the deployment of plug-in hybrid electric two-wheeler 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. Table 4.2 gives the typical characteristics of three important traction batteries available in the market (Wong et al 2006). The simulation flow chart and methodology adopted are given in section 4.3.1 and 4.3.2 respectively.

**Table 4.2 Typical characteristics of traction batteries**

<table>
<thead>
<tr>
<th>Type of battery</th>
<th>Specific energy (^a) (Wh/kg)</th>
<th>Energy density (^a) (Wh/L)</th>
<th>Specific power (^b) (W/kg)</th>
<th>Cycle life (Cycles)</th>
<th>Projected Cost (US$/kWh)</th>
<th>Projected Cost (^c) (INR/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VRLA</td>
<td>30-50</td>
<td>60-100</td>
<td>200-400</td>
<td>400-600</td>
<td>120-150</td>
<td>5504-6880</td>
</tr>
<tr>
<td>Ni-MH</td>
<td>50-70</td>
<td>100-140</td>
<td>150-400</td>
<td>800-2000</td>
<td>150-200</td>
<td>6880-9174</td>
</tr>
<tr>
<td>Li-ion</td>
<td>120-140</td>
<td>240-280</td>
<td>700-950</td>
<td>1200</td>
<td>150-180</td>
<td>6880-8256</td>
</tr>
</tbody>
</table>

\(^a\) At 80% depth-of-discharge, \(^b\) At 3-hour discharge rate, \(^c\) At 1US$ = INR 45.87
4.3.1 Simulation Flow Chart

START

Read in the values:
m, ρ, C_d, C_re, g, A, u, V, R_e, S, E_s, C, C_{battery}

Read acceleration, velocity & time values from driving cycle excel file

\[ i = 1 \]

\[ i < = \text{Cycle time} \]

Calculate the initial values:
\[ F_{\text{aero}}(i), F_{\text{grad}}, F_{\text{roll}}, F_{\text{la}}(i), F_{\text{tr}}(i), T_{w}(i), P_{tr}(i); \]
\[ i = i + 1 \]

\[ i = 2 \]

Assign \( P_{tr}(1) \)

\[ i < = \text{cycle time} \]

Calculate \( P_{tr}(j) \)
\[ i = i + 1 \]

\[ i = 2 \]

Assign \( E_{\text{a0}}(1) \)

\[ i < = \text{cycle time} \]

Calculate \( E_{\text{a0}}(i) \)
\[ i = i + 1 \]

Assign \( E_{\text{a0}}, S, S_e \)
\[ i = 1 \]

\[ i < = 11 \]

Calculate initial capacity in Wh, initial capacity in Ah & mass of the batteries and the final vehicle mass in Kg
\[ i = i + 1 \]
4.3.1 Simulation Flow Chart (Continued)

Generate 108 current values using $P_d$

$i = 1$

Yes

$i <= 11$

No

Calculate $F_{\text{grad}}$, $F_{\text{roll}}$

$j = 1$

Yes

$j <= 108$

No

Calculate $F_{\text{aero}}(j)$, $F_{\text{la}}(j)$, $F_{\text{tr}}(j)$,

Assign $P_{\text{ref}}(1)$

$j = 2$

Yes

Calculate $P_{\text{ref}}(j)$

$j = j + 1$

$j <= 108$

No

Calculate $E_d(1)$

$j = 2$

Yes

Calculate $E_d(j)$

$j = j + 1$

Calculate capacity in Wh, capacity in Ah, battery cost and the total vehicle cost

$i = i + 1$

STOP
4.3.2 Simulation Methodology

The important steps in the simulation process are:

- 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 force, rolling resistance force, acceleration resistance force, gradient resistance force, tractive force, and power demand are calculated using the formulae.

- 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 (ranging from 5 – 10 km) of all-electric range (ranging from 5 to 50 km) is initialized.

- The 11 initial values of usable energy required, battery energy capacity and hence the final battery mass is calculated using the formulae.

- Now, using the final mass of the battery again a loop is initialized.

- The new energy required value 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.

The graphs and comparative curves are plotted.

