CHAPTER 2
STUDY ON HYBRID ELECTRIC VEHICLES AND DERIVING DRIVING CYCLE

2.1 HYBRID ELECTRIC VEHICLE

Hybrid electric vehicle comprises the merging or combination of electric vehicle with conventional internal combustion engine vehicle. So there are two propulsion sources present in the vehicle, internal combustion engine and electric motor. It uses both these sources to provide the complete propulsion required for the vehicle. The connection arrangements with respect to power flow to wheels are based on these two sources depending on series or parallel connection. When the electric motor and ICE are connected in series, vehicle becomes series hybrid and the required mechanical power for the wheels is provided by the electric motor. When the electric motor and ICE are connected in parallel, the vehicle becomes parallel hybrid and the required mechanical power is provided by both ICE and electric motor for the wheels.

In HEV, ICE utilizes liquid fuel as energy source and electric motor utilizes battery as energy source. By utilizing the electric motor compatibly with ICE, by adjusting the torque and speed, fuel consumption in the engine can be minimized. It provides an option for greater driving range because of presence of two propulsion sources thereby overcoming the disadvantages of pure electric vehicle.

2.2 TYPES OF HYBRID ELECTRIC VEHICLES

2.2.1 SERIES HYBRID

The Figure 2.1 shows the configuration arrangement of series hybrid electric vehicle. Here the liquid source, fuel provides the required mechanical energy from internal combustion engine. The mechanical energy in turn gets converted into electrical energy through electric generator. This electrical energy drives the final drive wheels for the vehicle. In alternative, the electrical energy also charges the battery which drives the drive wheels for the vehicle.
Based on the components used in this configuration arrangement, the series hybrid vehicle can operate for drive in several combinations.

- **Battery alone mode**: When the battery is having sufficient charge, the vehicle is propelled by the motor only. The inverter / generator are in turned off state during this process.

- **Combined mode**: when more power is required, both the inverter / generator set are kept on and the battery also acts as power source for creating propulsion in electric motor.

- **Engine alone mode**: When driving in highways, moderately there is demand for high power. So Inverter / generator are turned on at that time. The battery will not be in the charging mode which is not efficient in switching off the engine.

- **Power split mode**: When the battery SOC is low, then the inverter / generator is turned on for charging the batteries at that instant.

- **Regenerative braking**: The electric motor used acts as generator in converting the vehicle’s kinetic energy into electrical energy for charging the batteries.
2.2.2 PARALLEL HYBRID

Figure 2.2 shows the parallel hybrid configuration arrangement. In this configuration ICE and electric motor both will contribute in delivering the power in parallel to the driving wheels. Belts, clutches, pulleys and gears are utilized in coupling the ICE and the electric motor to the driving wheels. Combination of the two sources ICE and electric motor can be utilized or stand alone mode can also be utilized in this type of parallel hybrid. The electric motor can be made to act as generator during the regenerative braking process.

Parallel hybrid vehicles can be operated in the following modes

- Motor alone mode: When the battery is at full SOC, then the engine can be turned off keeping the electric motor in on condition which is used for obtaining the propulsion of the vehicle.
- Combined power mode: Whenever more power is required, both the engine and the electric motor can be turned on, where both of them will be supplying the required power for the driving wheels.
- Engine alone mode: At cruising levels, when the battery is fully charged, engine is not made to turn off, keeping the motor in idle condition. Engine will be providing the required propulsion for the vehicle.
- Power split mode: In this mode the engine power will be used to charge the batteries.
- Stationary charging mode: In this mode, the battery is charged by running the motor as generator and driven by the engine, without actually driving the vehicle.
- Regenerative braking: The electric motor functions as generator in converting the vehicle kinetic energy into electrical energy and storing it in the battery. If the engine is in on condition then it supplies additional power for charging the batteries so that the charging process becomes really quick.

### 2.2.3 SERIES-PARALLEL HYBRID

Figure 2.3 shows the series-parallel hybrid. It incorporates both the features of series and parallel hybrid vehicles. Therefore it can be operated as both series and parallel hybrid electric vehicles. Here there is a mechanical coupling present between the engine and the driving wheels of the vehicle. As Compared to parallel hybrid, in series-parallel hybrid electric motors acts more as generator and less as motor.

