



ANNAMACHARYA UNIVERSITY

(ESTD UNDER AP PRIVATE UNIVERSITIES (ESTABLISHMENT AND REGULATION) ACT, 2016)

New Boyanapalli, Rajampet,
Annamayya (Dist), Andhra Pradesh – 516 126



DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

Course: Hybrid Electric Vehicles

Course Code: 20A27FT

Branch: EEE

Prepared by: BAYA REDDY LOMADA

Designation: Assistant Professor

Department: EEE

ANNAMACHARYA INSTITUTE OF TECHNOLOGY AND SCIENCES RAJAMPET
(An Autonomous Institution)
Department of Electrical and Electronics Engineering

Title of the Course Hybrid Electric Vehicles
Category PEC
Course Code 20A27FT

Year IV
Semester I
Branch EEE

Lecture Hours	Tutorial Hours	Practice Hours	Credits
3	-	-	3

Course Objectives:

- To explain the basics of electric and hybrid electric vehicles, their architecture, technologies and fundamentals.
- To analyze various electric drives suitable for hybrid electric vehicles.
- To list the energy storage technologies used for hybrid electric vehicles and their control.

Unit 1 Introduction to Electric Vehicles 10

Introduction – History of hybrid and electric vehicle -Components of EV System – EV Advantages – Vehicle Mechanics – Performance of EVs – Electric Vehicle drive train– EV Transmission Configurations and components- Tractive Effort in Normal Driving – Energy Consumption – Types of Electric Vehicle in Use Today – Electric Vehicles for the Future.

Learning Outcomes: At the end of the unit, the student will be able to:

- Analyze the operation of Electric vehicles (L4)
- Discuss hybrid vehicle configuration and its components (L2)

Unit 2 Electric Vehicle Modelling 10

Consideration of Rolling Resistance – Transmission Efficiency – Consideration of Vehicle Mass – Tractive Effort – Modelling Vehicle Acceleration – Modelling Electric Vehicle Range -Aerodynamic Considerations – Ideal Gearbox Steady State Model – EV Motor Sizing – General Issues in Design

Learning Outcomes: At the end of the unit, the student will be able to:

- Explain the electrical vehicles modeling(L2)
- Apply the concepts of tractive power to solve numerical problems. (L3)

Unit 3 Energy sources 10

Electric vehicle power source - battery capacity, state of charge and discharge, specific energy, specific power, Ragone plot. Battery modeling - run time battery model, first principle model, battery management system- soc measurement, battery cell balancing. Traction batteries - nickel metal hydride battery, Li-Ion, Li-polymer battery.

Learning Outcomes: At the end of the unit, the student will be able to:

- Identify power sources for electric vehicles (L1)
- Classify the batteries for electric vehicles. (L1)

Unit 4 Hybrid Electric Vehicles 10

HEV Fundamentals -Architectures of HEVs- Interdisciplinary Nature of HEVs – State of the Art of HEVs – Advantages and Disadvantages – Challenges and Key Technology of HEVs – Concept of Hybridization of the Automobile-Plug-in Hybrid Electric Vehicles – Design and Control Principles of Plug-In Hybrid Electric Vehicles .

Learning Outcomes: At the end of the unit, the student will be able to:

- Analyze the plug-in hybrid electric vehicle design and control(L4)
- Identify the challenges of hybrid electric vehicles (L1)

Unit 5 Electric and hybrid vehicle – Case studies 10

Parallel hybrid, series hybrid -charge sustaining, charge depleting. Hybrid vehicle case study –Toyota Prius,

Honda Insight, Chevrolet Volt. 42 V system for traction applications. Lightly hybridized vehicles and low voltage systems. Electric vehicle case study - GM EV1, Nissan Leaf, Mitsubishi Miev. Hybrid electric heavy-duty vehicles, fuel cell heavy duty vehicles.

Learning Outcomes: At the end of the unit, the student will be able to:

- List the various electric and hybrid vehicles(L1)
- Discuss lightly hybridized vehicles (L2)
- Distinguish hybrid electric heavy-duty vehicles and fuel cell heavy duty vehicles. (L2)

Prescribed Text Books:

1. Modern Electric, Hybrid Electric and Fuel Cell Vehicles – Fundamentals, Theory and Design – Mehrdad Ehsani, Uimin Gao and Ali Emadi – Second Edition – CRC Press, 2010
2. Iqbal Hussein, “Electric and Hybrid Vehicles: Design Fundamentals”, 2nd edition, CRC Press, 2003.
3. Electric Vehicle Technology Explained – James Larminie, John Lowry – John Wiley & Sons Ltd, – 2003.
4. Electric & Hybrid Vehicles – Design Fundamentals – Iqbal Hussain, Second Edition, CRC Press, 2011.

Reference Books:

1. Hybrid electric Vehicles Principles and applications With practical perspectives -Chris Mi, Dearborn – M. Abul Masrur, David Wenzhong Gao – A John Wiley & Sons, Ltd., – 2011
2. Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles – Murat Yilmaz, and Philip T. Krein, – IEEE transactions on power electronics, vol. 28, no. 5, May 2013
3. James Larminie, John Lowry, “Electric Vehicle Technology”, Explained, Wiley, 2003.

Web Resources:

1. <https://nptel.ac.in/courses/108/106/108106170/>
2. <https://nptel.ac.in/courses/108/102/108102121/>
3. <https://nptel.ac.in/courses/108/103/108103009/>
4. <https://nptel.ac.in/courses/108/106/108106182/>

Course Outcomes:

At the end of the course, the student will be able to

Blooms Level of Learning

- | | |
|---|----|
| 1. Explain the operation of hybrid electric vehicles | L2 |
| 2. Identify suitable drive for developing hybrid and electric vehicles depending on resources | L3 |
| 3. List the energy storage technologies used for hybrid electric vehicles. | L2 |
| 4. Describe Plug-in hybrid electrical vehicles | L3 |
| 5. Discuss various hybrid electrical vehicles for usage | L1 |

CO-PO Mapping:

CO	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PS01	PS02
20A27FT.1	-	2	-	3	-	-	2	-	-	-	-	-	2	-
20A27FT.2	3	-	-	2	-	3	-	-	-	-	-	-	2	-
20A27FT.3	3	2	2	-	-	-	-	-	-	-	-	-	-	-
20A27FT.4	-	3	-	2	-	-	-	-	-	-	-	-	-	-
20A27FT.5	3	-	-	3	-	-	2	-	-	-	2	-	-	-

Hybrid Electric Vehicles (20A27FT)

UNIT 1: INTRODUCTION TO ELECTRIC VEHICLES

Introduction – History of Hybrid and Electric Vehicle - Components of EV System – EV Advantages – Vehicle Mechanics – Performance of EVs – Electric Vehicle drivetrain – EV Transmission Configurations and components- Tractive Effort in Normal Driving – Energy Consumption – Types of Electric Vehicle in Use Today – Electric Vehicles for the Future.

1. INTRODUCTION:

What is a hybrid? A hybrid vehicle combines any two power (energy) sources. Possible combinations include diesel/electric, gasoline/fly wheel, and fuel cell (FC)/battery. Typically, one energy source is storage, and the other is conversion of a fuel to energy. The combination of two power sources may support two separate propulsion systems. Thus to be a True hybrid, the vehicle must have at least two modes of propulsion.

For example, a truck that uses a diesel to drive a generator, which in turn drives several electrical motors for all-wheel drive, is *not a hybrid*. But if the truck has electrical energy storage to provide a second mode, which is electrical assists, then it is a hybrid Vehicle.

These two power sources may be paired in series, meaning that the gas engine charges the batteries of an electric motor that powers the car, or in parallel, with both mechanisms driving the car directly.

Hybrid electric vehicle (HEV)

Consistent with the definition of hybrid above, the hybrid electric vehicle combines a gasoline engine with an electric motor. An alternate arrangement is a diesel engine and an electric motor (figure 1).

As shown in **Figure 1**, a HEV is formed by merging components from a pure electrical vehicle and a pure gasoline vehicle. The Electric Vehicle (EV) has an M/G which allows regenerative braking for an EV; the M/G installed in the HEV enables regenerative braking. For the HEV, the M/G is tucked directly behind the engine. In

Honda hybrids, the M/G is connected directly to the engine. The transmission appears next in line. This arrangement has two torque producers; the M/G in motor mode, M-mode, and the gasoline engine. The battery and M/G are connected electrically.

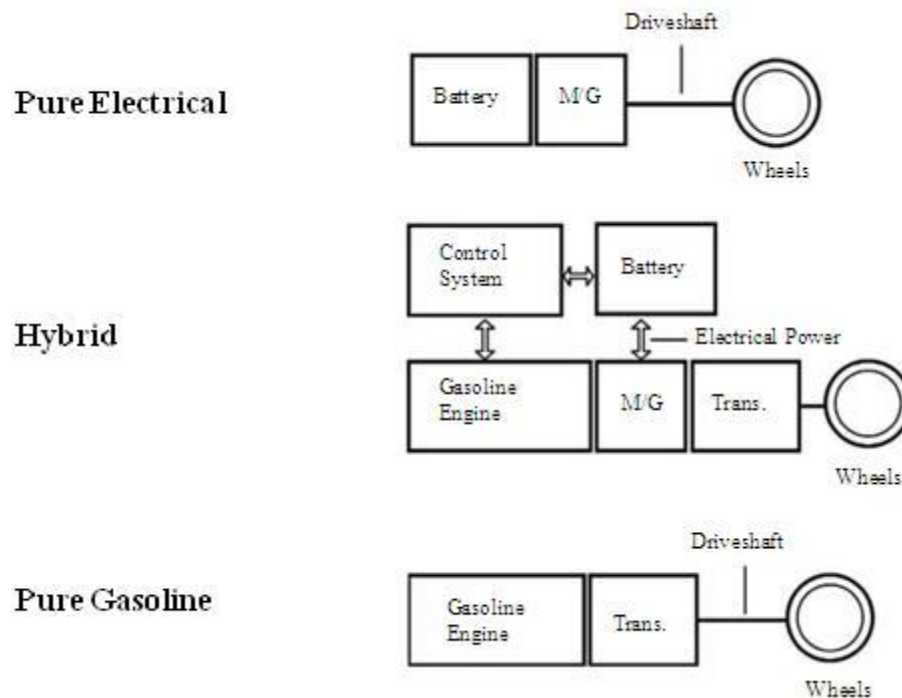


Figure 1: Components of a hybrid Vehicle that combines a pure gasoline with a pure EV.

HEVs are a combination of electrical and mechanical components. Three main sources of electricity for hybrids are batteries, FCs, and capacitors. Each device has a low cell voltage, and, hence, requires many cells in series to obtain the voltage demanded by an HEV. Difference in the source of Energy can be explained as:

- The FC provides high energy but low power.
- The battery supplies both modest power and energy.
- The capacitor supplies very large power but low energy.

The components of an electrochemical cell include anode, cathode, and electrolyte (shown in fig2). The current flow both internal and external to the cell is used to describe the current loop.

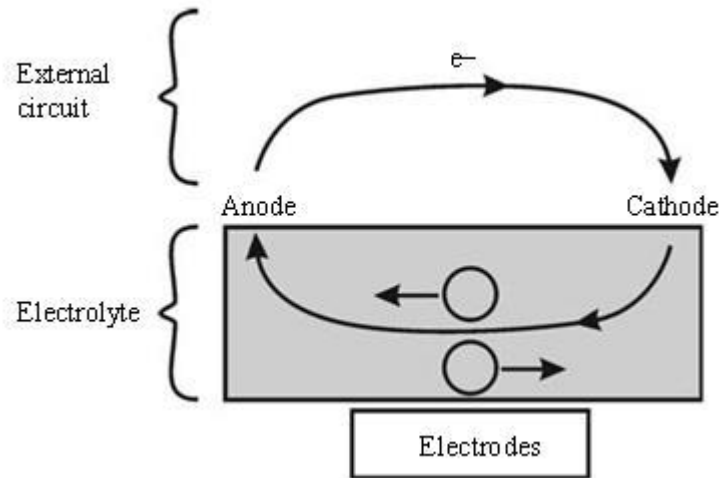


Figure 2: An electrode, a circuit for a cell which is converting chemical energy to electrical energy. The motion of negative charges is clockwise and forms a closed loop through external wires and load and the electrolyte in the cell.

A critical issue for both battery life and safety is the precision control of the Charge/Discharge cycle. Overcharging can be traced as a cause of fire and failure. Applications impose two boundaries or limitations on batteries. The first limit, which is dictated by battery life, is the minimum allowed State of Charge. As a result, not all the installed battery energy can be used. The battery feeds energy to other electrical equipment, which is usually the inverter. This equipment can use a broad range of input voltage, but cannot accept a low voltage. The second limit is the minimum voltage allowed from the battery.

2. HISTORICAL DEVELOPMENT (ROOT) OF AUTOMOBILES:

In 1900, steam technology was advanced. The advantages of **steam-powered cars** included high performance in terms of power and speed. However, the disadvantages of steam-powered cars included poor fuel economy and the need to “fire up the boiler” before driving. Feed water was a necessary input for steam engine, therefore could not tolerate the loss of fresh water. Later, Steam condensers were applied to the steam car to solve the feed water problem. However, by that time Gasoline cars had won the marketing battle.

Gasoline cars of 1900 were noisy, dirty, smelly, cantankerous, and unreliable. In comparison, electric cars were comfortable, quiet, clean, and fashionable. Ease of control was also a desirable feature. Lead acid batteries were used in 1900 and are still used in modern cars. Hence lead acid batteries have a long history (since 1881) of use as a viable energy storage device. Golden age of **Electrical vehicle** marked

from 1890 to 1924 with peak production of electric vehicles in 1912. However, the range was limited by energy storage in the battery. After every trip, the battery required recharging. At the 1924 automobile show, no electric cars were on display. This announced the end of the Golden Age of electric-powered cars.

The range of a **gasoline car** was far superior to that of either a steam or an electric car and dominated the automobile market from 1924 to 1960. The gasoline car had one dominant feature; it used gasoline as a fuel. The modern period starts with the oil embargoes and the gasoline shortages during the 1970s which created long lines at gas stations. Engineers recognized that the good features of the gasoline engine could be combined with those of the electric motor to produce a superior car. A marriage of the two yields the hybrid automobile.

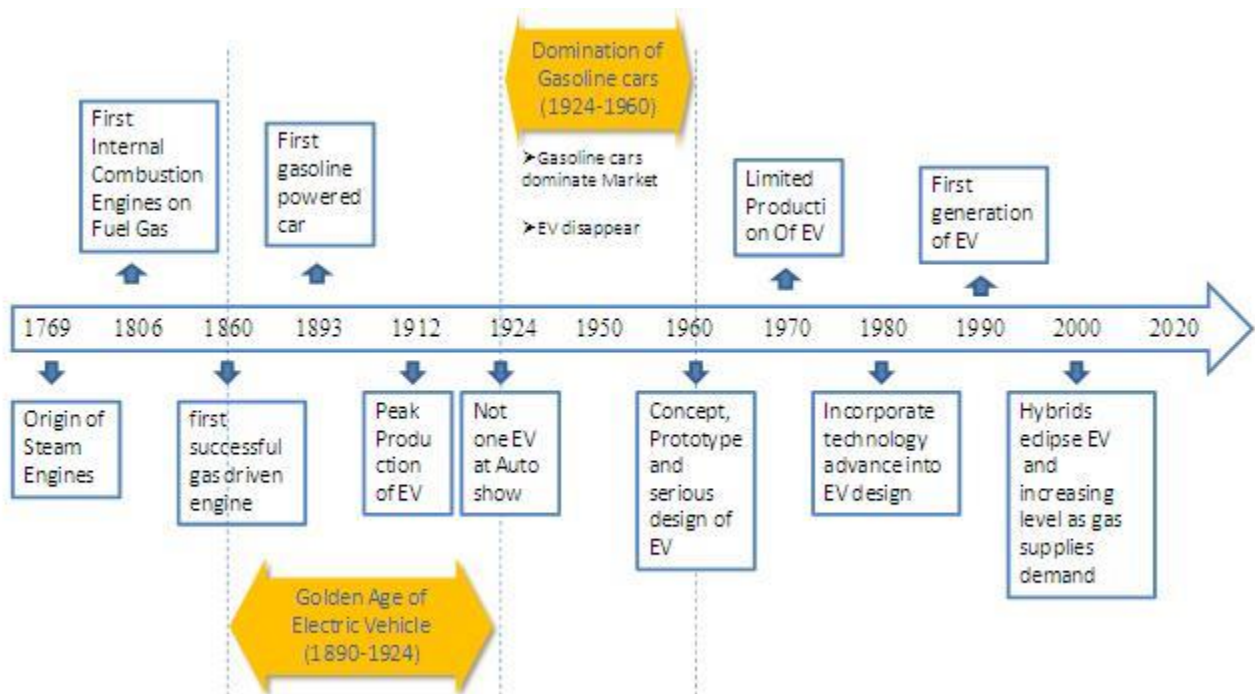


Figure 3: Historical development of automobile and development of interest and activity in the EV from 1890 to present day. Electric Vehicle merged into hybrid electric vehicle.

1769 - The **first steam-powered vehicle** was designed by Nicolas-Joseph Cugnot and constructed by M. Brezin that could attain speeds of up to 6 km/hour. These early steam-powered vehicles were so heavy that they were only practical on a perfectly flat surface as strong as iron.

1807 - The next step towards the development of the car was the invention of the internal combustion engine. Francois Isaac de Rivaz designed the ***first internal combustion engine*** in, using a mixture of hydrogen and oxygen to generate energy.

1825 - British inventor Goldsworthy Gurney built a steam car that successfully completed an 85 mile round-trip journey in ten hours time.

1839 - Robert Anderson of Aberdeen, Scotland built the ***first electric vehicle*** .

1860 - In, Jean Joseph Etienne Lenoir, a Frenchman, built the ***first successful two-stroke gas driven engine*** .

1886 - Historical records indicate that ***an electric-powered taxicab*** , using a battery with 28 cells and a small electric motor, was introduced in England.

1888 - Immisch & Company built a four-passenger carriage, powered by a one-horsepower motor and 24-cell battery, for the Sultan of the Ottoman Empire. In the same year, Magnus Volk in Brighton, England made a three-wheeled electric car. ***1890 – 1910 (Period of significant improvements in battery technology)***

Invention of Hybrid Vehicle:

1890 - Jacob Lohner, a coach builder in Vienna, Austria, foresaw the need for an electric vehicle that would be less noisy than the new gas-powered cars. He commissioned a design for an electric vehicle from Austro-Hungarian engineer Ferdinand Porsche, who had recently graduated from the Vienna Technical College. Porsche's first version of the electric car used a pair of electric motors mounted in the front wheel hubs of a conventional car. The car could travel up to 38 miles. To extend the vehicle's range, Porsche added a gasoline engine that could recharge the batteries, thus giving birth to the first hybrid, the ***Lohner-Porsche Elektromobil*** .

Early Hybrid Vehicles

1900 - Porsche showed his hybrid car at the Paris Exposition of 1900. A gasoline engine was used to power a generator which, in turn, drove a small series of motors. The electric engine was used to give the car a little bit of extra power. This method of ***series hybrid engine*** is still in use today, although obviously with further scope of performance improvement and greater fuel savings.

1915 - Woods Motor Vehicle manufacturers created the Dual Power hybrid vehicle, second hybrid car in market. Rather than combining the two power sources to give

a single output of power, the Dual Power used an electric battery motor to power the engine at low speeds (below 25km/h) and used the gasoline engine to carry the vehicle from these low speeds up to its 55km/h maximum speed. While Porsche had invented the series hybrid, Woods invented the parallel hybrid.

1918 - The Woods Dual Power was the *first hybrid to go into mass production*. In all, some 600 models were built by. However, the evolution of the internal combustion engine left electric power a marginal technology

1960 - Victor Wouk worked in helping create numerous hybrid designs earned him the nickname of the “Godfather of the Hybrid”. In 1976 he even converted a Buick Skylark from gasoline to hybrid.

1978 - Modern hybrid cars rely on the regenerative braking system. When a standard combustion engine car brakes, a lot of power is lost because it dissipates into the atmosphere as heat. Regenerative braking means that the electric motor is used for slowing the car and it essentially collects this power and uses it to help recharge the electric batteries within the car. This development alone is believed to have progressed hybrid vehicle manufacture significantly. The Regenerative Braking System, was first designed and developed in 1978 by David Arthurs. Using standard car components he converted an Opel GT to offer 75 miles to the gallon and many home conversions are done using the plans for this system that are still widely available on the Internet.

Modern Period of Hybrid History:

The history of hybrid cars is much longer and more involved than many first imagine. It is, however, in the last ten years or so that we, as consumers, have begun to pay more attention to the hybrid vehicle as a viable alternative to ICE driven cars. Whether looking for a way to save money on spiraling gas costs or in an attempt to help reduce the negative effects on the environment we are buying hybrid cars much more frequently.

1990s - Automakers took a renewed interest in the hybrid, seeking a solution to dwindling energy supplies and environmental concerns and created modern history of hybrid car

1993 - In USA, Bill Clinton's administration recognized the urgency for the mass production of cars powered by means other than gasoline. Numerous government agencies, as well as Chrysler, Ford, GM, and USCAR combined forces in the PNGV (Partnership for a New Generation of Vehicles), to create cars using alternative

power sources, including the development and improvement of hybrid electric vehicles.