### 4.3.3 Simulation using the Indian Driving Cycle

The driving cycle of any country is the probable plot of vehicle speed right over a prescribed time. The data is available as a plot of vehicle speed in km/h against time in seconds and is called the urban or highway driving cycle of the country. A typical driving profile consists of complicated series of accelerations, decelerations, cruise and frequent stops. 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 (Tzirakis et al 2006).

The Indian driving cycle (IDC) was formulated after extensive road tests by scientists at Automotive research association of India (ARAI). 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. The IDC used for certification consists of six cycles with total distance of 3.948 km, each cycle consists about 108 seconds with average speed of 21.9 km/h (EPA 1996 and Mohan et al 2006). Figure 4.2 shows the Indian driving cycle pattern adopted for two-wheelers in India and table 4.3 gives the details of this cycle. The basic input parameters adopted for IDC simulation considering lead-acid battery pack as energy storage device are given in Table 4.4. Typical values of $C_r$, $C_d$ and $\rho$ are taken as 0.015, 0.6 and 1.21 kg/m$^3$ (Nathan and Ramesh 2004).
As per IDC simulation, the variation of aerodynamic force, rolling force, inertia force and tractive force with respect to time as per IDC are shown in Figure 4.3. The tractive force is negative at certain instances because of deceleration. The maximum value of tractive force is 164 N, however, the average value of tractive force (43 N) is much lower.
Table 4.4 Basic input parameters adopted for simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle weight (Excluding battery)</td>
<td>175 kg</td>
</tr>
<tr>
<td>Vehicle frontal area</td>
<td>0.53 m²</td>
</tr>
<tr>
<td>Wheel radius</td>
<td>0.21 m</td>
</tr>
<tr>
<td>Coefficient of rolling resistance</td>
<td>0.015</td>
</tr>
<tr>
<td>Coefficient of drag</td>
<td>0.6</td>
</tr>
<tr>
<td>Density of air</td>
<td>1.21 kg/m³</td>
</tr>
<tr>
<td>Acceleration due to gravity</td>
<td>9.81 m/s²</td>
</tr>
<tr>
<td>Road inclination</td>
<td>0°</td>
</tr>
<tr>
<td>Nominal battery voltage</td>
<td>48 V</td>
</tr>
<tr>
<td>Battery specific energy</td>
<td>35 Wh/kg</td>
</tr>
<tr>
<td>Battery cost per Wh</td>
<td>Rs 5.50</td>
</tr>
</tbody>
</table>

Figure 4.3 Variation of aerodynamic force, rolling force, inertia force and tractive force as per IDC

The torque requirements at wheel with respect to time are shown in Figure 4.4. The maximum wheel torque demanded is about 33 N-m. Whereas the average wheel torque demand is around 9 N-m.
During the simulation, the power is arrived by feeding the velocity values from the IDC data sheet. For the developed model, the peak power demand at IDC is found to be 1406 W as shown in Figure 4.5. The negative values shown in the plot are regions of deceleration. However the average power demand (296 W) is much lower comparatively.
The energy demand using IDC cycle can be calculated by taking the time integral of the power request. The energy consumption per unit distance is generally used to evaluate the vehicle energy consumption. Figure 4.6 shows the energy demanded of the developed model is about 16.1 Wh for the travel distance of about 0.658 km in one cycle that last for 108 seconds.

![Figure 4.6 Energy demand for the developed model using IDC](image)

The simulation process was repeated for different all-electric ranges using sealed lead-acid battery as energy source. Initial battery energy capacity and its mass is assumed as zero and during the simulation process they vary according to corresponding AER in each iteration. Table 4.5 gives the typical estimated figures of these parameters.