![Series-Parallel Hybrid Configuration](image)

Figure 2.3: Series-Parallel Hybrid Configuration

As this type of hybrid acts as both series and parallel hybrid types, fuel efficiency can be optimized based on the operating conditions. But design and development of this type of hybrid is more complex and expensive compared to other hybrid types.
2.3 GENERAL CHALLENGES ENCOUNTERD IN DESIGNING HEV

Compared to EVs, HEVs can be preferred for fuel economy and reduced emissions. These vehicles also provide increased range per charge and reduced charging time. But there is complexity in its designs, packaging of the components, reducing electromagnetic interference, power management and vehicle control strategies. The key challenges in designing of HEVs involves

- Power electronics components and electric machine: Using of power electronic components efficiently is a big challenge. Weather conditions may be too low or too high in temperature, shock vibrations, transient behavior analysis, switching losses, design of converters, packaging the components and thermal management are some of the challenges in designing the power electronic equipments to be used in HEVs.
- Electromagnetic Interference: Switching at high frequencies and high power operation of electric motor and power electronic components gives rise to electromagnetic noise.
- Energy Storage system: Life cycle of the batteries and their performance in HEVs has to be majorly analyzed in designing. Presently Ni-hydride and lithium-ion batteries are majorly used in HEVs. These batteries are also very expensive to purchase or replace. The power density and potential safety issues also play major role in designing the HEV sources.
- Power management and vehicle control strategy: As HEV are operated with multiple propulsion process, good coordination (synchronization) is required between the propulsion source components. An optimized vehicle controller design may lead achieve efficient HEV.
- Thermal management: Cooling process is required for the batteries, electric motors, engine system to manage the temperature of the components utilized in HEV.
2.4 HEV FUNDAMENTALS

Hybrid electric vehicles (HEVs) are vehicles that involve both internal combustion engine (ICE) with an electrical traction system for deriving the propulsion of the vehicle. It usually consists of either two or more propulsion sources of energy storage devices or two or more power sources inside the vehicle. In HEVs, the ICE is mainly used for steady state operation while the electric machine powertrain is utilized or relied for dynamic operation. Some of the advantages offered by HEVs are as follows:

- Regenerative braking is an efficient technology not available in conventional vehicles.
- As ICE will be operating in less idling, it leads to more fuel economy.
- Easy drivability through electric traction powertrain.
- Reduced emissions.

2.5 RESEARCH METHODOLOGY ADOPTED IN DESIGNING OF HYBRID ELECTRIC VEHICLE TO MEET THE OBJECTIVES

The Hybrid electric vehicles are classified based on the configuration of the drivetrain arrangement. The classification includes series, hybrid, parallel hybrid and series-parallel hybrid. Whenever a hybrid electric vehicle is being designed, the rating of the propulsion engine, electric traction motor, generator, and energy storage elements based on the desired vehicle performance is needed. After the completion of the design it has to be verified that the vehicle performance specifications are efficient.

2.5.1 ROAD LOAD MODELING

In this section we will be modeling the road load. The vehicle and the associated forces are being modeled here.
Considering a vehicle of mass $M$, moving at a velocity $v$, up a slope of angle $\alpha$ (in degrees) as shown in the Figure 2.4. The propulsion force required for the vehicle to propel forward is known as tractive force $F_{te}$. This tractive force has to overcome the rolling resistance force $F_{rr}$, aerodynamic drag $F_{ad}$, the climbing resistance force $F_{rg}$ (the component of the vehicle’s weight or mass acting down the slope). Considering these parameters, the road load force $F_{rl}$ is given by expression 2.1.

$$F_{rl} = F_{rr} + F_{ad} + F_{rg}$$ \hspace{1cm}(2.1)

The frictional hysteresis produced by the tyre resistance with the road forms the rolling resistance, which depends upon coefficient of rolling friction between the tire and the road $C_f$, the normal force $F_n$ due to the vehicle’s weight $Mg$, where $g$ is the gravitational acceleration. The expression for the rolling resistance is given by expressions 2.2 to 2.4.