1997 - The Audi Duo was the first European hybrid car put into mass production and hybrid production and consumer take up has continued to go from strength to strength over the decades.

2000 - Toyota Prius and Honda Insight became the first mass market hybrids to go on sale in the United States, with dozens of models following in the next decade. The Honda Insight and Toyota Prius were two of the first mainstream Hybrid Electric Vehicles and both models remain a popular line.

2005 - A hybrid Ford Escape, the SUV, was released in 2005. Toyota and Ford essentially swapped patents with one another, Ford gaining a number of Toyota patents relating to hybrid technology and Toyota, in return, gaining access to Diesel engine patents from Ford.

Present of Hybrid Electric Vehicle:

Toyota is the most prominent of all manufacturers when it comes to hybrid cars. As well as the specialist hybrid range they have produced hybrid versions of many of their existing model lines, including several Lexus (now owned and manufactured by Toyota) vehicles. They have also stated that it is their intention to release a hybrid version of every single model they release in the coming decade. As well as cars and SUVs, there are a select number of hybrid motorcycles, pickups, vans, and other road going vehicles available to the consumer and the list is continually increasing.

Future of Hybrid Electrical Vehicle:

Since petroleum is limited and will someday run out of supply. In the arbitrary year 2037, an estimated one billion petroleum-fueled vehicles will be on the world's roads. gasoline will become prohibitively expensive. The world need to have solutions for the “***400 million otherwise useless cars***”. So year 2037 “gasoline runs out year” means, petroleum will no longer be used for personal mobility. A market may develop for solar-powered EVs of the size of a scooter or golf cart. Since hybrid technology applies to heavy vehicles, hybrid buses and hybrid trains will be more significant.

3. EV SYSTEM:

An EV has the following two features:

1. The energy source is portable and chemical or electromechanical in nature.
2. Traction effort is supplied only by an electric motor.

Figure 2, shows an EV system driven by a portable energy source. The electromechanical energy conversion linkage system between the vehicle energy source and the wheels is the drivetrain of the vehicle. The drivetrain has electrical as well as mechanical components.

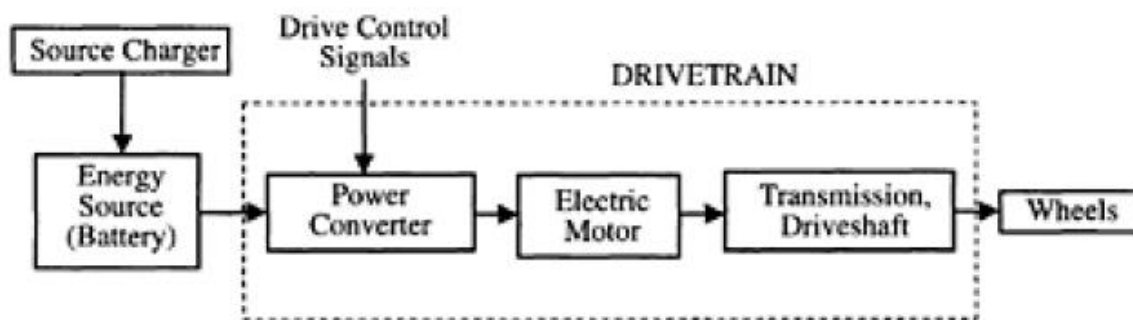


Figure 2: Top-level perspective of an EV system

3.1 COMPONENTS OF AN EV:

The primary components of an EV system are the motor, controller, power source, and transmission. The detailed structure of an EV system and the interaction among its various components are shown in Figure 2.1 also shows the choices available for each of the subsystem level components. Electrochemical batteries have been the traditional source of energy in EVs. Lead-acid batteries have been the primary choice, because of their well-developed technology and lower cost, although promising new battery technologies are being tested in many prototype vehicles. The batteries need a charger to restore the stored energy level once its available energy is near depletion due to usage. Alternative energy sources are also being developed for zero-emission vehicles. The limited range problem of battery-driven EVs prompted the search for alternative energy sources, such as fuel cells and flywheels. Prototypes have been developed with fuel cells, while production vehicles will emerge in the near future.

The majority of electric vehicles developed so far are based on DC machines, induction machines, or permanent magnet machines. The disadvantages of DC machines pushed EV developers to look into various types of AC machines. The maintenance-free, low-cost induction machines became an attractive alternative to many developers. However, high-speed operation of induction machines is only possible with a penalty in size and weight. Excellent performance together with high-power density features of permanent magnet machines make them an attractive solution for EV applications, although the cost of permanent magnets can become prohibitive. High-power density and a potentially low production cost of switched reluctance machines make them ideally suited for EV applications. However, the acoustic noise problem has so far been a deterrent for the use of switched reluctance machines in EVs. The electric motor design includes not only electromagnetic aspects of the machine but also thermal and mechanical considerations. The motor design tasks of today are supported by finite element studies and various computer-aided design tools, making the design process highly efficient.

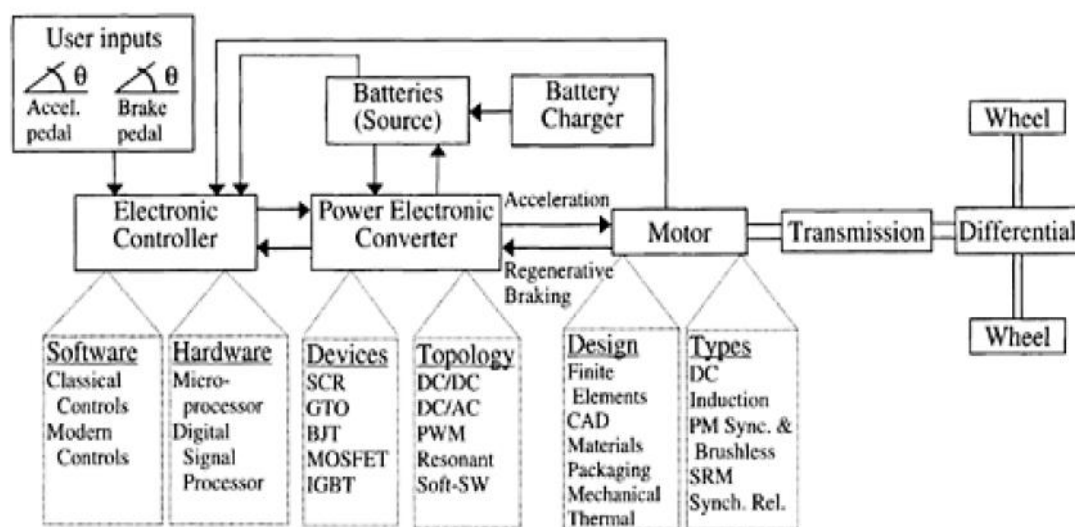


Figure 2.1: Major electrical components and choices for an EV system.

The electric motor is driven by a power-electronics-based power-processing unit that converts the fixed DC voltage available from the source into a variable voltage, variable frequency source controlled to maintain the desired operating point of the vehicle. The enabling technology of power electronics is a key driving force in developing efficient and high-performance power-train units for EVs. High-power devices in compact packaging are available today, enabling the development of lightweight and efficient power-processing units known as **power electronic motor**

drives. Advances in power solid state devices and **very large-scale integration (VLSI) technology** are responsible for the development of efficient and compact power electronics circuits.

4. EV ADVANTAGES:

- **Environment-friendly:** Electric vehicles do not use fuels for combustion and hence there is no emission or exhaust of gasses. Vehicles using fossil fuels are large contributors to harmful gas buildup in the environment so the use of an electric car can help contribute to a cleaner atmosphere.
- **Renewable energy source:** Electric vehicles run on electricity that is renewable whereas conventional cars work on the burning of fossil fuels that exhaust the fossil-fuel reserves on earth.
- **Cost-effective:** Electricity is much cheaper than fuels like petrol and diesel which suffer a frequent price hike. The recharging of batteries is cost-effective if solar power is used at home.
- **Low maintenance:** Electric vehicles have fewer moving parts so wear and tear is less as compared to conventional auto parts. Repair work is also simple and less expensive relative to combustion engines.
- **Less noise and smoother motion:** Electric vehicles give a much smoother driving experience. The absence of rapidly moving parts makes them much quiet with low sound generation.
- **Government support:** Governments in various countries have offered tax credits as an incentive to encourage people to use electric vehicles as a go-green initiative.

DISADVANTAGES OF ELECTRIC VEHICLE:

- **High initial cost:** Electric vehicles are still very expensive and many consumers consider them not as affordable as conventional vehicles.
- **Charging station limitations:** People who need to drive long distances are worried about getting suitable charging stations midway which is not available everywhere.
- **Recharging takes time:** Unlike conventional cars that require a few minutes for refilling fuel, recharging of the electric vehicle takes much more time which is generally a few hours.
- **Limited choices:** Presently there aren't too many electric models of cars available to choose from when it comes to the looks, designs, or customized versions.
- **Less driving range:** The driving range of the electric vehicles is found to be less as compared to conventional vehicles. Electric vehicles can be suitable for day-to-day travel but can be problematic for a long-distance journey.

5. VEHICLE MECHANICS:

The fundamentals of vehicle design are embedded in the basic mechanics of physics, particularly in Newton's second law of motion relating force and acceleration. Newton's second law states that the acceleration of an object is proportional to the net force exerted on it. The object accelerates when the net force is nonzero, where the term "net force" refers to the result of the forces acting on the object. In the vehicle system, several forces act on it, with the resultant or net force dictating the motion according to Newton's second law. A vehicle moves forward with the aid of the force delivered by the propulsion unit overcoming the resisting forces due to gravity, air, and tire resistance. The acceleration and speed of the vehicle depend on the torque and power available from the traction unit and the

existing road and aerodynamic conditions. Acceleration also depends on the composite mass of the vehicle, including the propulsion unit, all mechanical and electrical components, and the batteries.

A vehicle is designed based on certain given specifications and requirements. Furthermore, the electric and hybrid vehicle system is large and complex, involving multidisciplinary knowledge. The key to designing such a large system is to divide and conquer. The system-level perspective helps in mastering the design skills for a complex system, where the broad requirements are first determined and then system components are designed with more focused guidelines. For example, first, the power and energy requirements from the propulsion unit are determined from a given set of vehicle cruising and acceleration specifications. The component-level design begins in the second stage, where the propulsion unit, the energy source, and other auxiliary units are specified and designed. In this stage, the electrical and mechanical engineers start designing the electric motor for electric vehicles (EVs) or the combination of electric motor and internal combustion (IC) engine for hybrid electric vehicles (HEVs). The power electronics engineers design the power conversion unit that links the energy source with the electric motor. The controls engineer works in conjunction with the power electronics engineer to develop the propulsion control system. The chemists and the chemical engineers have the primary responsibility of designing the energy source based on the energy requirement and guidelines of the vehicle manufacturer. Many of the component designs proceed in an iterative manner, where various designers interact to ensure that the design goals are met.

We will develop the tools for scientific analysis of vehicle mechanics based on Newton's second law of motion. After defining and describing a roadway, the vehicle kinetics issues will be addressed. The roadway and kinetics will be linked to establish the equation for the force required from the propulsion unit. The force from the propulsion unit, which can be an electric motor or an IC engine or a combination of the two, is known as **TRACTIVE FORCE**, F_{TR} .

6. PERFORMANCE OF EV'S:

A vehicle's driving performance is usually evaluated by its acceleration time, maximum speed, and gradeability. In EV drive train design, proper motor power rating and transmission parameters are the primary considerations to meet the performance specification. The design of all these parameters depends mostly on the speed–power (torque) characteristics of the traction motor.

1. Traction Motor Characteristics:

Variable-speed electric motor drives usually have the characteristics shown in Figure 3. At the low-speed region (less than the base speed as marked in Figure 3), the motor has a constant torque. In the high-speed region (higher than the base speed), the motor has a constant power. This characteristic is usually represented by a speed ratio x , defined as the ratio of its maximum speed to its base speed. In low-speed operations, voltage supply to the motor increases with the increase of the speed through the electronic converter while the flux is kept constant. At the point of base speed, the voltage of the motor reaches the source voltage. After the base speed, the motor voltage is kept constant and the flux is weakened, dropping hyperbolically with increasing speed. Hence, its torque also drops hyperbolically with increasing speed. Figure 4 shows the torque–speed profiles of a 60 kW motor with different speed ratios x ($x=2, 4$, and 6). It is clear that with a long constant power region, the maximum torque of the motor can be significantly increased, and hence vehicle acceleration and gradeability performance can be improved and the transmission can be simplified. However, each type of motor inherently has its limited maximum speed ratio. For example, a permanent magnet motor has a small x (<2) because of the difficulty of field weakening due to the presence of the permanent magnet. Switched reluctance motors may achieve $x=6$ and induction motors about $x=4$.

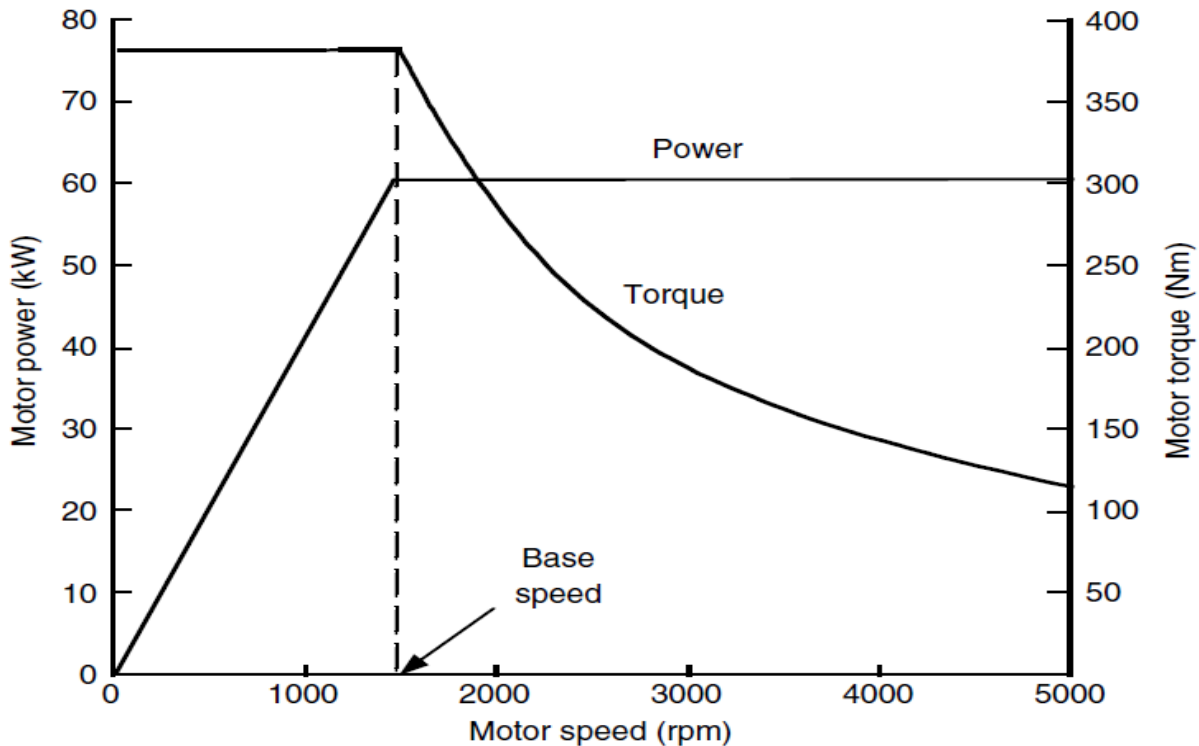


FIGURE 3: Typical variable-speed electric motor characteristics

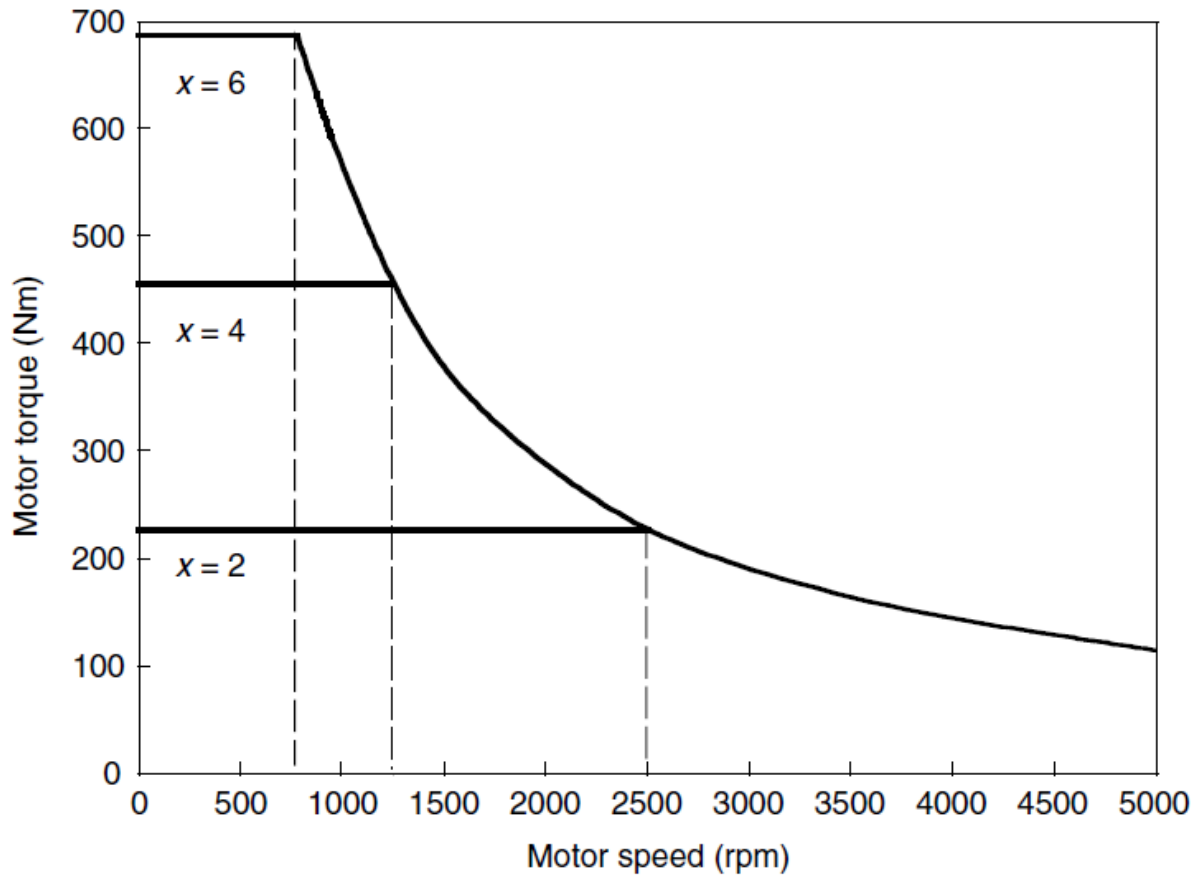


FIGURE 4: Speed–torque profile of a 60 kW electric motor with $x = 2, 4$, and 6

2. Tractive Effort and Transmission Requirement:

The tractive effort developed by a traction motor on driven wheels and the vehicle speed are expressed as

$$F_t = \frac{T_m i_g i_0 \eta_t}{r_d} \quad \dots\dots\dots(1)$$

$$V = \frac{\pi N_m r_d}{30 i_g i_0} (\text{m/s}),$$

And \dots\dots\dots(2)

where T_m and N_m are the motor torque output and speed in rpm, respectively,

i_g is the gear ratio of transmission, i_0 is the gear ratio of final drive, η_t is the efficiency of the whole driveline from the motor to the driven wheels, and r_d is the radius of the drive wheels. The use of a multigear or single-gear transmission depends mostly on the motor speed–torque characteristics. That is, at a given rated motor power, if the motor has a long constant power region, a single-gear transmission would be sufficient for a high tractive effort at low speeds. Otherwise, a multigear (more than two gears) transmission has to be used. Figure 5 shows the tractive effort of an EV, along with the vehicle speed with a traction motor of $x=2$ and a three-gear transmission. The first gear covers the speed region of a–b–c, the second gear covers d–e–f, and the third gear covers g–f–h. Figure 6 shows the tractive effort with a traction motor of $x=6$ and a two-gear transmission. The first gear covers the speed region of a–b–c and the second gear d–e–f. Figure 7 shows the tractive effort with a traction motor of $x=6$ and a single-gear transmission. These three designs have the same tractive effort vs. vehicle speed profiles. Therefore, the vehicles will have the same acceleration and gradeability performance.