**Table 4.5 Battery energy capacity and its mass for different AERs with IDC**

<table>
<thead>
<tr>
<th>Battery Parameter</th>
<th>AER 5</th>
<th>AER 10</th>
<th>AER 15</th>
<th>AER 20</th>
<th>AER 25</th>
<th>AER 30</th>
<th>AER 35</th>
<th>AER 40</th>
<th>AER 45</th>
<th>AER 50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Capacity (Wh)</td>
<td>153</td>
<td>306</td>
<td>460</td>
<td>613</td>
<td>766</td>
<td>920</td>
<td>1073</td>
<td>1226</td>
<td>1380</td>
<td>1533</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>3.7</td>
<td>7.5</td>
<td>11.3</td>
<td>15.1</td>
<td>18.8</td>
<td>22.6</td>
<td>26.4</td>
<td>30.2</td>
<td>33.9</td>
<td>37.7</td>
</tr>
</tbody>
</table>
4.4 STUDY AND ANALYSIS OF DRIVING RANGE

Driving range is an important factor affecting vehicles’ versatility. With wider driving range, automobiles are responsible for more than just commute, but also long distance road trip as customers’ wish. Conventional automobiles can basically satisfy the driving range requirements because the specific energy of the fossil fuel is relatively high and the fossil fuel is very easy to refuel with the available infrastructure. On the contrary, the driving range is one serious restrain upon plug-in hybrid electric vehicles because the battery’s energy density is lower than the petroleum and it takes longer time to charge the battery, let alone lack of infrastructures to charge the battery by the road like fuel filling stations. One of the most critical issues for plug-in hybrid electric vehicles is how far they can run on a single battery charge. These vehicles make some improvements in driving range with the driving range extender which is internal combustion engine. Still, charging the battery is an issue in PHEVs.

PHEVs are differentiated according to their all-electric range (AER) i.e. the distance driven electrically up to the point at which the internal combustion engine first turns on. It can also be defined as the distance travelled before the vehicle switches from charge-depleting (CD) to charge-sustaining (CS) or conventional engine operation. In the charge-depleting operation, the vehicle is powered only by the energy stored in the battery and the battery's state-of-charge (SOC) gradually decreases up to a minimum level. The vehicle thus mostly behaves as an electric vehicle, which particularly suits to urban driving.

This research work mainly focuses on sizing of the battery pack based on the energy requirements of plug-in hybrid electric two-wheeler suitable for daily travel needs and driving styles of two-wheeler riders in India. The AER designed for the plug-in hybrid electric two-wheeler should be able to satisfy the
daily average travel distance. As per Sharma et al (2004), the national average
daily travelled distance by two-wheelers in India is close to 24 km/day.
Figure 4.7 illustrates daily average travel distance for two-wheelers in major
Indian cities. However, rapid urbanisation and introduction of thousands of
vehicles per month in every city, the travel needs of automobiles vary
significantly. As a consequence, traffic congestion is increasing alarmingly and
hence average speeds on the city roads are greatly impaired.

![Daily average travel distance (km) for two-wheelers](image)

**Figure 4.7 Daily average travel distance for two-wheelers in Indian cities**

### 4.4.1 Survey in Coimbatore City

To observe the daily travel distance of two-wheelers, a study has
been conducted in Coimbatore city, which is one of the top 10 fastest growing
cities in India and is the second largest city in the south Indian state of Tamil
Nadu. For this study, the data has been collected from authorised two-wheeler
service stations like Hero Honda, Bajaj, TVS and Honda. The data involves
the number of kilometres travelled between two successive vehicle services
with date. Based on the study conducted on approximately 500 number of
two-wheelers, it was observed that the average travel distance travelled by
two-wheeler commuters in Coimbatore city is 25 km per day, which is very close to the national average daily travel distance estimated.

**Figure 4.8 Distribution of the daily travel distance**

Figures 4.8 and 4.9 shows the distribution and percentage of the distance during daily driving. It was also observed that about 61% of two-wheelers drive less than 25 kilometres per day. Only 7% of two-wheelers travel more than 50 km per day and about 32% of two-wheelers travel in between 25 to 50 km per day.