$$F_{rr} = -F_{te}, \hspace{0.5cm} \text{if } v = 0$$ \hspace{1cm}(2.2)

$$F_{te} = C_f M v g \cos \frac{\alpha \pi}{180}$$ \hspace{1cm}(2.3)

$$F_{rr} = -C_f M v g \cos \frac{\alpha \pi}{180}$$ \hspace{1cm}(2.4)

Where $\alpha$ is the road gradient angle. Air density decides the aerodynamic drag expressed as $\rho \text{ kg/m}^3$, coefficient of drag $C_d$, frontal area of the vehicle $A_f$ and the vehicle speed $v$. The equation for the aerodynamic drag will be given by expression 2.5.

$$F_{ad} = 0.5 \rho C_d A_f v^2 \ sgn \ (v)$$ \hspace{1cm}(2.5)

Where $\ sgn \ (v) =+1 \text{ if } v>0 \text{ or } sgn(v)=-1 \text{ if } v<0$
With respect to varying road angles, the load curves for the vehicle are shown in the Figure 2.5.

Figure 2.4: Descriptive Figure for road modeling

Figure 2.5: Load curve for the vehicle
From the graph (Figure 2.5) it can be observed that, with respect to parameters velocity and road angle, the load increases. Considering an example, list of the vehicle parameters are given in the table 2.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerodynamic Drag coefficient</td>
<td>0.3</td>
</tr>
<tr>
<td>Wind speed coefficient</td>
<td>0.2</td>
</tr>
<tr>
<td>Rolling resistance coefficient</td>
<td>0.015</td>
</tr>
<tr>
<td>Frontal area in sq. meter</td>
<td>2.18</td>
</tr>
<tr>
<td>Transmission efficiency</td>
<td>0.85</td>
</tr>
<tr>
<td>Electric motor efficiency</td>
<td>0.90</td>
</tr>
<tr>
<td>Generator efficiency</td>
<td>0.9</td>
</tr>
<tr>
<td>Total mass of the vehicle (Kg)</td>
<td>1543</td>
</tr>
<tr>
<td>Mass factor</td>
<td>0.9</td>
</tr>
<tr>
<td>Air density (Kg/m²)</td>
<td>0.9</td>
</tr>
<tr>
<td>Maximum speed (km/h)</td>
<td>50</td>
</tr>
<tr>
<td>Final acceleration speed (km/h)</td>
<td>50</td>
</tr>
<tr>
<td>Gravity</td>
<td>9.81</td>
</tr>
</tbody>
</table>

The acceleration force is the force required to accelerate the vehicle, governed by Newton’s second law. This force will provide the linear acceleration to the vehicle given by expression 2.6, Where \(a\) is the acceleration.

\[
F_{ac} = Ma
\]  
(2.6)

Thus the total tractive effort is the sum of all the above forces given by expression 2.7.

\[
F_{te} = F_{rr} + F_{ad} + F_{rg} + F_{ac}
\]

(2.7)

By integrating the vehicle’s acceleration with the starting value set to 0km/h at \(t=0\) seconds the velocity of the vehicle can be calculated given by expression 2.8.

\[
v = \frac{1}{M} \int_{t=0}^{t} F_{te} + F_{rr} + F_{ad} + F_{rg} \, dt
\]

(2.8)
In the internal combustion engine vehicles, the tractive force is obtained from the engine shaft torque. The engine torque and axle torque are related by expression 2.9.

\[ T_{\text{axle}} = (T_{\text{ICE}}) (GR_{\text{trans}}) (GR_{\text{diff}}) (\eta_{\text{trans}}) (\eta_{\text{diff}}) \]  

(2.9)

Where, GR represents gear ratio, \( \eta \) represents efficiency, subscripts Trans. and diff. represents transmission and differential relevancy respectively. So the tractive force is given by the expression 2.10.

\[ F_{te} = \frac{T_{\text{axle}}}{\text{tyre radius}} \]  

(2.10)

The traction motor shaft provides the required tractive force in case of series hybrid vehicles, whereas in parallel hybrid, the tractive force will be the combined effort of torque produced by ICE and electric traction motor. A suitable electric motor has to be selected for designing relevantly based on the configuration arrangement of the HEV.