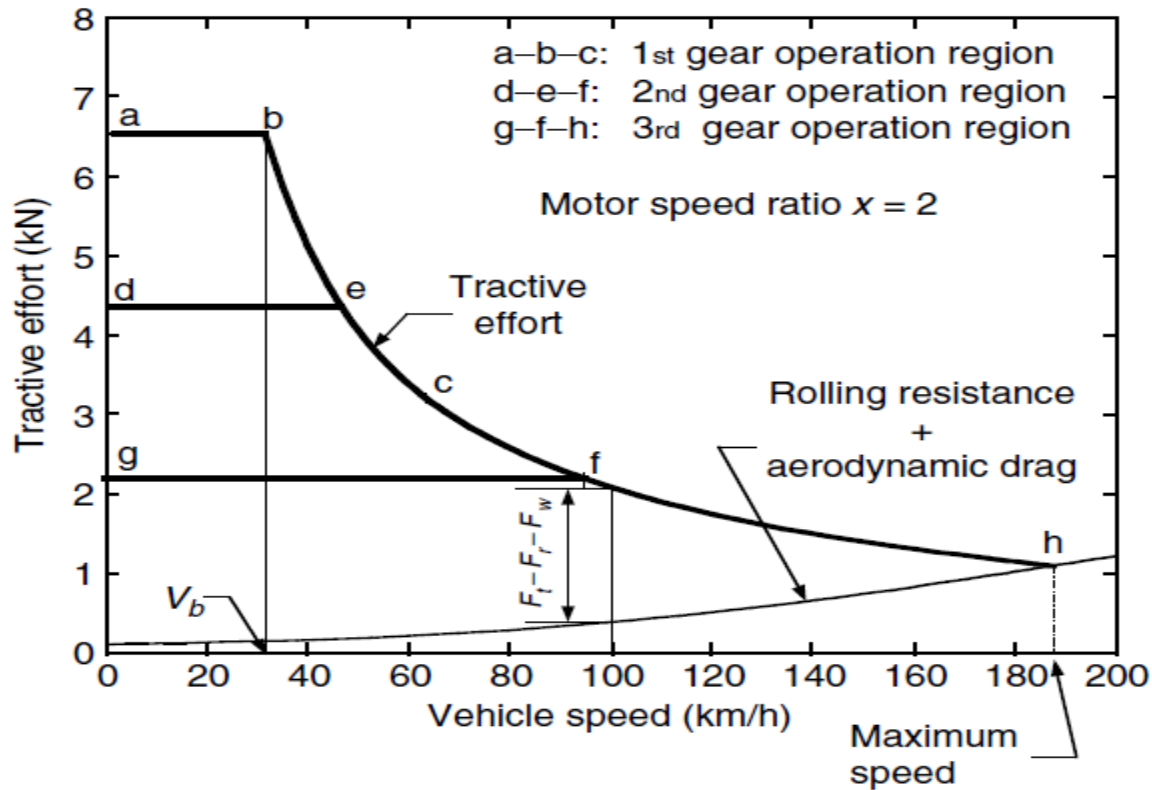


FIGURE 5: Tractive effort vs. vehicle speed with a traction motor of $x = 2$ and three-gear transmission

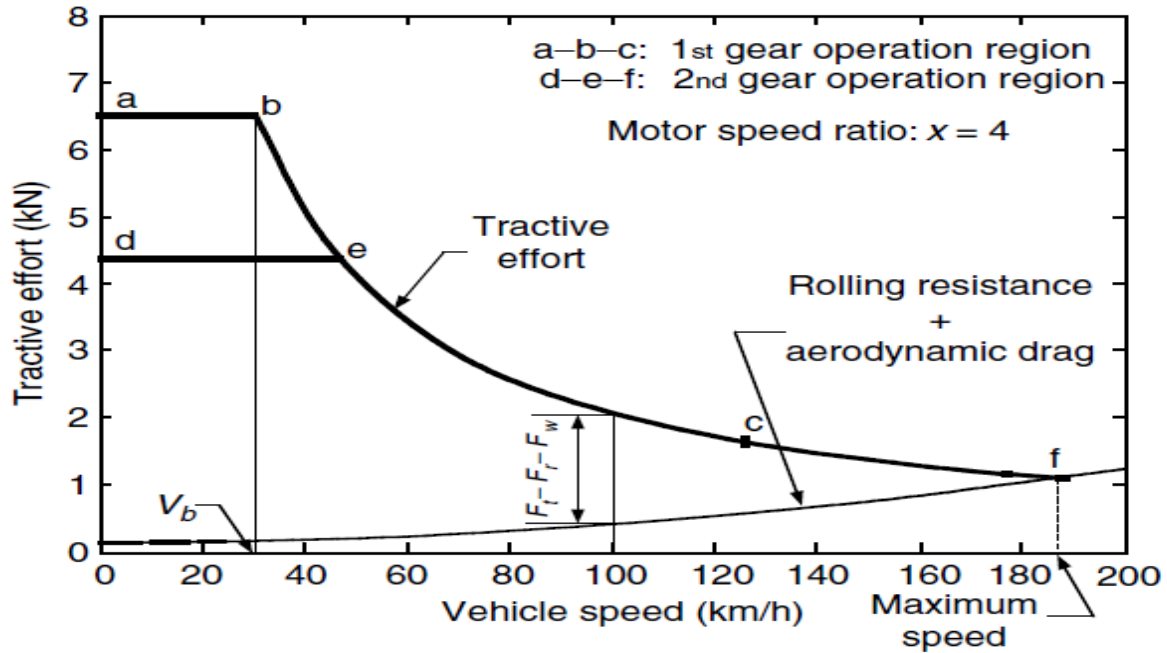


FIGURE 6: Tractive effort vs. vehicle speed with a traction motor of $x=4$ and two-gear transmission

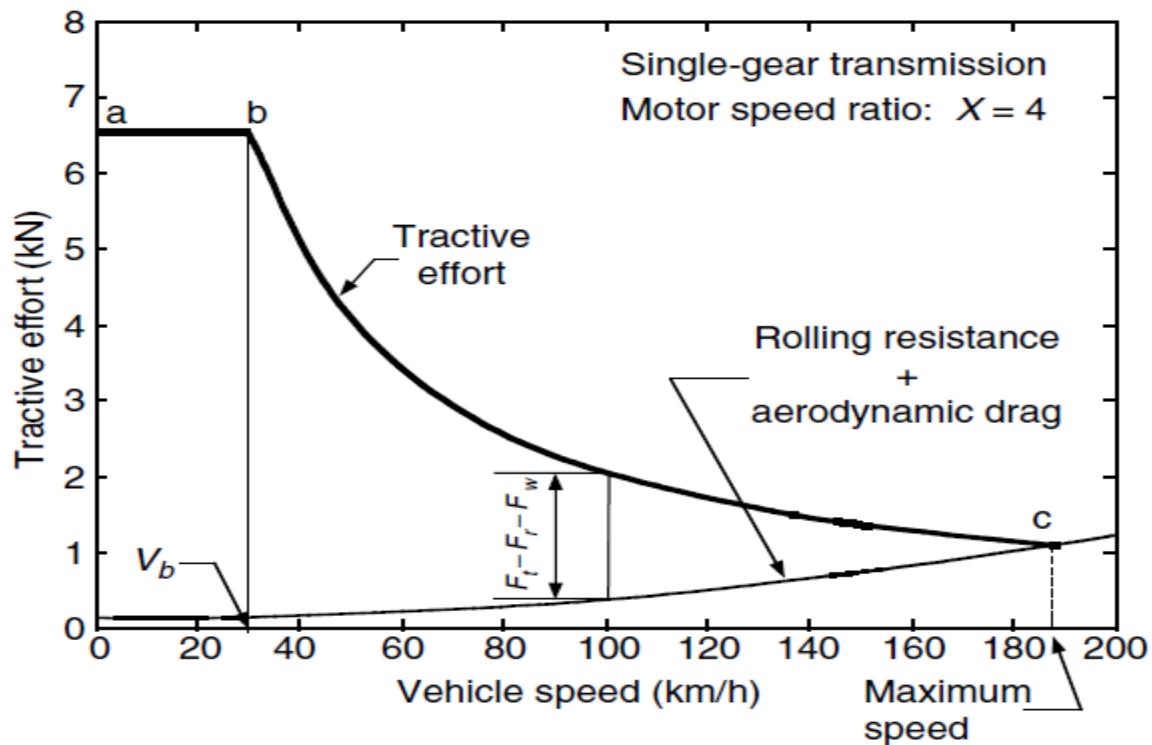


FIGURE 7: Tractive effort vs. vehicle speed with a traction motor of $x=6$ and single-gear transmission

3. Vehicle Performance:

Basic vehicle performance includes maximum cruising speed, gradeability, and acceleration. The maximum speed of a vehicle can be easily found by the intersection point of the tractive effort curve with the resistance curve (rolling resistance plus aerodynamic drag), in the tractive effort vs. vehicle speed diagram shown in Figures 4-6. It should be noted that such an intersection point does not exist in some designs, which usually use a larger traction motor or a large gear ratio. In this case, the maximum vehicle speed is determined by the maximum speed of the traction motor as

$$V_{max} = \frac{\pi N_{m\ max} r_d}{30 i_{g\ min} i_0} \text{ (m/s)}, \quad \dots\dots(3)$$

where $N_{m\ max}$ is the allowed maximum rpm of the traction motor and $i_{g\ min}$ is the minimum gear ratio of the transmission (highest gear).

Gradeability is determined by the net tractive effort of the vehicle, F_{t-net} ($F_{t-net} = F_t - F_r - F_w$), as shown in Figures 4. – 6. At mid- and high speeds, the gradeability is smaller than the gradeability at low speeds. The

maximum grade that the vehicle can overcome at the given speed can be calculated by

$$i = \frac{F_{t-net}}{M_v g} = \frac{F_t - (F_r + F_w)}{M_v g}, \quad (4.4)$$

where F_t is the tractive effort on the driven wheels, F_r is the tire rolling resistance, and F_w is the aerodynamic drag. However, at low speeds, the gradeability is much larger. Calculations with higher accuracy uses the formula

$$\sin \alpha = \frac{d - f_r \sqrt{1 - d^2 + f_r^2}}{1 + f_r^2}, \quad (4.5)$$

where $d = (F_t - F_m)/M_v g$, which is called the vehicle performance factor and f_r is the tire rolling resistance coefficient.

Acceleration performance of a vehicle is evaluated by the time used to accelerate the vehicle from a low-speed V_1 (usually zero) to a higher speed (100 km/h for passenger cars). For passenger cars, acceleration performance is more important than maximum cruising speed and gradeability, since it is the acceleration requirement, rather than the maximum cruising speed or the gradeability, that dictates the power rating of the motor drive.

For initial evaluation of the acceleration time vs. the tractive power, one can ignore the rolling resistance and the aerodynamic drag and obtain

$$t_a = \frac{\delta M_v}{2P_t} (V_f^2 + V_b^2), \quad (4.7)$$

where V_b and V_f are the vehicle base speed P_t is the tractive power on the driven wheels transmitted from the traction motor corresponding to the vehicle base speed.

where the vehicle mass factor, δ , is a constant. The tractive power, P_t , can then be expressed as

$$P_t = \frac{\delta M_v}{2t_a} (V_f^2 + V_b^2). \quad (4.8)$$

To determine the tractive power rating accurately, the power consumed in overcoming the rolling resistance and dynamic drag should be considered.

The total tractive power for accelerating the vehicle from zero to speed V_f in t_a seconds can be finally obtained as

$$P_t = \frac{\delta M_v}{2t_a} (V_f^2 + V_b^2) + \frac{2}{3} M_v g f_r V_f + \frac{1}{5} \rho_a C_D A_f V_f^3. \quad (4.12)$$

Equation (4.12) indicates that for a given acceleration performance, low vehicle base speed will result in small motor power rating. However, the power rating decline rate to the vehicle base speed reduction is not identical. Differentiating equation (4.12) with respect to the vehicle speed V_b , one can obtain

$$\frac{dP_t}{dV_b} = \frac{\delta M_v}{t_a} V_b. \quad (4.13)$$

Figure 4.9 shows an example of the tractive power rating and the power rating decline rate to the vehicle speed reduction (dP_t/dV_b) vs. the speed factor x .

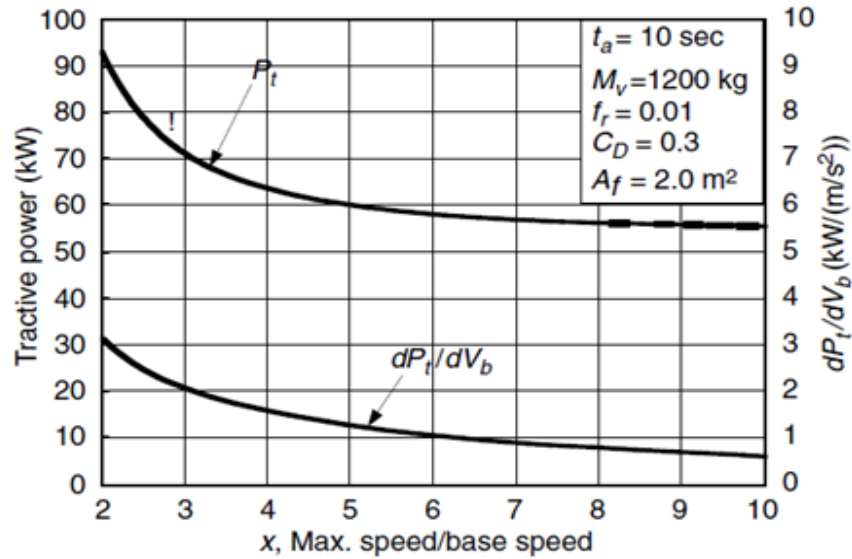


FIGURE 4.9
Power rating vs. speed factor

7. ELECTRIC VEHICLE DRIVETRAIN:

Previously, the electric vehicles (EV) were mainly converted from the exiting internal combustion engine vehicle (ICEV) by replacing the internal combustion engine and fuel tank with an electric motor drive and battery pack while retaining all the other components, as shown in Figure 5.1. Drawbacks such as its heavy weight, lower flexibility, and performance degradation have caused the use of this type of EV to fade out. In its place, the modern EV is purposely built, based on original body and frame designs. This satisfies the structure requirements unique to EVs and makes use of the greater flexibility of electric propulsion.

A modern electric drive train is conceptually illustrated in Figure 5.2. The drive train consists of three major subsystems: electric motor propulsion, energy source, and auxiliary. The electric propulsion subsystem comprises the vehicle controller, power electronic converter, electric motor, mechanical transmission, and driving wheels. The energy source subsystem involves the energy source, the energy management unit, and the energy refuelling unit. The auxiliary subsystem consists

of the power steering unit, the hotel climate control unit, and the auxiliary supply unit.

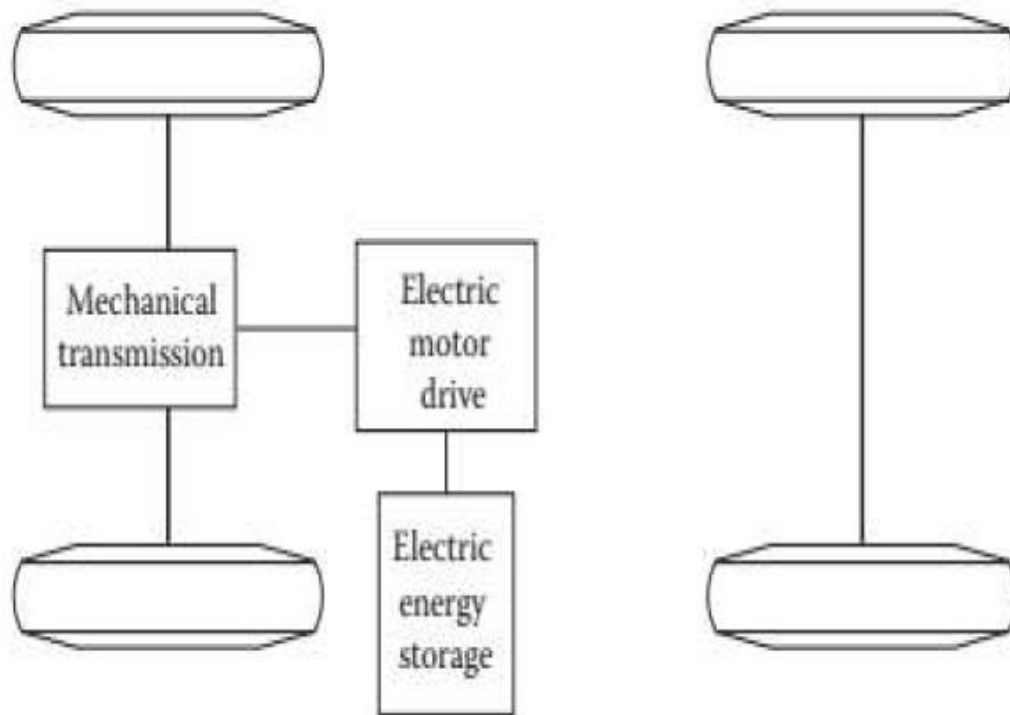


FIGURE 5.1 Primary electric vehicle power train.

Based on the control inputs from the accelerator and brake pedals, the vehicle controller provides proper control signals to the electronic power converter, which functions to regulate the power flow between the electric motor and energy source. The backward power flow is due to the regenerative braking of the EV and this regenerated energy can be restored into the energy source, provided the energy source is receptive. Most EV batteries as well as ultra-capacitors and flywheels readily possess the ability to accept regenerative energy. The energy management unit cooperates with the vehicle controller to control the regenerative braking and its energy recovery. It also works with the energy refuelling unit to control the refuelling unit and to monitor the usability of the energy source. The auxiliary power supply provides the necessary power with different voltage levels for all the EV auxiliaries, especially the hotel climate control and power steering units.

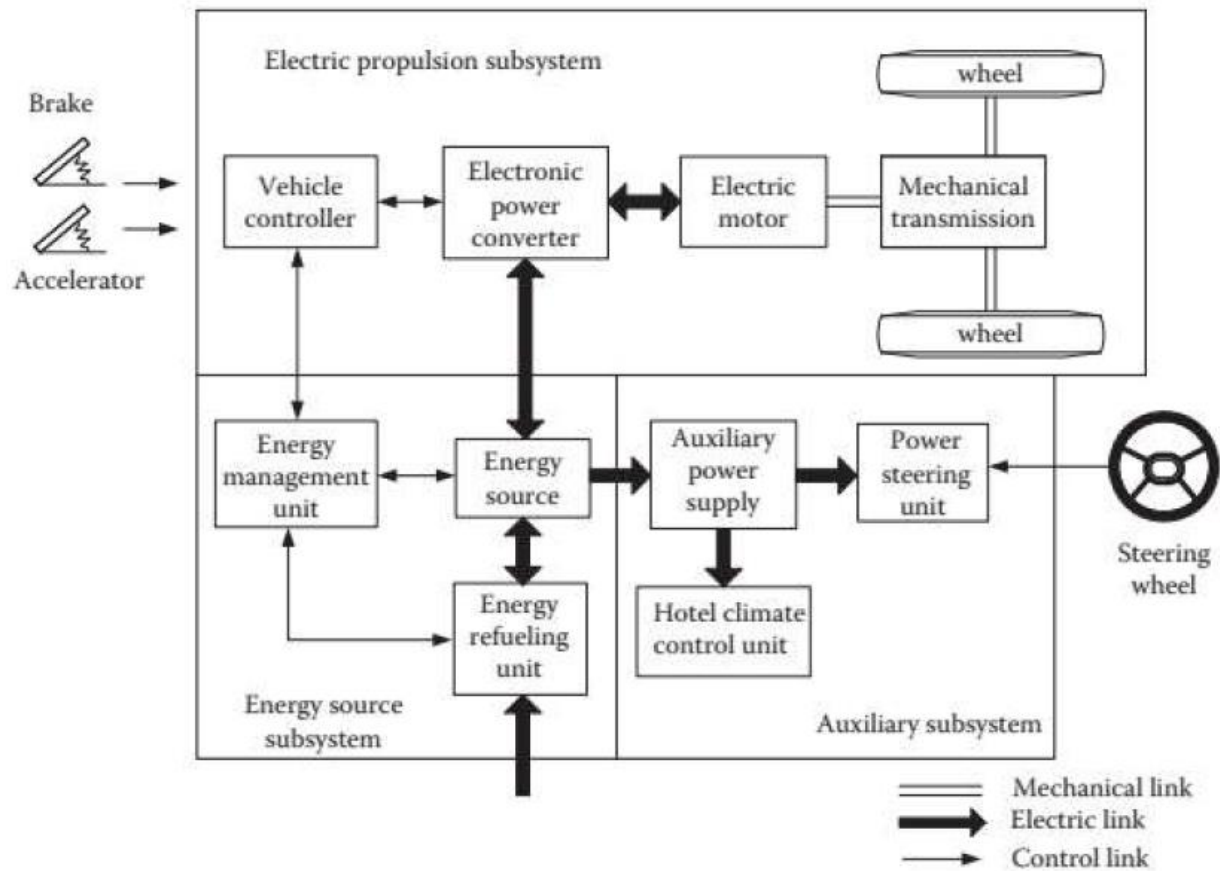


FIGURE 5.2 Modern Electric Vehicle Drivetrain.