**Figure 4.9 Percentage of two-wheeler daily average travel**
4.5 SELECTION OF ELECTRIC MOTOR

The more recent EVs and HEVs employ AC and brushless motors, which include induction motor, permanent magnet motors and switched reluctance (SR) motors. The brushless DC (BLDC) and SR motors are more efficient than that of induction motors. The BLDC motors are more efficient at converting electricity into mechanical power than brushed DC motors. This improvement is largely due to the absence of electrical and friction losses due to brushes. Brushless DC motors can operate in a wide variety of environmental conditions while still providing the linear speed-torque characteristics found in brushed motors. However, for two wheelers, wheel hub motors are an interesting development which could offer benefits for the proposed plug-in hybrid electric two-wheeler. These motors have stators fixed at the axle, with the permanent magnet rotor embedded in the wheel. By directly driving the wheel, they eliminate the need for transmission system and its packaging. Also, the losses in the transmission are eliminated. Other advantages include higher efficiencies, less space, and often easier servicing. Hub motors run at relatively low speed – equal to the actual rotation of wheel since there is no final gearing stage. The benefit is about 10% increase in efficiency due to the lack of transmission.

The desired power rating of the wheel hub motor is calculated by using Equation (4.6) and based on the simulation of Indian driving cycle, instantaneous power required at varying speeds is shown in Figure 4.5. Table 4.6 gives the values of wheel torque and power for set of operating conditions (From 17th second to 22nd second) with IDC. For the developed vehicle model, the peak power demand is noted as 1406 W, however, this peak power demand is sustained only for few second during the cycle. For short periods of time, an electric motor can deliver two to three times the rated power (Rahman et al 2000, Iqbal 2003, Ehsani et al 2004 and Yimin and Mehrdad
2006). The power that an electric motor can continuously deliver without overheating is its rated power. Therefore, the selection of motor should be based on continuous power demand. Based on the simulation results, it is observed that, 800 W power is more or less continuously demanded by the vehicle. So, the selected hub motor should have power rating of 800 W, which can also support the higher powers for short period of time.

Table 4.6  Wheel torque and power for set of operating conditions with IDC

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Time (s)</th>
<th>Speed (km/h)</th>
<th>Acceleration (m/s²)</th>
<th>Tractive force (N)</th>
<th>Wheel torque (N-m)</th>
<th>Tractive power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>17</td>
<td>2.6</td>
<td>0.65</td>
<td>161</td>
<td>34</td>
<td>116</td>
</tr>
<tr>
<td>2.</td>
<td>18</td>
<td>4.8</td>
<td>0.65</td>
<td>161</td>
<td>34</td>
<td>215</td>
</tr>
<tr>
<td>3.</td>
<td>19</td>
<td>7.0</td>
<td>0.65</td>
<td>162</td>
<td>34</td>
<td>315</td>
</tr>
<tr>
<td>4.</td>
<td>20</td>
<td>9.5</td>
<td>0.65</td>
<td>162</td>
<td>34</td>
<td>428</td>
</tr>
<tr>
<td>5.</td>
<td>21</td>
<td>11.8</td>
<td>0.65</td>
<td>163</td>
<td>34</td>
<td>535</td>
</tr>
<tr>
<td>6.</td>
<td>22</td>
<td>14.0</td>
<td>0.65</td>
<td>164</td>
<td>34</td>
<td>638</td>
</tr>
</tbody>
</table>

Similarly, the torque demanded at wheel hub motor was calculated using Equation (4.7) and based on the simulation of Indian driving cycle, instantaneous torque required at varying speeds is shown in Figure 4.4. The motor delivers rated torque up to the base speed or rated speed of the motor when reaches its rated power condition. The motor rated speed is defined as the speed at which the motor can deliver rated torque at rated power. The motor operates in a constant power mode beyond the rated speed, where torque falls steadily at a rate that is inversely proportional to speed. The rated torque for electric motors is the torque that must be available for an indefinite length of time (Rahman et al 2000, Iqbal 2003, Ehsani et al 2004 and Yimin and Mehrdad 2006). Based on the simulation results, it is noted that the
maximum torque demand is about 33 N-m and as the speed increases, the torque demand decreases gradually. Hence, the rated torque of the wheel hub motor should be 33 N-m.

In the market, there are wheel hub motors for two-wheelers with different ratings. Based on the above observations and discussions, the wheel hub motor selected for plug-in hybrid electric two-wheeler is a 48 Volt BLDC type with rated power and rated torque of 800 W and 33 N-m respectively. The selected brushless DC wheel hub motor with chopper control unit and accelerator unit is shown in Figure 4.10.