### 2.5.2 VEHICLE PERFORMANCE

Any type of vehicle, the performance constraints to be satisfied must be defined first. These constraints are different depending on the vehicle type and architecture. From the powertrain part of view, typical performance specification included initial acceleration, cruise speed, maximum gear speed, gradabality, drive range and many more.

Drive cycles are developed or created and referred for analyzing the designed vehicle performance, fuel economy and emissions. For example two different cycles for reference, Federal Highway Driving Schedule (FHDS) and Federal Urban Driving Schedule (FUDS) are shown in the Figure 2.6.
Figure 2.6: Examples of FHDS and FUDS driving cycle

The required power for operating a vehicle can be calculated from the driving cycles, depending on the mass of the vehicle. For example, the required power for driving a vehicle with a total weight of 1380 Kg under US06 driving cycle is shown in Figure 2.7. US06 is an aggressive driving cycle, proposed by the US Environmental Protection Agency (EPA) to measure fuel economy and emissions. The positive power represents the acceleration during driving while the negative power represents the deceleration during driving. Part of the negative power relevant to braking can be recovered or utilized through regeneration in the HEV.
Figure 2.7: Examples of Speed-time curve for US-06 Cycle with Power Curve

Initial method after the design of the hybrid electric vehicle will be the determination of the driving cycle, its analysis for fuel economy and emissions. Presently, the drive cycles mostly come from Europe, North America, and Japan. China is also developing its own drive cycles based on its own road systems. The first step in developing a driving cycle is to measure and record real driving behaviors that is real time driving behavior corresponding to the vehicle being designed. The obtained data has to be analyzed in forming a representative cycle from real driving
conditions. The obtained data is classified in different sections based on traffic conditions.

The measurement of speed is divided into two groups

1. Using the equipment provided in the vehicle like speedometer which will be present in all types of vehicles in the universe according to regional motor regulations.
2. Usage of some additional equipment like Global Positioning System (GPS).

In any area, the driving conditions will vary accordingly to traffic density, road arrangements and other factor. Average speed and percentage of idle time are used as parameters for classifying the traffic conditions on a specific trip. The four traffic conditions based on the above criteria are as follows

1. With an average speed of 8kmph to 10kmph provided with low to high idling time in the trip derives the congested urban driving conditions.
2. Urban conditions: With an average speed of 10kmph to 25kmph provided with moderate to low idle time derives the urban driving conditions.
3. With an average speed of 40kmph provided with low idling time derives Extra Urban Driving conditions.
4. With an average speed more than 40kmph provided with low idling time derives Highway Driving conditions.

As an example, considering any vehicle available in the market, which is driven in stock condition through the test ring road route of Bangalore city, India covering a distance of 3Km. The propulsion is only carried through ICE running on petrol fuel. The route chosen in the test area is as shown in the Figure 2.8.

The speed-time data are recorded by making the vehicle to travel in the selected route from starting point to ending point marked on the map.
The recorded data is analyzed as quadrilateral curve shown in the Figure 2.9 and related parameters which are defined from that are shown in table 2.2.
Table 2.2: Nominal Parameters defined from the speed-time curve analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum speed attained at the end of acceleration period</td>
<td>40Km/h</td>
</tr>
<tr>
<td>Total time of run</td>
<td>450 seconds</td>
</tr>
<tr>
<td>Total distance</td>
<td>3Km</td>
</tr>
<tr>
<td>Average speed</td>
<td>30Km/h</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>50Km/h</td>
</tr>
</tbody>
</table>

The Speed-curve has to be plotted for the test area chosen for research, that is Mysore city, India, and the designed configuration of hybrid electric vehicle has to be analyzed for the speed-time curve, power-speed curve (Engine and ICE), ICE alone mode tractive effort, Engine alone mode tractive effort, Hybrid mode tractive effort, relevantly to design. The fuel consumption of the designed vehicle comparative to conventional has to be analyzed in the drive.

From the obtained average speed from the test area, it can be concluded that, the selected test area comes under the category of Extra Urban traffic conditions [52, p. 138].