The transmission elements and the propulsion unit combined are referred to as the drivetrain of the vehicle. The transmission is the mechanical linkage that transmits power between the electric motor shaft and the wheels. The drivetrain is also often referred to as the powertrain of the vehicle. The drivetrain of an electric vehicle (EV) consists of the electric motor, gearbox, driveshaft (only in rear wheel drives), differential, half-shafts, and wheels. The ability of electric motors to start from zero speed and operate efficiently over a wide speed range makes it possible to eliminate the clutch that is used in internal combustion engine vehicles (ICEV). A single gear ratio is sufficient to match the wheel speed with the motor speed. EVs can be designed without a gear, but the use of a speed reducer allows the electric motor to operate at much higher speeds for given vehicle speeds, which minimizes the motor size because of the low torque requirement at higher speeds. The transmission of a hybrid electric vehicle (HEV) is more complex than that of the EV

because of the coupling necessary between the electric motor and the internal combustion (IC) engine.

8. EV TRANSMISSION CONFIGURATION AND COMPONENTS:

8.1 EV TRANSMISSION CONFIGURATIONS:

In the case of front-wheel drive, the electric motor drives the gearbox, which is mounted on the front axle, as shown in Figure 3. This configuration is for an EV using a single propulsion motor. The single motor drives the transaxle on a common axis, delivering power to the two wheels differentially through a hollow motor shaft. The use of two motors driving two front wheels simplifies the transmission and eliminates the differential. Several configurations are possible with two propulsion motors driving two wheels. In one arrangement, the motors, mounted to the chassis, can be connected to the wheels through two short half shafts. The suspension system of the vehicle isolates the wheels and its associated parts from the rest of the components of the vehicle for easier handling of the vehicle, depending on roadway conditions. The wheels are able to move freely without the weight of the motors when they are mounted on the chassis. In an alternate arrangement, the motors are mounted on the half-shafts with the motor driveshaft being part of the half-shaft. The half-shafts connect the wheels on one side and the chassis through a pivot on the other side. In-wheel mounting of motors is another arrangement possible in EVs. The difficulty in this case is that the unsprung weight of the vehicle increases due to motors inside the wheels, making traction control more complex.

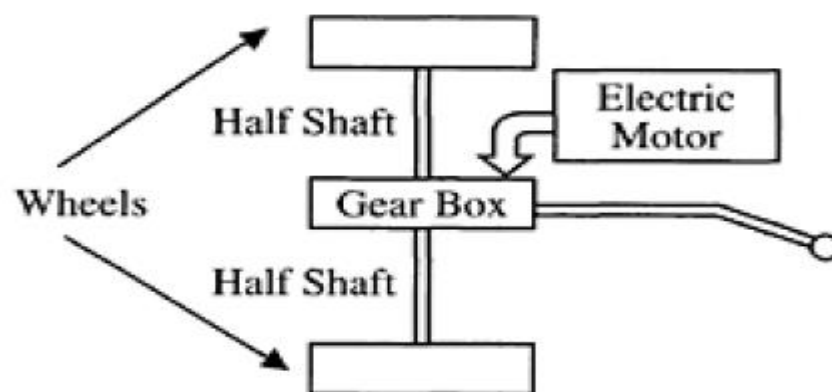


FIGURE 3: Typical front-wheel drive

To minimize the unsprung weight of the vehicle and because of the limited space available, the in-wheel motors must be of high-power density. As mentioned at the beginning, the use of a speed reducer is desirable, which adds to the constraint of limited space. The cost of a high-power, high-torque motor is the primary impediment in using in-wheel motors for EVs. Another problem with in-wheel motors is the heating due to braking compounded by the limited cooling capability in the restricted space. Nevertheless, the transmission simplicity has led to several projects for the development of in-wheel motors for EVs. The transmission is more complex in the case of a rear-wheel drive, which requires a differential to accommodate unequal speeds of the inside and outside wheels of the rear axle during vehicle cornering. A typical rear-wheel drive transmission configuration is shown in Figure 4.

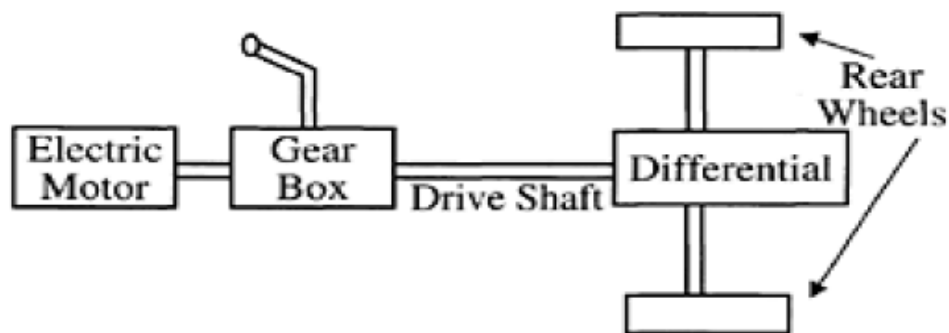


FIGURE 4: Typical rear-wheel drive.

8.2 EV TRANSMISSION COMPONENTS:

The gearbox (including the clutch or automatic transmission), driveshaft, and differential (in the case of rear-wheel drive) are the major components of the transmission. The axles, wheels, and the braking systems are the auxiliary components of the transmission or powertrain. The output of the electric motor is the input to the transmission.

1. GEARS:

The gear is a simple mechanical power transmission machine used to gain a mechanical advantage through an increase in torque or reduction in speed. This simple mechanical device uses the law of conservation of energy, maintaining the

steady flow of power or energy, because torque times speed is power that remains constant in the ideal transmission process. In an ideal gearbox, the motion is frictionless, and the power and energy supplied at the input point of the gearbox are equal to the power and energy available at the delivery point. The gearbox is not used to increase the shaft speed of an electric motor, because this means that a high-torque motor is unnecessarily designed, where the size of a motor is proportional to the torque output. Therefore, the gearbox can be used as a torque multiplier or speed reducer. A typical gear mechanism is shown in Figure 5. Structurally, a gear is a round disk with teeth cut at equal intervals around the rim designed to engage with similar teeth of another disk. The round disks, placed in combination, transmit power from one gear to another. The teeth at both the disks lock the driving and the driven shafts together to transfer the energy through contact with little, if any, loss.

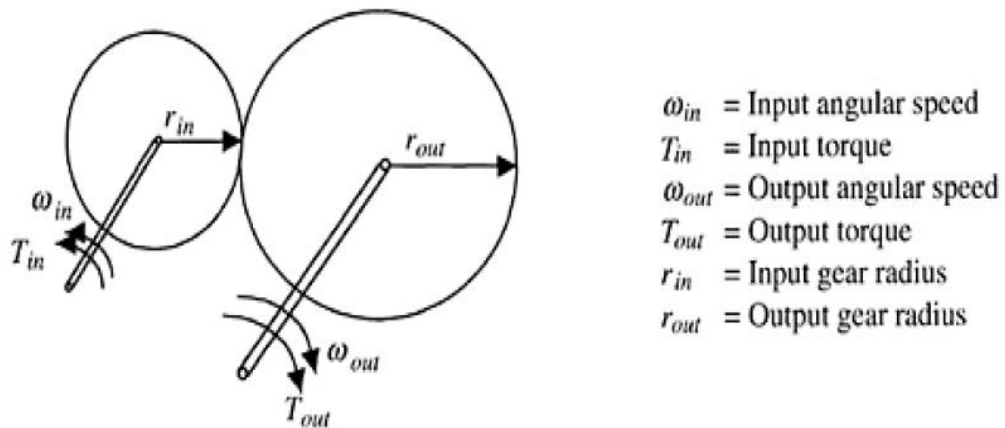


FIGURE 5: Gear mechanism

2. AUTOMOBILE DIFFERENTIAL

The automobile differential provides a mechanism of differential movement of the wheels on the rear axle. When a vehicle is turning a corner, the rear wheel to the outside of the curve must rotate faster than the inside wheel, because the former has a longer distance to travel. The type of gear used in an automobile differential is known as the planetary gear, where a set of gear trains operates in a coordinated manner. A simplified schematic of an automobile differential is given in Figure 6. The figure omits the teeth of the gears for simplicity. The driveshaft connected to the engine drives the pinion that is connected to the bevel (perpendicular) gear. The bevel gear is connected to the differential cage, which drives the wheel axles. The cage is connected to only one of the wheel axles, connecting the other axle only by

means of the differential pinion. The differential pinion connecting the differential gears does not rotate as long as the speeds of the two wheels on the axle are the same. If one of the wheels slows due to cornering, the differential pinion starts rotating to produce a higher speed on the other wheel. The system described above is a simple differential that is not suitable for full torque transfer in low-traction conditions, such as on ice.

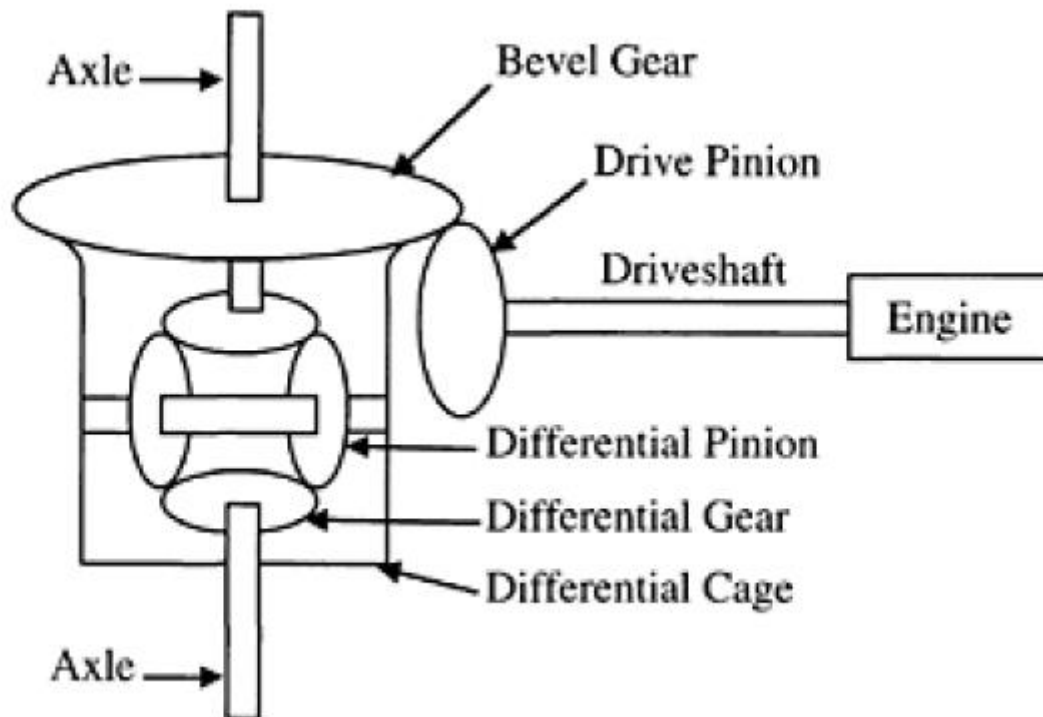


FIGURE 6: Simplified schematic of an automobile differential.

3. CLUTCH:

The clutch is a mechanical device used to smoothly engage or disengage the power transmission between a prime mover and the load. The most common use of a clutch is in the transmission system of an automobile, where it links the IC engine with the rest of the transmission system of the vehicle. The clutch allows the power source to continue running, while the load is freely running due to inertia or is idle. For efficient operation of the IC engine, the wheel speed needs to be matched with the narrow range of high-torque operating speed of the IC engine. The clutch engages and disengages the IC engine from the road load as the gear ratio of the

transmission is changed to match vehicle speed with the desired IC engine speed. Clutches can be eliminated in EVs, because the motor can start from zero speed and operate all the way to its maximum speed using a single gear ratio. The clutch in the automotive transmission is an example of a positive clutch. There is a second general type of clutch, which is known as friction clutches, used to bring the rotational speed of one disk to that of the other disk. The clutching action can be brought about by electrical, pneumatic, or hydraulic action in addition to mechanical means discussed here.

4. BRAKES:

The brakes in automobiles are mechanical clutches known as friction clutches, which use friction to slow a rotational disk. The driver controls the brake action through a foot-operated linkage. The friction clutch is composed of two disks, each connected to its own shaft. As long as the disks are not engaged, one disk can spin freely without affecting the other. When the rotating and the stationary disks are engaged through the operation action, friction between the two disks reduces the speed of the rotating disk. The kinetic energy of the vehicle transfers directly between the disks and is wasted due to friction. The two types of brakes used in automobiles are disk and drum. Disk brakes have friction pads controlled by a caliper arrangement, which when engaged, clamps to a disk rotating with the wheel. The brake pads are designed to assist cooling and resist fading. Fading causes the friction coefficient of braking to change with temperature rise. The high force required for caliper actuation is typically supplied from a power-assist device following the brake command input from the driver. Currently, hydraulic actuator systems are used for power assist, but the technology trend is to replace the hydraulic actuator system with an electric-motor-driven actuator system for superior performance.

Drum-type brake units have cylindrical surfaces and shoes instead of pads that hold the friction material. The shoes press against the drum cylinder upon a brake command input from the driver. The shoes can be arranged to press against the outer or inner surface of the rotating drum to retard wheel rotation. If the shoes are applied to the inner surface, then the centrifugal force of the drum due to rotation will resist disk engagement. If the shoes are pressed against the outer drum surface, the centrifugal force will assist engagement, but at the same time may cause overheating.

9. TRACTIVE EFFORT IN NORMAL DRIVING:

The vehicle capabilities with respect to speed, grade ability, and acceleration, thus dictating the power capacity of the power train. However, in normal driving conditions these maximum capabilities are rarely used. During most of the operation time, the power train operates with partial load. Actual tractive effort (power) and vehicle speed vary widely with operating conditions, such as acceleration or deceleration, uphill or downhill motion, etc. These variations are associated with the traffic environment as well as the type of vehicles. City and highway traffic conditions vary greatly, as do the different missions of the vehicles, such as a universal passenger car and vehicles with regular operation routes and schedules. It is difficult to describe the tractive effort and vehicle speed variations in all actual traffic environments accurately and quantitatively. However, some representative drive cycles (driving schedules) have been developed to emulate typical traffic environments. These drive cycles are represented by the vehicle speeds vs. the operating time while driving on a flat road. The J227a series is recommended by the Society of Automotive Engineers in the U.S.A and is applied in the evaluation of EVs and batteries. In a specific drive cycle, the tractive effort of a vehicle can be expressed as

$$F_t = M_v g f_r \cos \alpha + \frac{1}{2} \rho_a C_D A_f V^2 + M_v \delta \frac{dV}{dt} .$$

In a short time period, the speed is assumed to be linear with time, and acceleration is constant. The acceleration, dV/dt in a drive cycle, can be obtained by

$$\frac{dV}{dt} = \frac{V_{k+1} - V_k}{t_{k+1} - t_k} (k = 1, 2, \dots, n; n — \text{total number of points}).$$

The operating points of the tractive effort vs. the vehicle speed scatter over the plane, and they clearly show the operating area in which the power train operates most of the time.

10. ENERGY CONSUMPTION:

In transportation, the unit of energy is usually kilowatt-hour (kWh) rather than joule or kilojoule (J or kJ). The energy consumption per unit distance in kWh/km is generally used to evaluate the vehicle energy consumption. However, for ICE vehicles the commonly used unit is a physical unit of fuel volume per unit distance, such as liters per 100 km (l/100 km). In the U.S., the distance per unit volume of fuel is usually used; this is expressed as miles per gallon (mpg). On the other hand, for battery-powered EVs, the original energy consumption unit in kWh, measured at the battery terminals, is more suitable. The battery energy capacity is usually measured in kWh and the driving range per battery charge can be easily calculated. Similar to ICE vehicles, l/100 km (for liquid fuels) or kg/100 km (for gas fuels, such as hydrogen) or mpg, or miles per kilogram is a more suitable unit of measurement for vehicles that use gaseous fuels. Energy consumption is an integration of the power output at the battery terminals. For propelling, the battery power output is equal to resistance power and any power losses in the transmission and the motor drive, including power losses in electronics. The power losses in transmission and motor drive are represented by their efficiencies η_t and η_m respectively. Thus, the battery power output can be expressed as

$$P_{b-out} = \frac{V}{\eta_t \eta_m} \left(M_v g (f_r + i) + \frac{1}{2} \rho_a C_D A_f V^2 + M \delta \frac{dV}{dt} \right). \quad \text{..... (1)}$$

Here, the nontraction load (auxiliary load) is not included. In some cases, the auxiliary loads may be too significant to be ignored and should be added to the traction load. When regenerative braking is effective on an EV, a part of that braking energy — wasted in conventional vehicles — can be recovered by operating the motor drive as a generator and restoring it into the batteries. The regenerative braking power at the battery terminals can also be expressed as

$$P_{b-in} = \frac{\alpha V}{\eta_t \eta_m} \left(M_v g (f_r + i) + \frac{1}{2} \rho_a C_D A_f V^2 + M \delta \frac{dV}{dt} \right), \dots\dots (2)$$

where road grade i or acceleration dV/dt or both of them are negative, and α ($0 < \alpha < 1$) is the percentage of the total braking energy that can be applied by the electric motor, called the regenerative braking factor. The regenerative braking factor α is a function of the applied braking strength and the design of the power train. The net energy consumption from the batteries is

$$E_{out} = \int_{traction} P_{b-out} dt + \int_{braking} P_{b-in} dt. \dots\dots (3)$$

It should be noted that the braking power in (4.17) has a negative sign. When the net battery energy consumption reaches the total energy in the batteries, measured at their terminal, the batteries are empty and need to be charged. The traveling distance between two charges (usually called effective travel range) is determined by the total energy carried by the batteries, the resistance power, and the effectiveness of the regenerative braking α .

11. TYPES OF ELECTRIC VEHICLE IN USE TODAY:

The EVs are classified as

- (i) Battery Electric Vehicles (BEV) (ii) Hybrid Electric Vehicles (HEV).

Battery Electric Vehicles: Battery electric vehicles are propelled by electric motors by using energy stored on board in batteries. There are many similarities between an IC engine vehicle and a battery EV. To recharge the batteries of a BEV, periodically they must be plugged into an external source of electricity.

Hybrid Electric Vehicles (HEV): A vehicle that has two or more energy sources and energy converters is called a hybrid vehicle (HV). A HV with an electrical power train is called a hybrid EV. The sources of energy used in HEVs can be a combination of many resources such as battery, petrol, bio-fuels and fuel cells.

Types of HEV's are:

- | | |
|-----------------------------------|--|
| 1. Series Hybrid (SHEV) | 2. Parallel Hybrid (PHEV) |
| 3. Series-Parallel Hybrid (SPHEV) | 4. Complex Hybrids (CHEV) |
| 5. Fuel Cell Hybrids (FCHEV) | 6. Plug-in Hybrid Electric Vehicles (PHEV) |

1. Series Hybrid EVs (SHEV): In case of series hybrid system the mechanical output is first converted into electricity using a generator. The converted electricity either charges the battery or can bypass the battery to propel the wheels via the motor and mechanical transmission. The advantages of series hybrid drive trains are:

- Mechanical decoupling between the ICE and driven wheels allows the IC engine operating at its very narrow optimal region.
- Nearly ideal torque-speed characteristics of electric motor make multigear transmission unnecessary.

However, a series hybrid drive train has the following disadvantages:

- The energy is converted twice (mechanical to electrical and then to mechanical) and this reduces the overall efficiency.
- Two electric machines are needed and a big traction motor is required because it is the only torque source of the driven wheels.

The series hybrid drive train is used in heavy commercial vehicles, military vehicles and buses. The reason is that large vehicles have enough space for the bulky engine/generator system. **Example:** Nissan e-Power.

2. Parallel Hybrid EVs (PHEV): The parallel HEV allows both ICE and electric motor (EM) to deliver power to drive the wheels. Since both the ICE and EM are coupled to the drive shaft of the wheels via two clutches, the propulsion power may be supplied by ICE alone, by EM only or by both ICE and EM. The EM can be used as a generator to charge the battery by regenerative braking or absorbing power from the ICE when its output is greater than that required to drive the wheels. The advantages of the parallel hybrid drive train are:

- Both engine and electric motor directly supply torques to the driven wheels and no energy form conversion occurs, hence energy loss is less.

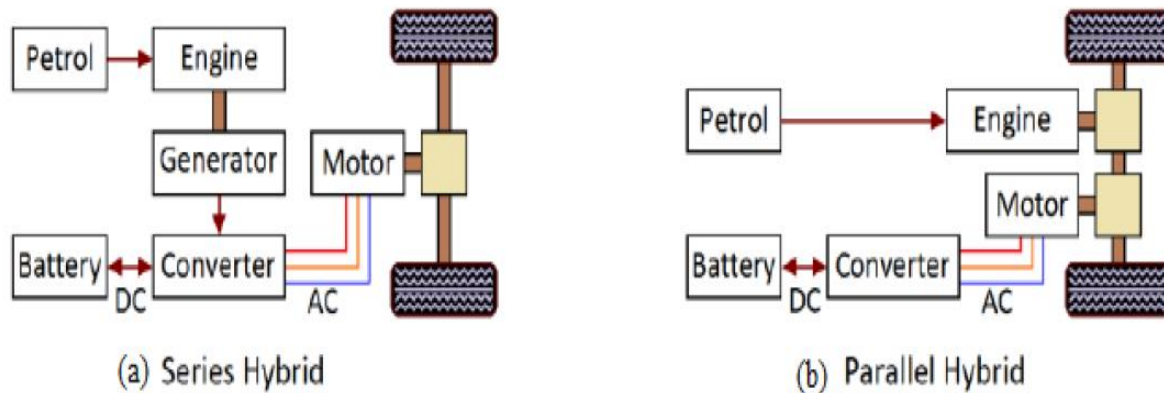
- Compactness due to no need of the generator and smaller traction motor.