![Permanent magnet BLDC wheel hub motor with chopper control unit and accelerator unit](image)

**Figure 4.10** Permanent magnet BLDC wheel hub motor with chopper control unit and accelerator unit

### 4.6 SELECTION OF BATTERY

Right now the biggest concern for plug-in hybrids is the selection of a battery. Typically, PHEVs provide greater amounts of on-board energy storage than HEVs by incorporating larger batteries. This larger battery size creates the possibility for displacing substantive amounts of fuel for the engine and electricity from the electrical power grid. For plug-in hybrid
electric vehicle designs, intended to have significant all-electric range, the energy storage unit must store sufficient energy to satisfy the driving range requirements. The electrical energy storage units must be sized so that they store sufficient energy and provide adequate power for the vehicle to have a specified acceleration performance and the capability to meet appropriate driving cycles (Wong et al 2006).

Batteries now available commercially of use in EVs and HEVs include: lead-acid, nickel-cadmium, nickel-metal hydride, sodium-metal chloride (Zebra) and lithium-ion. However, lead-acid batteries are well established commercially with good backup from industry. Lead-acid batteries have been most popular choice of batteries and can be designed to high power and are inexpensive, safe and reliable. They are cheapest rechargeable batteries per kilowatt-hour of charge.

To predict the all-electric range of the plug-in hybrid electric two-wheeler, the energy required to move the vehicle for each second of the driving cycle is calculated and the effect of this energy drain is calculated. The energy required can be obtained from the integration of the instantaneous power. The energy used per kilometre can be multiplied by the range and divided by the specific energy of the battery gives the approximate battery mass. The desired capacity of lead-acid battery was calculated using Equations (4.13) to (4.18) and based on the simulation of Indian driving cycle, energy demand or energy drain of battery after one IDC cycle is estimated (Figure 4.6). For the developed model, the battery energy capacity and its corresponding mass estimated is given in Table 4.4. The Ampere-hour of the battery pack can be calculated by dividing battery energy capacity with voltage.

Based on the simulation results, it is observed that, for the all-electric range of 25 km, the battery energy capacity required is 766 Wh.
By considering the same voltage (48 V) of the hub motor, the Ampere-hour of the battery pack is estimated as minimum of 16 Ah. By rounding-off the Ampere-hour to the nearest higher value and based on the availability of traction battery in the market, the choice is 12 V 20 Ah sealed lead-acid battery. The battery pack consists of four 12 V VRLA batteries with 20 Ah capacity. Hence, the total battery pack rating is 48 V and 20 Ah (Figure 4.11).

4.7 OTHER DRIVING CYCLES CONSIDERED FOR THE ANALYSIS

The Indian driving cycle (IDC) was formulated around late 1985 following extensive road tests by at Automotive Research Association of India (ARAI), which was representative of the driving patterns in the cities. However, the driving pattern of one city may not be same as the other city due to continuous change in the traffic pattern, such as synchronization of traffic signals, construction of flyovers, one way traffic and increase in density of vehicles. Hence, the available drive cycles obtained for certain cities or countries are not usually applicable for other cities. In this work, to study the
influence of driving cycle on battery characteristics, other than Indian driving cycle, an international driving cycle which is commonly used most of the countries for two-wheelers and a sample local driving cycle representing the actual city driving condition are considered for the analysis.

4.7.1 European Driving Cycle - ECE R40

The European driving cycle - ECE R40 (also known as urban driving cycle: UDC), cycle represents the city driving conditions in a typical European city. This is the most widely used test cycle for motorcycle/scooter. This cycle with slight modifications is used extensively in Europe and in many parts of Asia.

The ECE R40 consists of four segments with total travel distance of 4.052 km and each cycle about 195 seconds with average speed of 18.36 km/h and the maximum acceleration and deceleration are 1.48 m/s\(^2\) and 0.85 m/s\(^2\) respectively. Figure 4.12 shows the driving cycle with respect to time. The results of ECE R40 simulation are discussed in the section 7.3.