The drawbacks of parallel hybrid drive trains are:

- Mechanical coupling between the engines and the driven wheels, thus the engine operating points cannot be fixed in a narrow speed region.
- The mechanical configuration and the control strategy are complex compared to series hybrid drive train.

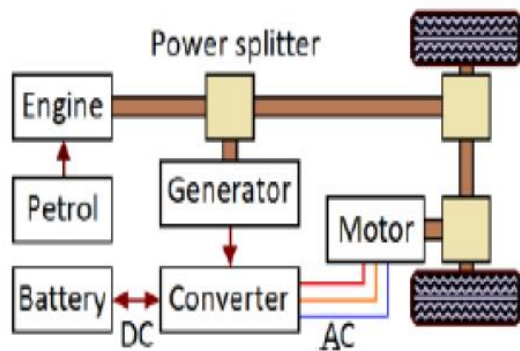
Due to its compact characteristics, small vehicles use parallel configuration. Most passenger cars employ this configuration.

Example: Honda: Insight and Civic.

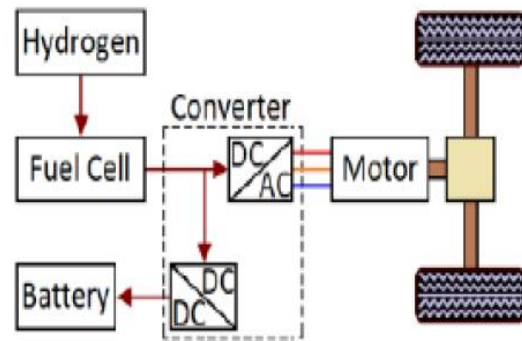


3. Series-Parallel Hybrid EVs (SPHEV): Series-parallel hybrids (or power-split hybrids) combine the benefits of both series and parallel architecture. The power-split device divides the output from the engine into mechanical and electrical transmission paths. This design is capable of providing continuous high output power as compared to series or parallel power train. They use smaller motors. Series-parallel hybrids can achieve similar operating modes as series hybrid vehicles. However, it requires very complex control system.

Example: Toyota Prius.



(c) Series-Parallel Hybrid



(d) Fuel Cell Hybrid

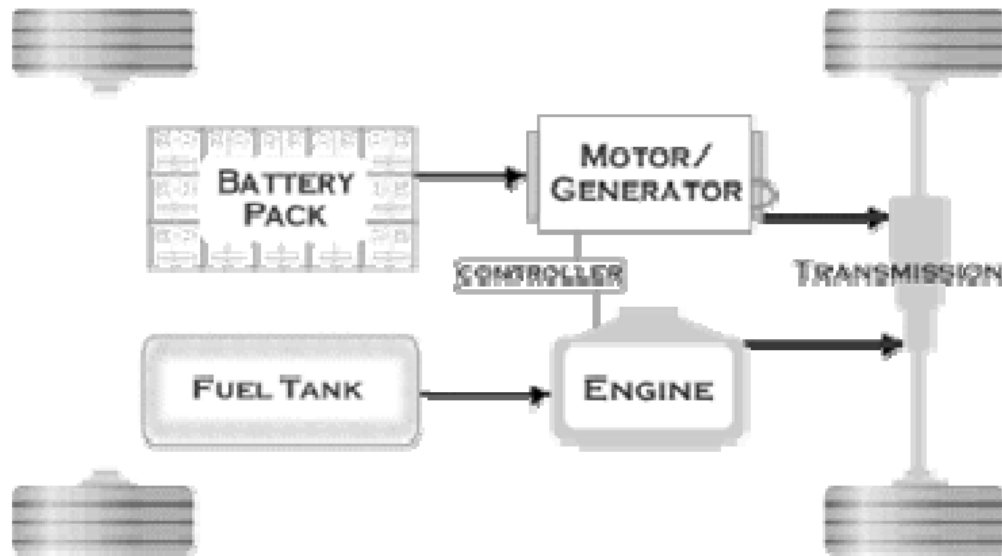
4. Fuel Cell Hybrid EVs (FCHEV): A fuel cell (FC) HEV is a series hybrid configuration in which fuel cell is the energy conversion system and a battery (or a super capacitor) is the energy storage system to deliver peak acceleration power. The operating principle of fuel cells is the reverse process of electrolysis in which hydrogen and oxygen gases combine to generate electricity with water and heat as by products. FC vehicles are true zero-emissions vehicles as they do not emit any greenhouse gases. Since fuel cells can offer high specific energy but cannot accept regenerative energy, it is usually combined with battery or other storage systems. At present, FCHEV technology is very premature and they are very expensive as compared to other HEVs.

Example: Honda Clarity.

5. Plug-in Hybrid Electric Vehicles (PHEV): The Plug-in hybrid EVs are full-hybrids which use a smaller engine, a larger battery and a larger motor. Batteries of PHEVs can be recharged from any external power source unlike in standard HEVs in which batteries are recharged only by means of the engine driven generator or regenerative braking. This feature of PHEV has the advantage of drawing electricity from any resource such as grid power including household supply, autonomous systems or even renewable energy. PHEVs have a shorter all-electric driving range per recharge as against battery EVs, but have a larger all-electric range as compared to standard HEVs because the engine-generator drive can assist the system when the batteries are depleted. Also, owing to the large electric motor, PHEVs have higher regenerative braking capability compared to traditional HEVs.

Examples: Chevy Volt, Toyota Prius, Ford CMax Energi.

Benefits of PHEV: Better fuel efficiency than regular HEV, long driving range than EVs, potential for distributed energy storage, low running cost compared to petrol, and environmentally friendly. Major disadvantages: High cost and non-availability of fast charging stations.

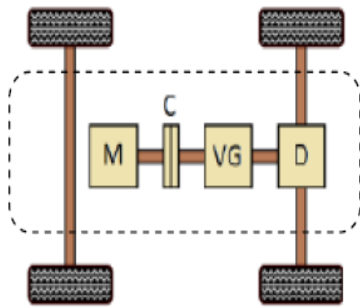


Plug-in Hybrid Electric Vehicles (PHEV)

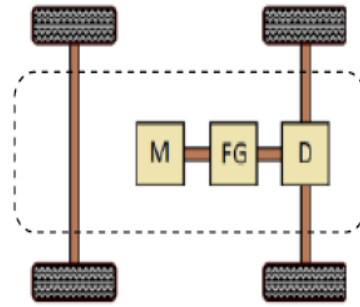
12. ELECTRIC VEHICLE CONFIGURATIONS:

Based on the type of transmission, clutch, gearbox, differential and the number of motors, the EV configurations/designs are

- a) The vehicles (as shown in figure (a)) with a clutch, a multi-speed gearbox and a differential. These EVs are modified versions of Internal Combustion Engine (ICE) vehicles with motors in place of engines.

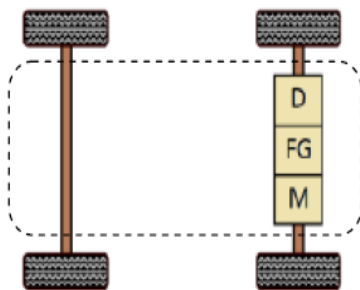


(a)

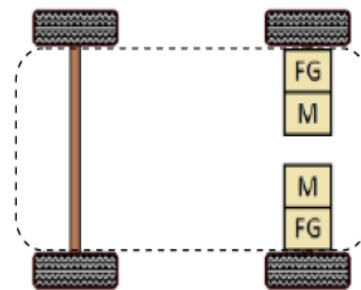


(b)

- b) The EVs with a fixed ratio gearbox and a differential as shown in figure (b). They do not use clutch as the electric motor that has constant power in a long speed range. This resulted in reduced size, weight and increased driving easiness.

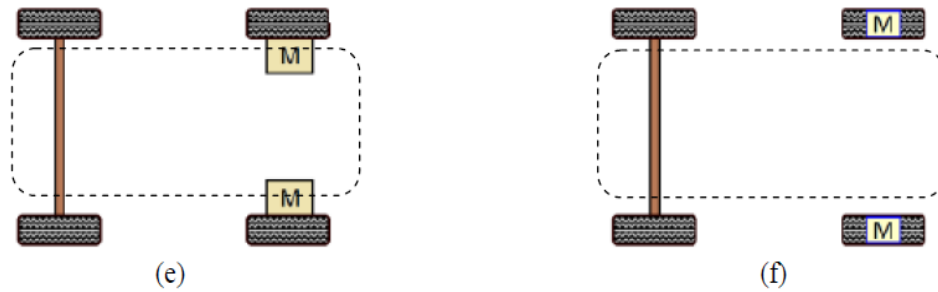


(c)



(d)

- c) Similar to the drive train in (b) but the motor, fixed gearing, and the differential are integrated into a single assembly. Result is a further simplified drive train.
- d) The differential is replaced by using two traction motors to drive front wheels as shown in figure (d) and operate at different speeds when the vehicle is running along a curved path.
- e) The *in-wheel* drive with a thin planetary gear in which the traction motor is placed inside the wheel as shown in figure (e). The gear is used to enhance the drive torque.



C: Clutch, M: Motor, VG: Variable Gearbox, D: Differential, FG: Fixed Gearbox

- f) Similar to the drive train in (e) except that the motor is placed inside the wheel without any gear. This design is relatively less complex than in (e).

The latest innovation in electric vehicles is the in-wheel configuration. In this design, as shown in Fig. f, separate motors (known as in-wheel motors) are installed at each wheel. Mounting the motor and power electronics within a wheel assembly can improve efficiency, save space and give designers more flexibility in body design. It is possible to regulate drive torque and braking force independently at each wheel without the need for any complex transmission or drive shaft. Regenerative braking capability of in-wheels is very high, about 85%. This design will require drive motors with higher torque to start and accelerate the vehicle. In-wheel motors of capacity up to 75 kW is currently available.

The EVs possess many advantages over conventional engine vehicles such as zero pollution, high efficiency etc., but they suffers from less travel range per battery charge than engine vehicles due to the lower energy content of batteries.

13. ELECTRIC VEHICLES FOR THE FUTURE:

Future development is always difficult to predict but there are several clear pointers as to how electric vehicles are likely to develop. New lithium technology may develop substantially and specific energies of new lithium batteries are predicted to double in the next few years.

This would allow the range of electric vehicles to double for the same battery mass. Doubling the range of electric vehicles would answer many of the criticisms of electric vehicles. In fact the Tesla Model S due to be released in 2012 has the option of a battery pack which gives a range of up to 300 miles (480 km). Another interesting development is the Honda FCX Clarity fuel cell car which has a similar range and can be refueled as quickly as a petrol or diesel car. It is likely that battery electric vehicles and fuel cell electric vehicles will both play a role in the future.

The benefits of high-speed trains for rapid long-distance travel. Maglev trains are already in use in China and it is believed that in the next decade these will become more widespread. There has been little use of road–rail systems which combine the benefits of both road and rail. Such systems can enable long-distance travel using

supply lines for recharging while allowing vehicles to travel to their destinations as a conventional road vehicle.

1. The Tesla S

Tesla is planning to release the Tesla S in 2012. The Model S is a pure electric vehicle which again uses lithium ion batteries. There is an option for three battery packs giving ranges of 160 miles (256 km), 230 miles (368 km) or 300 miles (480 km) per charge. The Model S is expected to have swappable batteries. It is intended to compete with more luxurious cars such as the Mercedes E series, the Audi A6 and the BMW 5 series. The car seats five adults (plus two children in rear-facing child seats) and has a 0–60 mph (96 kph) time of 5.5 seconds. The body panels and chassis will be primarily aluminium. Rapid charge time of 30 minutes.

2. The Honda FCX Clarity:

The Honda FCX Clarity is a fuel cell vehicle which uses hydrogen as a fuel. The FCX Clarity is currently available for lease in the USA, Japan and Europe. In the USA, it is only available to customers who live in southern California where fast-fill hydrogen stations are available.

This car is a five-seat saloon car which performs in a similar manner to its IC engine counterpart. It has a good range and given suitable infrastructure it can be refueled quickly. The hydrogen is kept in a 171 l tank at a pressure up to 35 bar. The car uses an AC permanent magnet synchronous motor and contains a PEMFC along with a lithium ion battery.

3. Maglev Trains:

The world speed record for crewed trains is currently held by a maglev train developed in Japan, which in December 2003 reached a maximum speed of 581 kph (363 mph) The train was developed by the Central Japan Railway (CJR) company in conjunction with Railway Technical Research.

The principle of maglev is essentially simple in that the train is levitated by magnets allowing it to run without wheels, therefore eliminating friction or other problems associated with wheels. Linear motors drive the train forward. The record-breaking Japanese maglev system uses an electro-suspension system. Maglev trains have superconducting magnetic coils and the guide-ways contain levitation coils. As the train moves, its moving magnetic fields create a current in the levitation coils due to the magnetic field induction effect. These currents create a magnetic field that

interacts with the magnetic field of the superconductive coils to create a force that holds up and stabilises the train.

4. Electric Road–Rail Systems

The idea of a road–rail system in which vehicles can travel on both roads and a track combines the benefit of a road vehicle with its free-ranging travel with train systems where vehicles can travel for considerable distances without hold-ups in relative safety and comfort.

5. Conclusion:

A recent system was tried in Gothenburg, Sweden, in which a line of cars, each outfitted with advanced steering and sensory technology, follow behind a leader vehicle which guides the cars as they travel along a preprogrammed route. Each car in the ‘train’ communicates with the leader via Wi-Fi links, thus requiring little or no input from their individual drivers, who are free to take their eyes off the road and relax.

At this moment in time we stand to see electric vehicles making a substantial impact on the future of transport. Traditionally electric vehicles have made their mark in niche markets such as invalid carriages, golf carts, fork-lift trucks, electric personnel carriers and electric bicycles. Electric trains have made a substantial impact but electric road vehicles have remained in the minority.

For the first time, the new electric lithium batteries have been able to provide electric vehicles with sufficient range to encourage their mass production. Development of fuel cell vehicles continues and these still show continuing promise for the future. High-speed trains have been developing quietly and are starting to be able to compete commercially with air transport.

Continued environmental concerns are pressing society to find alternatives to IC engines which will stop burning oil and other fossil fuels. Environmental concerns encompass both worries about carbon dioxide emissions and the effect of exhaust gas emissions on health.

There has been a proliferation of commercially available battery electric vehicles such as the Nissan Leaf and Mitsubishi MiEV. Hybrid vehicles such as the Chevrolet Volt in which the batteries can be charged from the mains are now commercially available and will be introduced to Europe in the form of the Vauxhall

or Opel Ampera. These vehicles can travel on shorter routes using mains electricity, but when a longer range is required they are able to use conventional fuels.

Most major vehicle manufacturers are also currently making developments in fuel cell vehicles. Clearly they see this as an area where electric cars could be produced, which would compete with conventional IC vehicles in terms of range, flexibility and cost. Fuel cell cars are further away from commercialization than hybrids, but fuel-cell-powered buses are closer to the market. Fuel cell road passenger cars have received a boost from the introduction of the Honda FCX Clarity, which is available for lease in the USA.

UNIT 2: ELECTRIC VEHICLE MODELING

Consideration of Rolling Resistance – Transmission Efficiency – Consideration of Vehicle Mass– Tractive Effort – Modeling Vehicle Acceleration – Modeling Electric Vehicle Range - Aerodynamic Considerations – Ideal Gearbox Steady State Model – EV Motor Sizing – General Issues in Design.

1. CONSIDERATION OF ROLLING RESISTANCE: The rolling drag on a vehicle F_{rr} is given by

$$F_{rr} = \mu_{rr}mg$$

where μ_{rr} is the coefficient of rolling resistance. The rolling drag is independent of speed. The power needed to overcome rolling P_{rr} is given by

$$P_{rr} = F_{rr} \times v = \mu_{rr}mgv$$

The value of μ_{rr} varies from 0.015 for a radial ply tyre down to 0.005 for tyres specially developed for electric vehicles. A reduction of rolling resistance to one-third is a substantial benefit, particularly for low-speed vehicles such as buggies for the disabled. For low-speed vehicles of this type the air resistance is negligible and a reduction of rolling resistance drag to one-third will either triple the vehicle range or cut the battery mass and cost by one-third – a substantial saving in terms of both cost and weight.

Power requirements/speed for an electric vehicle travelling on the flat, with typical drag ($C_d = 0.3$) and fairly standard tyres ($\mu_{rr} = 0.015$), with a mass of 1000 kg and a frontal area of 1.5 m^2 , is shown in Figure 9.4. The graph, derived from the above equations, shows how much power is required to overcome rolling resistance and aerodynamic drag.

It can be seen clearly in Figure 9.4 that at low speeds, for example under 50 kph, aerodynamics have very little influence, whereas at high speeds they are the major influence on power requirements. It may be concluded that streamlining is not very important at relatively low speeds, more important at medium speeds and very important at high speeds. So, for example, on a golf cart the aerodynamics are unimportant, whereas for a saloon car intended for motorway driving the aerodynamics are extremely important. (The rolling resistance of golf buggy wheels on turf will of course be considerably higher than can be expected on hard road surfaces.)

A graph of the total power requirement for two vans is shown in Figure 9.5, where a power/velocity curve for each vehicle is plotted. Both vans have a mass of 1000 kg,

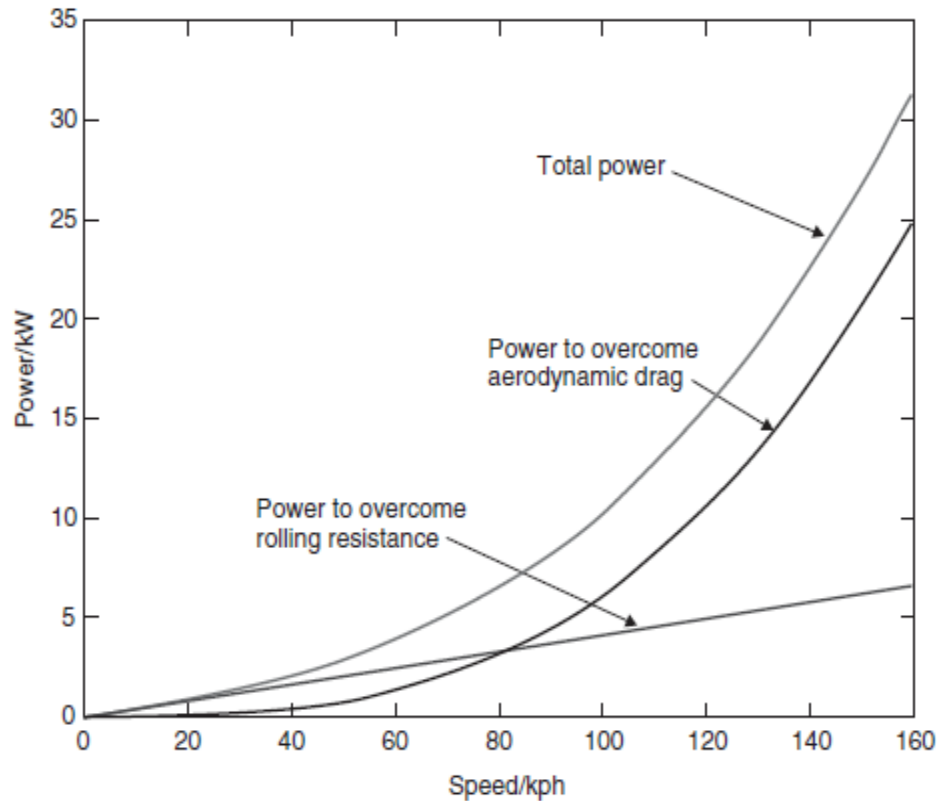


Figure 9.4 The power requirements to overcome rolling resistance and aerodynamic drag at different speeds. This is for a fairly ordinary small car, with $C_d = 0.3$, frontal area 1.5m^2 , mass = 1000 kg and $\mu_{rr} = 0.015$

frontal areas of 2m^2 and a C_d of 0.5. However, one has ordinary tyres with a μ_{rr} of 0.015, whereas the other has low-rolling-resistance tyres for which μ_{rr} is 0.005.

It can be concluded that for all electric vehicles a low rolling resistance is desirable and that the choice of tyres is therefore extremely important. A low coefficient of aerodynamic drag is very important for high-speed vehicles, but is less important for town/city delivery vehicles and commuter vehicles. On very low-speed vehicles such as electric bicycles, golf buggies and buggies for the disabled, aerodynamic drag has very little influence, whereas rolling resistance certainly does.

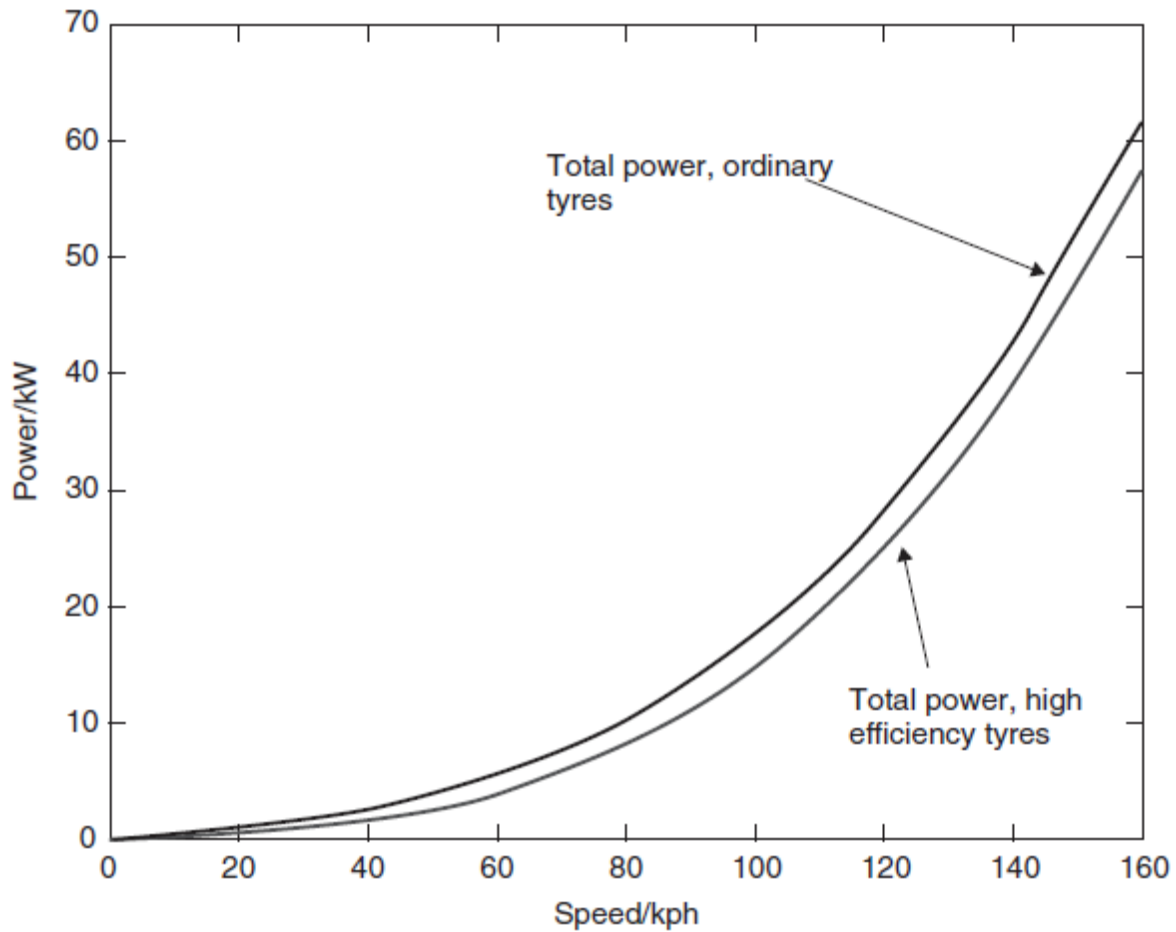


Figure 9.5 Power requirements for aerodynamic drag and rolling resistance at a range of speeds. This is for two vans, both of mass 1000 kg, frontal area 2 m^2 and $C_d = 0.5$. However, one has low-resistance tyres with $\mu_{rr} = 0.005$, whereas the other has ordinary tyres for which $\mu_{rr} = 0.015$

2. TRANSMISSION EFFICIENCY:

All vehicles need a transmission that connects the output of the motor to the wheels. In the case of an IC engine vehicle the engine is connected to a clutch which in turn connects to a gearbox, a prop shaft, a differential (for equalizing the torque on the driving wheels and an axle at different speeds). All of these have inefficiencies that cause a loss of power and energy. The transmission of electric vehicles is inherently simpler than that of IC engine vehicles. To start with, no clutch is needed as the motor can provide torque from zero speed upwards. Similarly, a conventional gearbox is not needed, as a single-ratio gear is normally all that is needed. The three basic variations of electric vehicle transmission are illustrated in Figure 9.6

The most conventional arrangement is to drive a pair of wheels through a differential. This has many advantages, the differential being a well-tested, reliable, quantity-produced piece of engineering. The disadvantage is that some power is lost through the differential, and differentials are relatively heavy. It can also take up space in areas where the space can be usefully utilized.

The differential can be eliminated by connecting a motor to each wheel via a single ratio gearbox or even a toothed belt drive. The torque from each wheel can be set by the electronic controller. This system has the advantage of clearing space within the vehicle, and the disadvantage of needing a more complicated electronic controller. Also, in terms of cost per kilowatt, two small motors are considerably more expensive than one larger one.

The third method is to connect the motor directly to the wheels via a shaft, or actually to design the motor as part of the hub assembly. This system has huge potential advantages, including a 100% transmission efficiency. The trouble with this system is that most electric motors typically run at two to four times faster than the vehicle's wheels, and designing a motor to work slowly results in a large heavy motor. However, this arrangement has and can be used. It is particularly popular in electric motors scooters and bicycles. Normally a vehicle's handling is improved if the unsprung mass is kept to a minimum. Placing the motor in the hub has advantages for space saving in vehicle layout, but will adversely affect handling. Also, the motor is certain to be considerably more expensive in terms of cost per kilowatt.

Of course, if you were designing a three-wheeler and driving the single wheel you would not need any differential, mechanical or electronic! You may still need to gear the motor to the wheel. A tricycle arrangement with one driven wheel at the back could also help in the production of a near-teardrop shape with its associated low aerodynamic drag. Such an arrangement has been used in some experimental vehicles. Whatever the arrangement for the transmission, the transmission efficiency is important. A percentage increase in transmission efficiency will allow a similar percentage reduction in battery mass and battery cost, or alternatively an equivalent increase in the vehicle range.

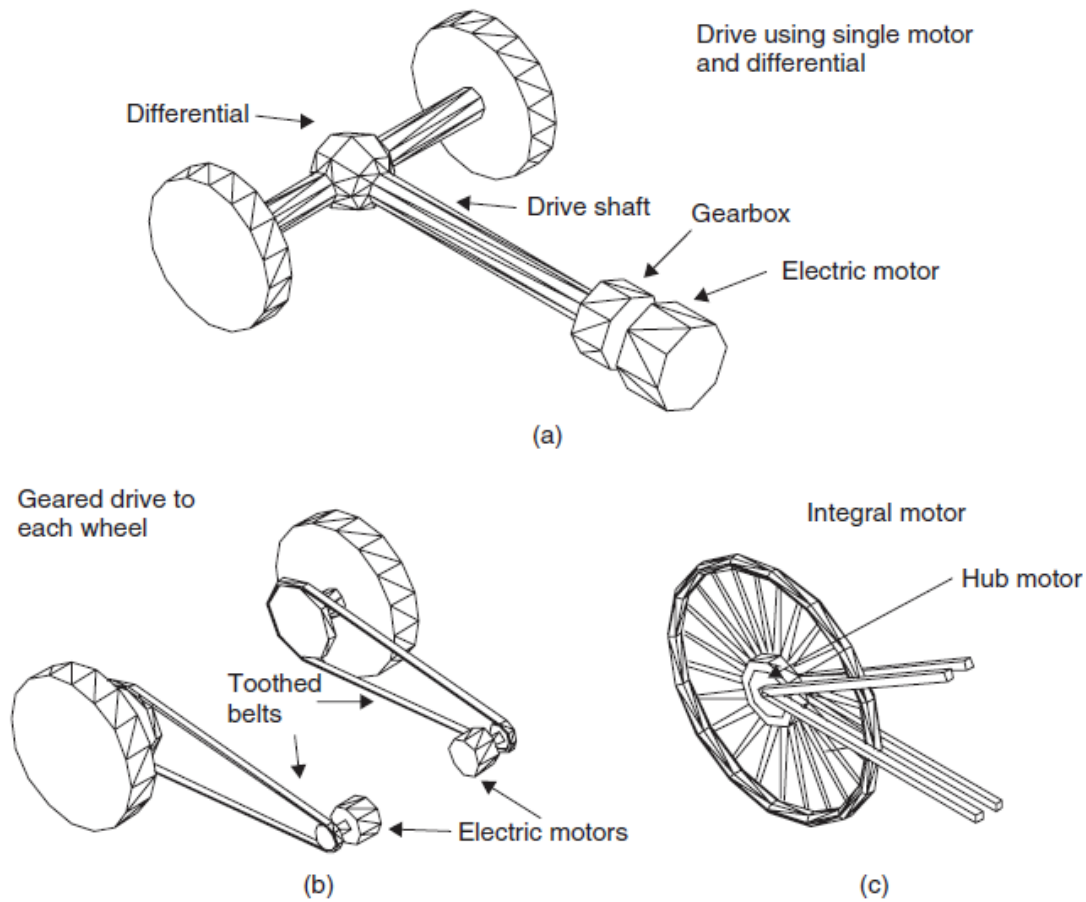


Figure 9.6 Three different arrangements for electric vehicle transmission: (a) drive using single motor and differential; (b) geared drive to each wheel; and (c) integral motor

3. CONSIDERATION OF VEHICLE MASS:

The mass of an electric vehicle has a critical effect on the performance, range and cost of an electric vehicle. There are two other effects of mass. The first concerns a vehicle climbing a hill and the second is the kinetic energy lost when the vehicle is accelerating and decelerating in an urban cycle.

the force F_{hc} in newtons along the slope for a car of mass $m(\text{kg})$ climbing a hill of angle ψ is given by

$$F_{hc} = mg \sin \psi$$

It follows that the power P_{hc} in watts for a vehicle climbing a slope at a velocity $v(\text{m s}^{-1})$ is given by

$$P_{hc} = F_{hc} \times v = mgv \sin \psi$$

Figure 9.10 shows the total power needed to travel at a constant 80 kph up slopes of varying angles up to 10° for vehicles of two different weights, but otherwise similar. They are based loosely on the GM EV1 electric car. They both have a drag coefficient of 0.19 and tyres with a coefficient of rolling resistance of 0.005, and the frontal area is 1.8m^2 . We can see that the 1500 kg car, which is approximately the weight of the real GM EV1, has to provide approximately 12 times as much power at 10° than is needed on the flat. With the 800 kg vehicle the power needed increases greatly, but only by about eight times.

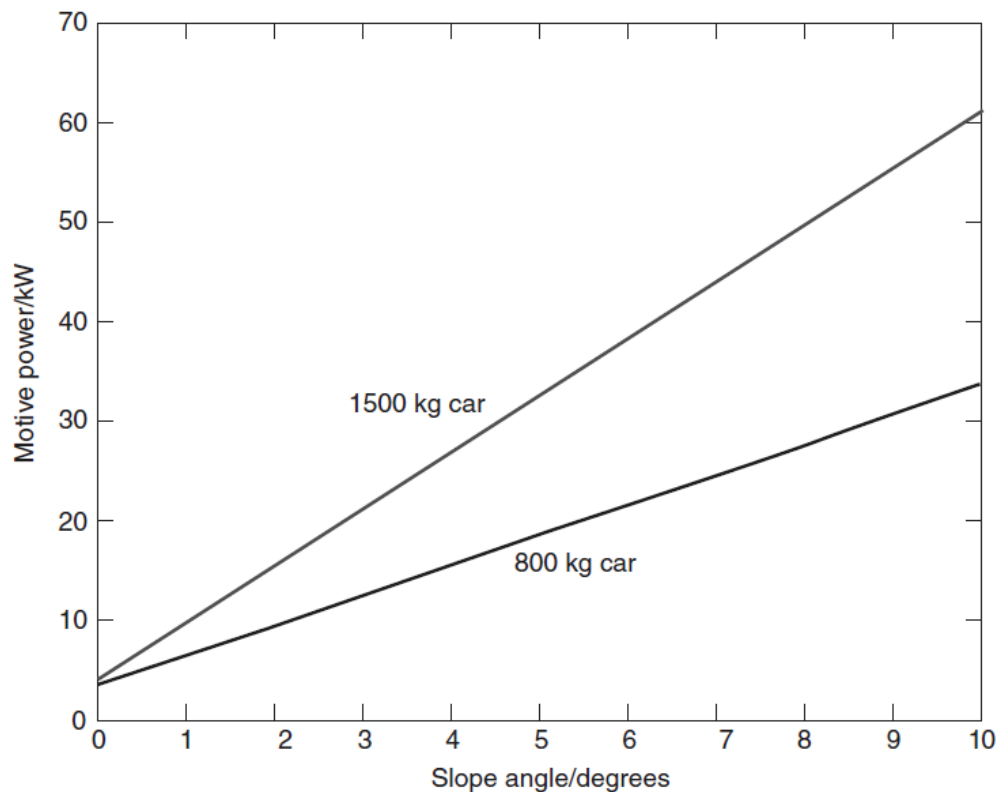


Figure 9.10 The total power requirements for two different vehicles moving at 80 kph up a hill of slope angle 0° – 10° . In both cases the vehicle has good tyres with $\mu_{rr} = 0.005$, low drag as $C_d = 0.19$, and a frontal area of 1.8m^2 . One car weighs 800 kg, the other 1500 kg

Looking at Figure 9.10 we see why the GM EV1 electric car needs a motor of power about 100 kW. In the SFUDS simulation we noted that the maximum power needed was only 12 kW. Taking heavy vehicles up hills requires high power. The results shown in the graph send a clear message. Considerable power is required for hill climbing, and such terrain will restrict the range of electric vehicles relying solely on rechargeable batteries. When designing electric vehicles the effect of hills must be taken into account, though there are no agreed ‘standard hills’ for doing this.

The effect of the vehicle mass when accelerating and stopping in town and city conditions is another area where the mass of the electric vehicle will have considerable influence on vehicle performance. Basically, when a vehicle of mass $m(\text{kg})$ is travelling at velocity $v(\text{ms}^{-1})$ its kinetic energy is given by

$$KE = \frac{1}{2}mv^2$$

If the vehicle brakes this energy is converted to heat. When regenerative braking is used a certain amount of the energy is recovered. The maximum practical limit on the recovery of kinetic energy is about 40%. In light vehicles the losses associated with continually creating and then losing kinetic energy are much less, and the benefits of regenerative braking are similarly reduced.

Apart from the importance of minimising vehicle weight, it is also important to try to minimise the moment of inertia of rotating components, as these store rotational kinetic energy. The energy stored E_r (joules) of a component with a moment of inertia I (kgm^2) rotating at $\omega(\text{rad s}^{-1})$ is given by

$$E_r = \frac{1}{2}I\omega^2$$

The moment of inertia I is normally expressed as

$$I = \sum_{n=1}^{n=N} m_n r_n^2$$

that is the sum of all the finite masses of a component which lie a distance r from the centre of rotation. In practice most rotating components such as the wheels are purchased as proprietary items, but the energy lost in rotary energy needs to be considered particularly for urban driving conditions.

4. TRACTIVE EFFORT:

1 Introduction

The first step in vehicle performance modelling is to produce an equation for the required ‘tractive effort’. This is the force propelling the vehicle forward, transmitted to the ground through the drive wheels.

Consider a vehicle of mass m , proceeding at a velocity v , up a slope of angle ψ , as in Figure 8.1. The force propelling the vehicle forward, the tractive effort, has to accomplish the following:

- overcome the rolling resistance;
- overcome the aerodynamic drag;
- provide the force needed to overcome the component of the vehicle’s weight acting down the slope;
- accelerate the vehicle, if the velocity is not constant.

We will consider each of these in turn.

2 Rolling Resistance Force

The rolling resistance is primarily due to the hysteresis losses in the vehicle tyres. Friction in bearings and the gearing system also play their part. The rolling resistance is approximately constant, and hardly depends on vehicle speed. It is proportional to vehicle weight. The equation is

$$F_{rr} = \mu_{rr}mg \quad (8.1)$$

where μ_{rr} is the coefficient of rolling resistance. The main factors controlling μ_{rr} are the type of tyre and the tyre pressure. Any cyclist will know this very well – the freewheeling performance of a bicycle becomes much better if the tyres are pumped up to a high pressure, though the ride may be less comfortable.

The value of μ_{rr} can reasonably readily be found by pulling a vehicle at a steady very low speed, and measuring the force required.

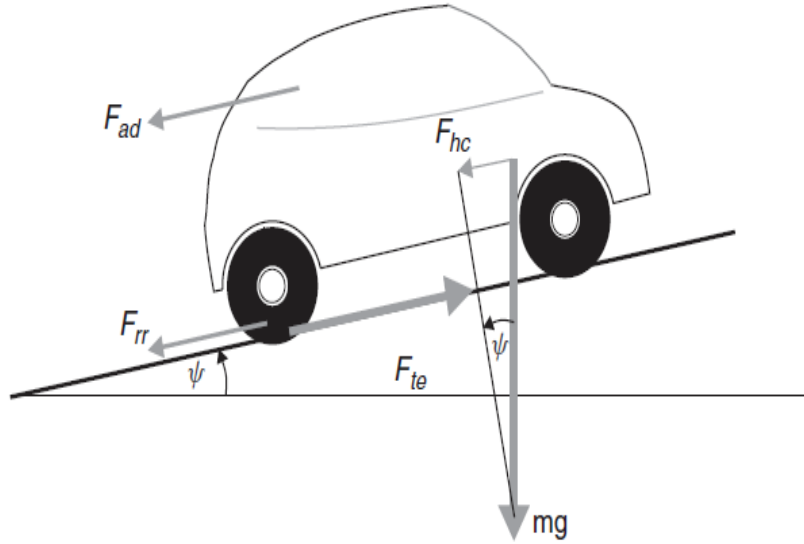


Figure 8.1 The forces acting on a vehicle moving up a slope

Typical values of μ_{rr} are 0.015 for a radial ply tyre, down to about 0.005 for tyres developed especially for electric vehicles.

3 Aerodynamic Drag

This part of the force is due to the friction of the vehicle body moving through the air. It is a function of the frontal area, shape, protrusions such as side mirrors, ducts and air passages, spoilers and many other factors. The formula for this component is

$$F_{ad} = \frac{1}{2} \rho A C_d v^2 \quad (8.2)$$

where ρ is the density of the air, A is the frontal area and v is the velocity. C_d is a constant called the ‘drag coefficient’.

The drag coefficient $\bar{C}_d$ can be reduced by good vehicle design. A typical value for a saloon car is 0.3, but some electric vehicle designs have achieved values as low as 0.19. There is greater opportunity for reducing C_d in electric vehicle design because there is more flexibility in the location of the major components, and there is less need for cooling air ducting and under-vehicle pipework. However, some vehicles, such as motorcycles and buses, will inevitably have much larger values, and C_d figures of around 0.7 are more typical in such cases.

The density of air does of course vary with temperature, altitude and humidity. However a value of 1.25 kg m^{-3} is a reasonable value to use in most cases. Provided that SI units are used (m^2 for A , m s^{-1} for v) then the value of F_{ad} will be given in newtons.

4 Hill Climbing Force

The force needed to drive the vehicle up a slope is the most straightforward to find. It is simply the component of the vehicle weight that acts along the slope. By simple resolution of forces we see that

$$F_{hc} = mg \sin \psi \quad (8.3)$$

5 Acceleration Force

If the velocity of the vehicle is changing, then clearly a force will need to be applied in addition to the forces shown in Figure 8.1. This force will provide the *linear acceleration* of the vehicle, and is given by the well-known equation derived from Newton's third law,

$$F_{la} = ma \quad (8.4)$$

However, for a more accurate picture of the force needed to accelerate the vehicle we should also consider the force needed to make the rotating parts turn faster. In other words, we need to consider *rotational* acceleration as well as *linear* acceleration. The main issue here is the electric motor – not necessarily because of its particularly high moment of inertia, but because of the higher angular speeds.