![Figure 4.12 ECE R40 driving cycle](image)
4.7.2 City Driving Cycle

The IDC is unsuitable for evaluating fuel consumption due to its gentle acceleration, braking and long periods spent in stationary mode. Nesamani and Subramanian (2006) 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.

Real-world driving cycles are the cycles derived from the movement of test vehicle on the road under real traffic conditions. There were number of studies relating driving characteristics using on-board measurement and remote sensing techniques. Conducting such studies would be expensive and difficult to collect large number of vehicle samples. Such drive cycles have not been developed for Coimbatore city yet, and at the moment, the IDC is used for simulation and test. The city driving cycle of Coimbatore city was captured through field study on designated routes during peak hours.

In this research work, a sample of city driving cycle was obtained by recording the speed of two-wheeler with respect to time. A test vehicle fitted with proximity sensor in the front wheel was driven along designated routes at approximately average speed of the respective stream of traffic flow. The driving cycle data were collected in the month of March. The speed of the vehicle in every five seconds, duration of each trip and distance travelled in it are recorded. On each road, the procedure was repeated for four times and the data was fed to excel sheets to get average trip pattern. The study was conducted during the week days and it was ensured that there were no special occasions such as major processions or any abnormal events during the field study. The test vehicle was driven at the respective speed of traffic and hence, actual traffic profile is captured. At the end of each trip, data were uploaded to
the computer for further analysis. Average speed was different across
different types of road, though the difference was not substantially high due to
high volume of traffic.

The city driving cycle approach used in this study was based on
building a series connection of a number of microtrips from the database
containing a number of real microtrips. Microtrip is an excursion between two
successive time points at which the vehicle is stopped. This part of motion
consists of acceleration, cruise and deceleration modes. Figure 4.13 shows the
examples of some collected speed-time profiles. The shape (sequence of
driving speed) of each microtrip clearly indicates the individual driving
characteristic.

![Microtrip 1](image1.png)
![Microtrip 2](image2.png)
![Microtrip 3](image3.png)
![Microtrip 4](image4.png)

*Figure 4.13 Typical microtrips obtained from the actual data*
The whole driving data was separated into microtrips to determine the predominant patterns occurred in the actual driving situations. These microtrips are then grouped and the driving parameters of each microtrip are calculated. The total duration of the driving pattern is considered based on the fact that it should be long enough to describe all traffic situations. Therefore, the total driving cycle duration in this study is set at 590 seconds. The idle duration 70 seconds is added at the end of each cycle. Hence, the total duration of city driving cycle is 660 seconds per cycle. The figure 4.14 shows an example of city driving cycle observed for Coimbatore city and it would be reflective of the driving patterns only during peak hours. The city driving cycle (CDC) has top speed of 50 km/h with average speed of 22.025 km/h. The results of CDC simulation are discussed in the section 7.4.

![Figure 4.14 Driving cycle obtained in Coimbatore city](image)

The simulation process was repeated for different all-electric ranges using driving cycles. Initial battery mass is assumed as zero and during the simulation process it varies according to corresponding AER and type of battery in each iteration. This process was repeated again for nickel-metal hydride (Ni-MH) and lithium ion (Li-ion) batteries.
4.8 CONCLUDING REMARKS

On the basis of simulation results and the survey conducted in Coimbatore city, some of the estimations are given below.

- Physical properties of a two-wheeler selected were used for the analytical vehicle model and MATLAB simulation.

- The dynamic equations of vehicle motion were used for the energy and power requirements estimation of the selected two-wheeler and driving cycle.

- The average travel distance estimated for the two-wheelers in Coimbatore city was found to be 25 km per day.

- Using the Indian driving cycle, the tractive force, power and torque requirements for the selected two-wheeler were estimated.

- The battery energy capacity and its mass were estimated for various all-electric ranges with the selected driving cycle.

- Other than Indian driving cycle, an international driving cycle and a sample local city driving cycle were also considered for simulation and analysis.

The formulation of a control strategy and the development of a control system suitable for Indian city driving conditions are discussed in detail in the next chapter. Modification of base two-wheeler into plug-in hybrid electric two-wheeler is also presented in this chapter.