Referring to Figure 8.2, clearly the axle torque equals $F_{te}r$, where r is the radius of the tyre and F_{te} is the tractive effort delivered by the powertrain. If G is the gear ratio

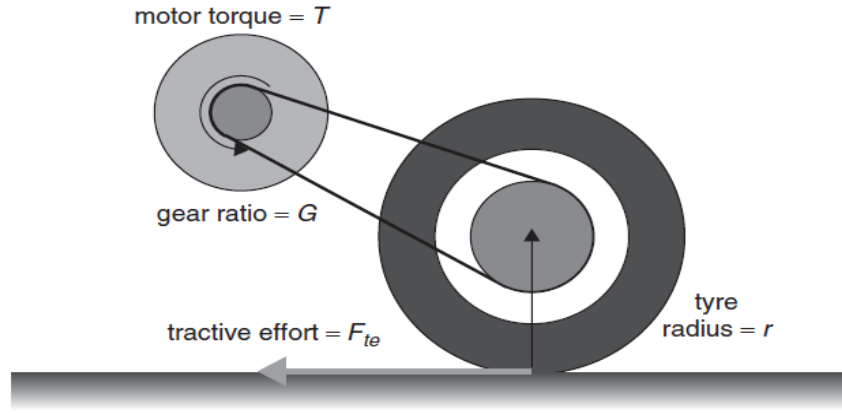


Figure 8.2 A simple arrangement for connecting a motor to a drive wheel

of the system connecting the motor to the axle and T is the motor torque, then we can say that

$$T = \frac{F_{te}r}{G} \quad \text{and} \quad F_{te} = \frac{G}{r}T \quad (8.5)$$

We will use this equation again when we develop final equations for vehicle performance. We should also note axle angular speed equals v/r radians per second, so motor angular speed is

$$\omega = G \frac{v}{r} \text{ rad s}^{-1} \quad (8.6)$$

and, similarly, motor angular acceleration is

$$\dot{\omega} = G \frac{a}{r} \text{ rad s}^{-2}$$

The torque required for this angular acceleration is

$$T = I \times G \frac{a}{r}$$

where I is the moment of inertia of the rotor of the motor. The force at the wheels needed to provide the angular acceleration ($F_{\omega a}$) is found by combining this equation with Equation (8.5), giving

$$F_{\omega a} = \frac{G}{r} \times I \times G \frac{a}{r} \quad \text{or} \quad F_{\omega a} = I \frac{G^2}{r^2} a \quad (8.7)$$

We must note that in these simple equations we have assumed that the gear system is 100% efficient – it causes no losses. Since the system will usually be very simple, the efficiency is often very high. However, it will never be 100%, and so we should refine the equation by incorporating the gear system efficiency η_g . The force required will be slightly larger, so Equation (8.7) can be refined to

$$F_{\omega a} = I \frac{G^2}{\eta_g r^2} a \quad (8.8)$$

Typical values for the constants here are 40 for G/r and 0.025 kg m^2 for the moment of inertia. These are for a 30kW motor, driving a car which reaches 60kph at a motor speed of 7000rpm. Such a car would probably weigh about 800kg. The IG^2/r^2 term in Equation (8.8) will have a value of about 40kg in this case. In other words, the angular acceleration force given by Equation (8.8) will typically be much smaller than the linear acceleration force given by Equation (8.4) In this specific (but reasonably typical) case, it will be smaller by the ratio

$$\frac{40}{800} = 0.05 = 5\%$$

It will quite often turn out that the moment of inertia of the motor I will not be known. In such cases a reasonable approximation is simply to increase the mass by 5% in Equation (8.4), and to ignore the $F_{\omega a}$ term.

6 Total Tractive Effort

The total tractive effort is the sum of all these forces

$$F_{te} = F_{rr} + F_{ad} + F_{hc} + F_{la} + F_{\omega a} \quad (8.9)$$

where:

- F_{rr} is the rolling resistance force, given by Equation (8.1)
- F_{ad} is the aerodynamic drag, given by Equation (8.2)
- F_{hc} is the hill climbing force, given by Equation (8.3)
- F_{la} is the force required to give linear acceleration given by Equation (8.4)
- $F_{\omega a}$ the force required to give angular acceleration to the rotating motor, given by Equation (8.8)

We should note that F_{la} and $F_{\omega a}$ will be negative if the vehicle is slowing down, and that F_{hc} will be negative if it is going downhill.

5. MODELING VEHICLE ACCELERATION:

1 Acceleration Performance Parameters

The acceleration of a car or motorcycle is a key performance indicator, though there is no standard measure used. Typically the time to accelerate from standstill to 60 mph, or 30 or 50 kph, will be given. The nearest to such a standard for electric vehicles are the 0–30 and 0–50 kph times, though these times are not given for all vehicles.

Such acceleration figures are found from simulation or testing of real vehicles. For IC engine vehicles this is done at maximum power. Similarly, for electric vehicles performance simulations are carried out at maximum torque.

the maximum torque of an electric motor is a fairly simple function of angular speed. In most cases, at low speeds, the maximum torque is a constant, until the motor speed reaches a critical value ω_c after which the torque falls.

In the case of a ‘brushed’ shunt or permanent magnet (PM) DC motor the torque falls linearly with increasing speed. In the case of most other types of motor, the torque falls in such a way that the power remains constant.

The angular velocity of the motor depends on the gear ratio G and the radius of the drive wheel r as in Equation (8.6) derived above. So, we can say that

$$\text{For } \omega < \omega_c, \text{ or } v < \frac{r}{G}\omega_c, \text{ then } T = T_{\max}$$

Once this constant torque phase is passed, that is $\omega \geq \omega_c$, or $v \geq (r/G)\omega_c$, then *either* the power is constant, as in most brushless type motors, and we have

$$T = \frac{T_{\max}\omega_c}{\omega} = \frac{rT_{\max}\omega_c}{Gv} \quad (8.10)$$

or the torque falls according to the linear equation we met in Section 7.1.2:

$$T = T_0 - k\omega$$

which, when Equation (8.6) is substituted for angular speed, gives

$$T = T_0 - \frac{kG}{r}v \quad (8.11)$$

Now that we have the equations we need, we can combine them in order to find the acceleration of a vehicle. Many of these equations may look quite complex, but nearly all the terms are constants, which can be found or estimated from vehicle or component data.

For a vehicle on level ground, with air density 1.25 kg m^{-3} , Equation (8.9) becomes

$$F_{te} = \mu_{rr}mg + 0.625AC_d v^2 + ma + I \frac{G^2}{\eta_g r^2} a$$

Substituting Equation (8.5) for F_{te} , and noting that $a = dv/dt$, we have

$$\frac{G}{r}T = \mu_{rr}mg + 0.625AC_d v^2 + \left(m + I \frac{G^2}{\eta_g r^2} \right) \frac{dv}{dt} \quad (8.12)$$

We have already noted that T , the motor torque, is either a constant or a simple function of speed [Equations (8.10) and (8.11)]. So, Equation (8.12) can be reduced to a differential equation, of first order, for the velocity v . Thus the value of v can be found for any value of t .

For example, in the initial acceleration phase, when $T = T_{\max}$, Equation (8.12) becomes

$$\frac{G}{r}T_{\max} = \mu_{rr}mg + 0.625AC_d v^2 + \left(m + I \frac{G^2}{\eta_g r^2} \right) \frac{dv}{dt} \quad (8.13)$$

Provided all the constants are known, or can reasonably be estimated, this is a very straightforward first-order differential equation, whose solution can be found using many modern calculators, as well as a wide range of personal computer programs. This is also possible for the situation with the larger motors.

6. MODELING ELECTRIC VEHICLE RANGE:

1 Driving Cycles

It is well known that the range of electric vehicles is a major problem. In the main this is because it is so hard to store electrical energy efficiently. In any case, this problem is certainly a critical issue in the design of any electric vehicle. There are two types of calculation or test that can be performed with regard to the range of a vehicle.

The first, and much the simplest, is the constant velocity simulation. Of course no vehicle is really driven at constant velocity, especially not on level ground, and in still air, which are almost universal further simplifications for these tests. However, at least the rules for the test are clear and unambiguous, even if the simulation is unrealistic. It can be argued that they do at least give useful comparative figures.

The second type of test – more useful and complex – is where the vehicle is driven, in reality or in simulation, through a profile of ever-changing speeds. These test cycles have been developed with some care, and there are (unfortunately) a large number of them. The cycles are intended to correspond to realistic driving patterns in different conditions. During these tests the vehicle speed is almost constantly changing, and thus the performance of all the other parts of the system is also highly variable, which makes the computations more complex. However, modern computer programs make even these more complex situations reasonably straightforward.

2 Range Modelling of Battery Electric Vehicles

2.1 Principles of Battery Electric Vehicle Modelling

The energy flows in a classical battery electric vehicle are shown in Figure 8.13. To predict the range, the *energy* required to move the vehicle for each second of the driving cycle is calculated, and the effects of this energy drain are calculated. The process is repeated until the battery is flat. It is important to remember that if we use time intervals of 1 second, then the *power* and the *energy consumed* are equal.

The starting point in these calculations is to find the tractive effort, which is found from Equation (8.9) The power is equal to the tractive effort multiplied by the velocity. Using the various efficiencies in the energy flow diagram, the energy required to move the vehicle for 1 second is calculated.

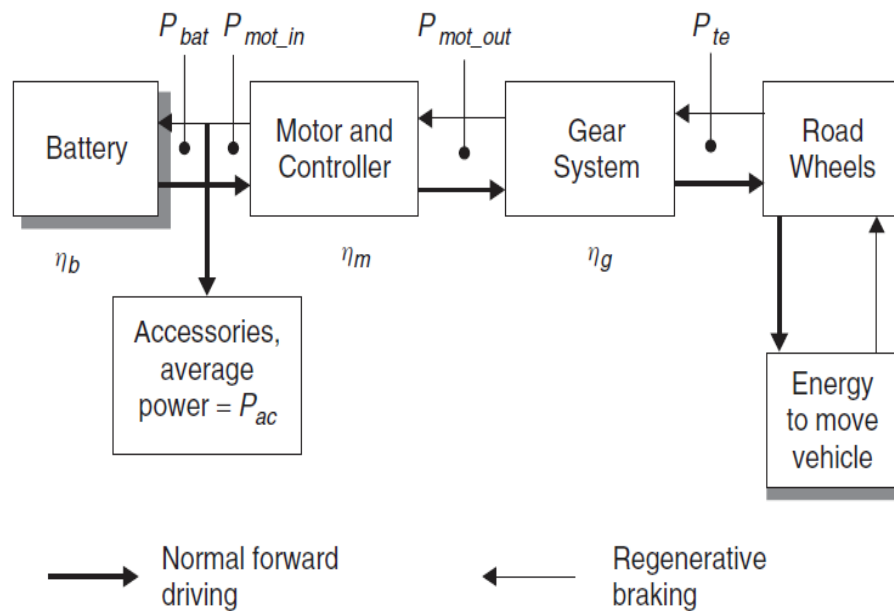


Figure 8.13 Energy flows in the ‘classic’ battery-powered electric vehicle, which has regenerative braking

The energy required to move the vehicle for 1 second is the same as the power, so

$$\text{Energy required each second} = P_{te} = F_{te} \times v \quad (8.23)$$

To find the energy taken from the battery to provide this energy at the road we clearly need to be able to find the various efficiencies at all operating points. Equations that do this have been developed in the previous chapters, but we will review here the most important system modelling equations.

2.2 Modelling Equations

The efficiency of the gear system η_g is normally assumed to be constant, as in electric vehicles there is usually only one gear. The efficiency is normally high, as the gear system will be very simple.

The efficiencies of the motor and its controller are usually considered together, as it is more convenient to measure the efficiency of the whole system.

that motor efficiency varies considerably with power, torque and also motor size. The efficiency is quite well modelled by the equation

$$\eta_m = \frac{T\omega}{T\omega + k_c T^2 + k_i \omega + k_w \omega^3 + C} \quad (8.24)$$

Table 8.2 Typical values for the parameters of Equation (8.24)

Parameter	‘Lynch’-type PM motor, with brushes, 2–5 kW	100 kW, high-speed induction motor
k_c	1.5	0.3
k_i	0.1	0.01
k_w	10^{-5}	5.0×10^{-6}
C	20	600

where k_c is the copper losses coefficient, k_i is the iron losses coefficient, k_w is the windage loss coefficient and C represents the constant losses that apply at any speed.

The inefficiencies of the motor, the controller and the gear system mean that the motor's power is not the same as the traction power, and the electrical power required by the motor is greater than the mechanical output power according to the simple equations

$$P_{mot_in} = \frac{P_{mot_out}}{\eta_m} \quad P_{mot_out} = \frac{P_{te}}{\eta_g} \quad (8.25)$$

Equations 8.25 are correct in the case where the vehicle is being driven. However, if the motor is being used to slow the vehicle, then the efficiency (or rather the inefficiency) works in the opposite sense. In other words, the electrical power from the motor is reduced, and we must use these equations:

$$P_{mot_in} = P_{mot_out} \times \eta_m \quad P_{mot_out} = P_{te} \times \eta_g \quad (8.26)$$

So, Equations 8.25 or 8.26 are used to give us the electrical and mechanical power to (or from) the motor. However, we also need to consider the other electrical systems of the vehicle, the lights, indicators, accessories such as the radio, and so on. An average power will need to be found or estimated for these, and added to the motor power, to give the total power required from the battery. Note that when braking, the motor power will be negative, and so this will reduce the magnitude of the power:

$$P_{bat} = P_{mot_in} + P_{ac} \quad (8.27)$$

2.3 Other uses of Simulations

The data produced during these simulations has many more uses than just predicting the range of a vehicle. At each 1 second step of the cycle many variables were calculated, including:

- vehicle acceleration
- tractive effort
- motor power
- motor torque
- motor angular speed
- motor power
- motor efficiency
- current out of (or into) the battery.

All of these variables are of interest, and it is instructive to plot them over one cycle. This can be done with great simplicity in MATLAB®, and gives very useful results. The basic principle is to create two arrays, with names such as XDATA and YDATA, and allocate then values during a cycle.

7. AERODYNAMIC CONSIDERATIONS

1 Aerodynamics and Energy

It is well known that the more aerodynamic a vehicle is, the lower is its energy consumption. Bearing in mind the high cost of onboard electrical energy, the aerodynamics of electric vehicles is particularly important, especially at high speeds.

Let us first consider the effect of aerodynamic drag. the drag force F_{ad} on a vehicle is

$$F_{ad} = \frac{1}{2} \rho A C_d v^2 \quad (9.1)$$

and the power P_{adw} (W) at the vehicle's wheels required to overcome this air resistance is

$$P_{adw} = F_{adw} \times v = \frac{1}{2} \rho A C_d v^3 \quad (9.2)$$

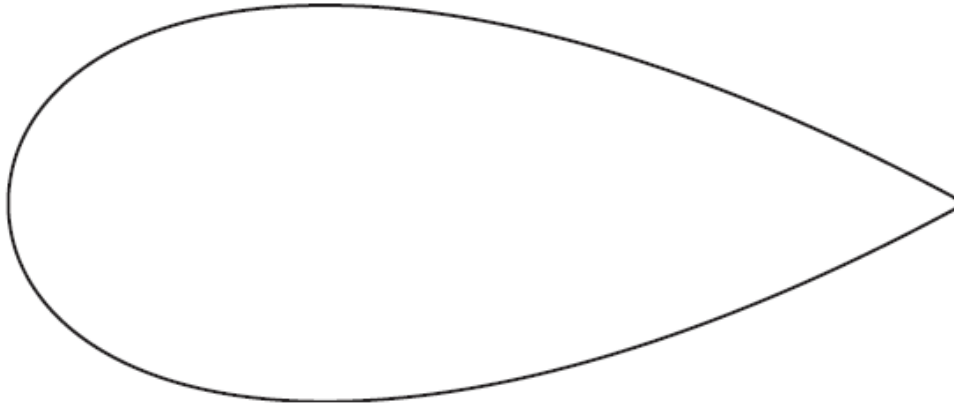


Figure 9.1 Aerodynamic ideal shape, a ‘teardrop’ of aspect ratio 2.4

where ρ is the density of air (kg m^{-3}), A is the frontal area (m^2), v is the velocity (m s^{-1}) and C_d is the drag coefficient, which is dimensionless.

The ideal aerodynamic shape is a teardrop, as achieved by a droplet of water freefalling in the atmosphere and illustrated in Figure 9.1. The coefficient of drag varies with the ratio of length to diameter, and having the lowest value of $C_d = 0.04$ when the ratio of the length to diameter is 2.4. Using Equation (9.2) and taking air density to be 1.23 kg m^{-3} , the power required to drive a teardrop-shaped body with $C_d = 0.04$ of cross-section 1 m^2 travelling at 100 kph (27.8 m s^{-1}) in clear air will be 664 W . If engineers and scientists could achieve such aerodynamic vehicle shapes they would revolutionise energy in transport. Unfortunately they cannot get near such a low value. However, the ideal teardrop shape is normally an ‘aiming point’ for vehicle aerodynamicists.

In reality the drag coefficients of vehicles are considerably higher due to various factors, including the presence of the ground, the effect of wheels, body shapes which vary from the ideal, and irregularities such as air inlets and protrusions.

The aerodynamic drag coefficient for a saloon or hatchback car normally varies from 0.3 to 0.5, while that of a reasonably aerodynamic van is around 0.5. For example, a Honda Civic hatchback has a frontal area of 1.9 m^2 and a drag coefficient of 0.36. This can be reduced further by careful attention to aerodynamic detail. Good examples are the Honda Insight hybrid electric car, with a C_d of 0.25, and the General Motors EV1 electric vehicle with an even lower C_d of 0.19. The Bluebird record-breaking electric car had a C_d of 0.16.

As the drag, and hence the power consumed, is directly proportional to the drag coefficient, a reduction of C_d from 0.3 to 0.19 will result in a reduction in drag of $0.19/0.3$, that is 63.3%. In other words, the more streamlined vehicle will use 63.3% of the energy to overcome aerodynamic drag compared with the less aerodynamic car. For a given range, the battery capacity needed to overcome aerodynamic resistance will be 36.7% less. Alternatively the range of the vehicle will be considerable enhanced.

The battery power P_{adb} needed to overcome aerodynamic drag is obtained by dividing the overall power delivered at the wheels P_{adw} by the overall efficiency η_0 (power at wheels/battery power):

$$P_{adb} = \frac{P_{adw}}{\eta_0} = \frac{\frac{1}{2} \rho A C_d v^3}{\eta_0} \quad (9.3)$$

The battery mass m_b (kg) of a battery with specific energy SE (Wh kg^{-1}) required to overcome the aerodynamic drag at a velocity v (m s^{-1}) over a distance d (m) is given by

$$m_b = \frac{P_{adb} \times d}{v \times SE \times 3600} \quad (\text{kg}) \quad (9.4)$$

The variation of battery power P_{adb} for overcoming aerodynamic drag with speed is shown in Figure 9.2 for vehicles of different drag coefficients and different frontal areas. The battery mass required to provide energy to overcome aerodynamic drag for a vehicle with a range of 100 km travelling at different constant speeds is shown in Figure 9.3. An efficiency η_0 of 0.7 is used. Figure 9.3 dramatically illustrates the importance of streamlining, as the battery weight shown in this graph is purely that needed to overcome wind resistance, and for the not very impressive range of 100 km. Figure 9.3 also clearly shows how ill-suited battery electric vehicles are to high-speed driving. Even a well-designed car, with a C_d of 0.19, still needs about 400 kg of lead acid batteries just to overcome wind resistance to travel for 100 km when going at 160 kph.

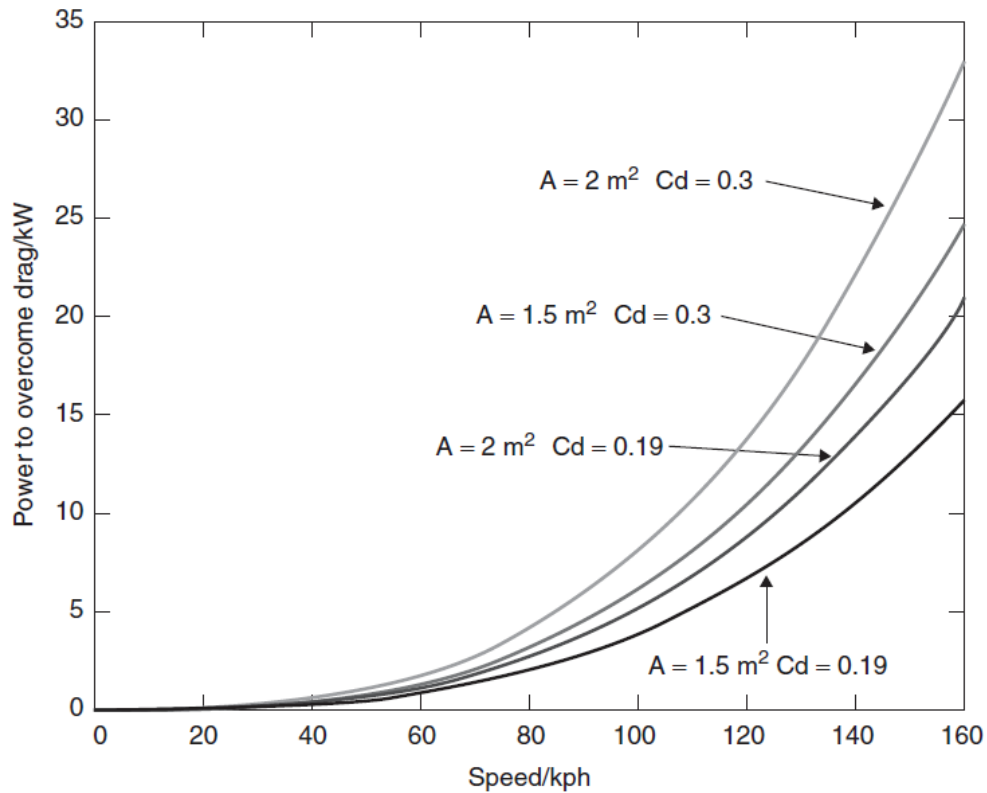


Figure 9.2 Power requirement to overcome aerodynamic drag for vehicle of different frontal areas and drag coefficients for a range of speeds up to 160 kph

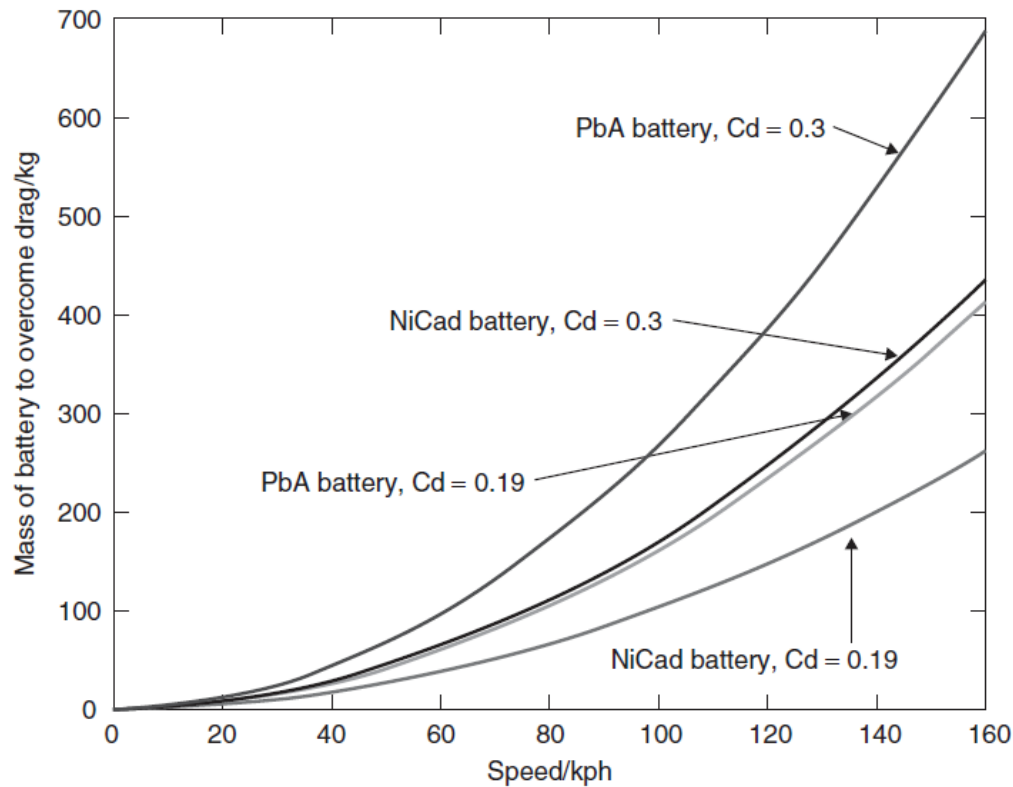


Figure 9.3 The effect of drag coefficient and speed on battery mass. The vehicles all have a frontal area of 1.5 m^2 , and the range is 100 km. The mass is only for the energy required to store the energy to overcome aerodynamic drag – the actual battery mass would need to be higher

It is clear from both Figures 9.2 and 9.3 that there are huge advantages in keeping both the aerodynamic resistance and the vehicle frontal area as low as possible. Bearing in mind the considerable cost saving on both battery weight and battery cost, it is well worth paying great attention to the aerodynamic details of the chassis/body. There is great scope for producing streamlined shapes with battery electric vehicles as there is much more flexibility in placing major components and there is less need for cooling air ducts and under-vehicle exhaust pipes. Similarly, as well as keeping the coefficient of drag low, it is equally important to keep down the frontal area of the vehicle if power requirements are to be minimised. While the car needs to be of sufficient size to house the passengers in comfort, the greater flexibility in which components can be placed in an electric car can be used to minimise frontal area.

Some consideration also needs to be given to items such as wing mirrors, aerials and windscreen wipers. These need to be designed to minimise the drag. Aerials do not need to be external to the car body and wing mirrors can be replaced by electronic video systems that can be contained within the aerodynamic envelope of the car. While the latter may appear an expensive option at first, the reduced drag will result in a lighter battery with associated cost savings.

2. Body/Chassis Aerodynamic Shape:

The aerodynamic shape of the vehicle will depend largely on the type of use to which the electric vehicle is to be put. If it is a city commuter car or van that will be driven at relatively low speeds, the aerodynamics are much less important than on a conventional vehicle which will be used for motorway driving. For the latter type of vehicle, to be used at relatively high speeds, a low frontal area and streamlining are vitally important. It is worth having a look at how this was achieved with vehicles such as the Honda Insight hybrid ($C_d = 0.25$) and the GM EV1 battery car ($C_d = 0.19$). While the aerodynamics of high-speed battery electric vehicles are vitally important, they are also important for hybrid vehicles, but optimisation can result in a slightly less aerodynamic vehicle with more reliance being placed on the IC engine to achieve range.

Most aerodynamic vehicles at least attempt to copy the teardrop shape and this is true of both these two vehicles. The body shape is also designed to keep the air flow around the vehicle laminar.

8. IDEAL GEARBOX STEADY STATE MODEL:

The EV transmission equations will be established assuming ideal gearbox assumptions, which are as follows:

1. $P_{losses} = 0 \Rightarrow \text{Efficiency} = 100\%$
2. Perfectly rigid gears
3. No gear backlash (i.e., no space between teeth)

1. GEAR RATIO (GR)

For a disk with radius r , the tangential and the angular velocity are related by

$$r_{in} \omega_{in} = v = r_{out} \omega_{out}$$

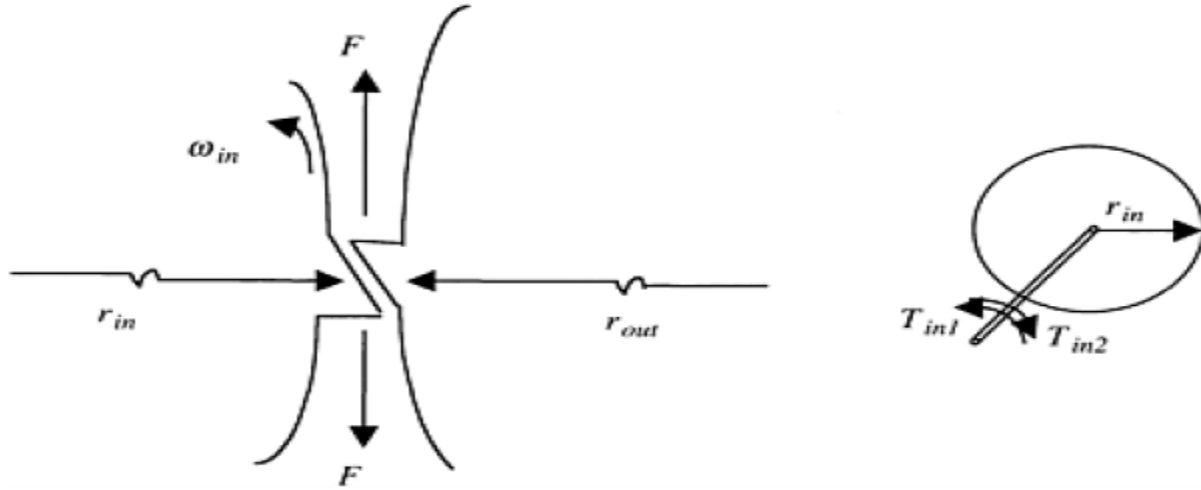


FIGURE : Force and torque working in a gear

The gear ratio is defined in terms of the ratio of speed transformation between the input shaft and the output shaft.

$$GR = \frac{\omega_{in}}{\omega_{out}} = \frac{r_{out}}{r_{in}} \quad (9.1)$$

Assuming 100% efficiency of the gear train:

$$\begin{aligned} P_{out} &= P_{in} \\ \Rightarrow T_{out} \omega_{out} &= T_{in} \omega_{in} \end{aligned}$$

The gear ratio in terms of the torque at the two shafts is

$$GR = \frac{T_{out}}{T_{in}} = \frac{\omega_{in}}{\omega_{out}} \quad (9.2)$$

The gear ratio can be alternately derived with the help of Figure above. At the point of gear mesh, the supplied and delivered forces are the same. This is an example of Newton's third law of motion, which states that every action has an equal and opposite reaction. The torque at the shaft is the force at the mesh divided by the radius of the disk. In the two-gear combination, the torque ratio between the two gears is proportional to the ratio of gear disk radii. The torque of the inner disk in

terms of its radius and force at the gear mesh is

Similarly, for the other disk with radius r_{out} , the force at the gear mesh is

$$F = \frac{T_{out}}{r_{out}}$$

Therefore, the gear ratio is

$$GR = \frac{T_{out}}{T_{in}} = \frac{r_{out}}{r_{in}} \quad (9.3)$$

2 TORQUE-SPEED CHARACTERISTICS

The electric motor is typically designed to operate at higher speeds to minimize the size of the motor. The gearbox functions as a torque multiplier to deliver high torque at a reduced speed at the vehicle wheels. The advantage of using a gear will be shown through a DC motor-driven EV system. Let the overall gear ratio between the electric motor and the vehicle wheel be GR with ω_m and let T_m represent the motor speed and torque, respectively. The speed and torque at the wheels are ω_{out} and T_{out} , respectively. Part of the drivetrain for the EV is shown in [Figure 9.7](#). For a separately excited DC motor, the speed-torque relationship at steady state is

$$\omega_m = \frac{V_t}{k\phi} - \frac{R_a}{(k\phi)^2} T_m \quad (9.4)$$

However,

$$\frac{\omega_m}{\omega_{out}} = GR = \frac{T_{out}}{T_m}$$

Substituting in Equation 9.4,

$$\omega_{out} = \frac{V_t}{GR(k\phi)} - \frac{R_a}{(GRk\phi)^2} T_{out} \quad (9.5)$$

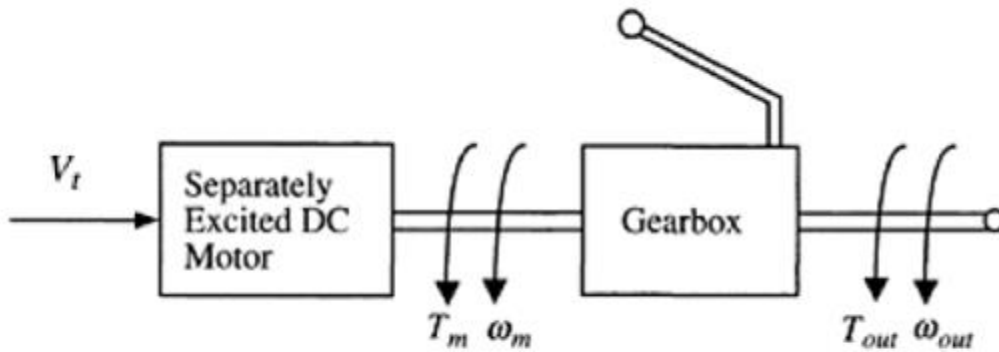


FIGURE 9.7 Connection of a gear with the motor.

9. EV MOTOR SIZING:

Electric motors have three major segments in its torque-speed characteristics: constant torque region, constant power regions, and natural mode region. The envelope of the electric motor torque-speed characteristics is shown in Figure 9.10. The motor delivers rated torque up to the base speed or rated speed pm of the motor when it 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. Electric motors can operate at speeds higher than rated using field weakening in the constant power region. There is a third natural mode region for high motor speeds, where the torque falls rapidly, being inversely proportional to the square of the speed. The natural characteristic region can be an important part of the overall torque-speed curve of certain motors that can be used to reduce the power rating of the motor. However, in most cases, the vehicle's maximum speed is considered to be at the end of the constant power region. Note that the curves in Figure 9.10 show the envelope, i.e., the operating torque and speed limits in different regions.

The electric motor can operate at any point within the envelope through the feed from a power electronics based motor drive component. The salient feature of wide-operating speed range characteristics of an electric motor makes it possible to eliminate multiple gear ratios and the clutch in EV and other applications. A single

gear ratio transmission is sufficient for linking the electric motor with the driveshaft. Electric motors with extended constant power region characteristics are what is needed to minimize the gear size in EVs.

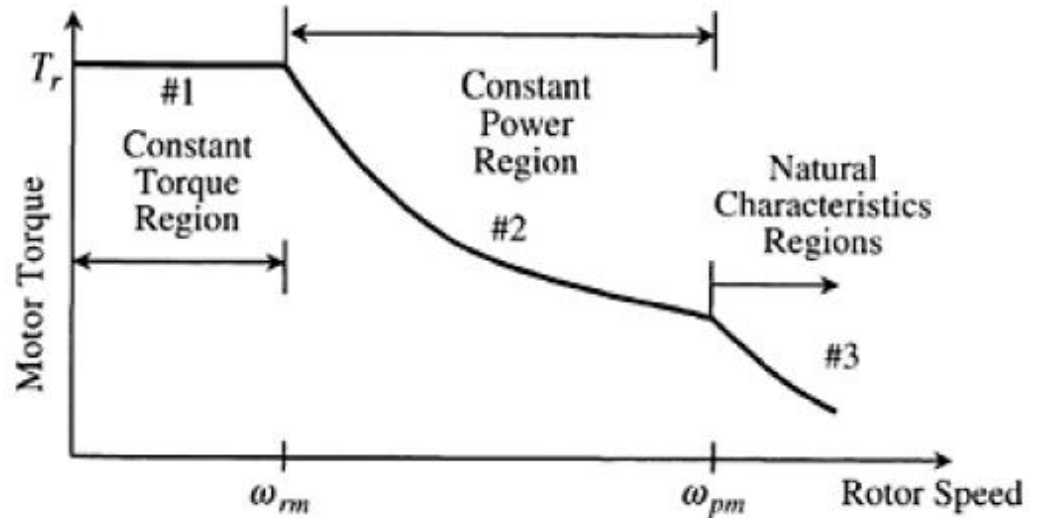


FIGURE 9.10 Electric motor torque-speed envelope.

The size of an electric motor depends on the maximum torque required from the machine. The higher the maximum torque required, the larger will be the size of the motor. In order to minimize the size and weight, electric motors are designed for high-speed operation for a given power rating. Gears are used to match the higher speed of the electric motor with the lower speed of the wheels. Typical motor speeds can be in the vicinity of 15,000 rev/m for typical wheel speeds of around 1000 rev/m for lightweight passenger vehicles. The transmission gear achieves this speed reduction in the range of ~ 10 to $15:1$, typically in two stages of 3 to $4:1$ of speed reduction. The gear sizing depends on whether the low speed or the high speed performance of the EV is more important based on the power rating determined for the EV.

The tractive force vs. speed characteristics of the propulsion system can be widely different for two gear ratios, as shown in Figure 9.11. Note that the rated speeds shown are for the drivetrain unit comprising the electric motor and transmission system, and that the electric motor rated speed is different from these values. The electric motor speed can first be converted into drivetrain unit speed or vehicle wheel speed using the gear ratio.

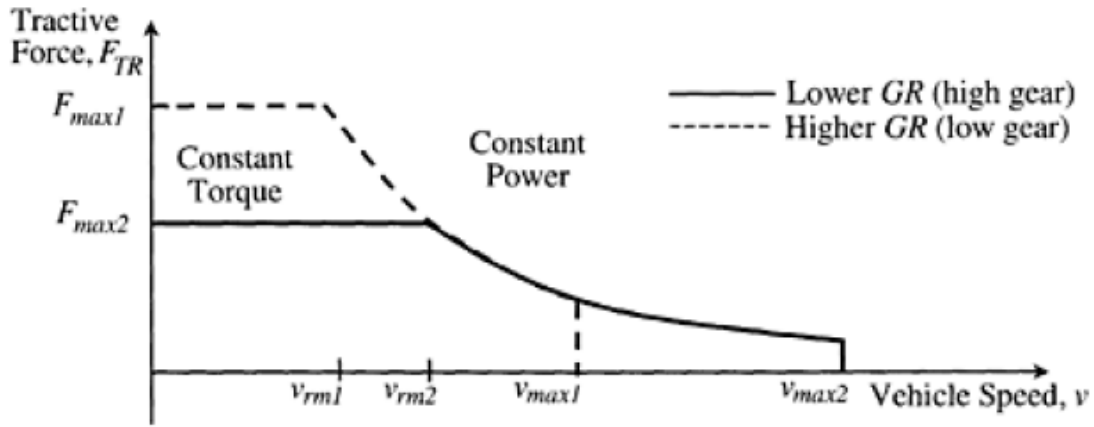


FIGURE 9.11 Electric motor torque-speed characteristics in terms of traction force and vehicle speed for two gear ratios.

The motor rated speed at the wheel $r_{m,wh}$ in rad/s can be converted to linear vehicle speed using $v_{rm} = r_{m,wh} \cdot r_{wh}$, where r_{wh} is the radius of the wheel. The symbol v_{rm} is referred to here as the equivalent vehicle linear speed after accounting for the transmission gear and the wheel radius. A higher wheel speed or vehicle speed can be attained with a smaller gear ratio, but the peak traction force that the drivetrain can deliver will be smaller. The smaller traction force will limit the initial acceleration and maximum gradability capabilities of the vehicle. On the other hand, if a high gear ratio is used in the transmission for the same electric motor, the peak tractive force available at the wheels will be higher, but the maximum vehicle speed v_{max} will be limited. Therefore, we can conclude that the gear ratio depends on the rated motor speed, vehicle rated speed, vehicle maximum speed, wheel radius, and maximum gradability. It must be observed that a higher gear ratio entails a larger gear size. Therefore, the gear ratio and the electric motor rated speed must be selected simultaneously to optimize the overall size and performance requirements.

The complete design of the powertrain is a complex issue involving numerous variables, such as rated motor power P_m , rated motor speed, r_m , rated wheel speed, f_{wh} , rated vehicle speed v_f etc., and numerous system parameters, such as vehicle total mass, rolling resistance coefficient, aerodynamic drag coefficient, etc. The design process starts with a set of known parameters and some educated estimate and ends with final design values that meet the requirements after several iterations. In the following, the design of the electric motor will be discussed in view of the specified requirements of the initial acceleration, rated velocity on a given slope, maximum steady state velocity, and maximum gradability.

9.1 INITIAL ACCELERATION

The initial acceleration is specified as 0 to v_f in t_f s. v_f is the vehicle rated speed obtained from $v_f = f_{wh} r_{wh}$. The design problem is to solve for F_{TR} starting with a set of parameters including vehicle mass, rolling resistance, aerodynamic drag coefficient, percent grade, wheel radius, etc., some of which are known, while others

have to be assumed. The acceleration of the vehicle in terms of these variables is given by Equation

$$a = \frac{dv}{dt} = \frac{F_{TR} - F_{RL}}{m}$$

The motor power rating can be obtained by solving the above differential equation for a given force-velocity profile, such as one of the two shown in Figure 9.11, and the following boundary conditions:

At $t=0$, vehicle velocity $v=0$.

At $t=t_f$, vehicle velocity $v=v_f$.

Integrating the differential equation within the interval $t=0$ to $t=t_f$ for velocities 0 to v_f

$$m \int_0^{v_f} \frac{dv}{F_{TR} - F_{RL}(v)} = \int_0^{t_f} dt$$

The rated vehicle velocity is higher than the rated motor velocity and lies in the constant power region of motor torque-speed characteristics. Splitting the integral on the left side into two velocity regions of 0- v_{rm} for the constant torque mode and of v_{rm} - v_f for the constant power mode, one can write:

$$m \int_0^{v_{rm}} \frac{dv}{\frac{P_m}{v_{rm}} - F_{RL}(v)} + m \int_{v_{rm}}^{v_f} \frac{dv}{\frac{P_m}{v} - F_{RL}(v)} = t_f \quad (9.6)$$

The road load resistance force F_{RL} can be expressed as a function of velocity, for given values of rolling resistance, aerodynamic drag force, and roadway slope. Equation 9.6 can then be solved for motor power rating P_m for specified vehicle-rated velocity v_f and rated motor speed. Note that Equation 9.6 is a transcendental equation with F_{RL} being a function of velocity and can be solved numerically to find the motor power rating P_m . In fact, extensive computer computation and simulation aids a practical design to derive the required motor power rating and gear ratio of the powertrain.

9.2 RATED VEHICLE VELOCITY

The drivetrain designed to accelerate the vehicle from zero to rated velocity will always have sufficient power to cruise the vehicle at rated speed, provided the roadway slope specified for initial acceleration has not been raised for rated velocity cruising conditions.

9.3 MAXIMUM VELOCITY

The tractive power required to cruise the vehicle at maximum vehicle velocity v_{max} is

$$P_{TR,max} = mgv_{max} \sin\beta + \left[mgC_1 + \frac{P}{2} A_F C_D \right] v_{max}^3 + mgv_{max} C_0 \quad (9.8)$$

The dominant resistance force at high speeds is the aerodynamic drag force, with the power requirement to overcome it increasing at a cubic rate. For vehicles designed with fast acceleration characteristics, P_m is likely to be greater than $P_{TR,max}$. If $P_{TR,max} > P_m$ derived earlier to meet the initial acceleration requirement, then $P_{TR,max}$ will define the electric motor power rating. The natural mode region of electric motors can be used to meet very high maximum vehicle velocity requirements to minimize the motor size.

9.4 MAXIMUM GRADABILITY

The maximum gradability of a vehicle for a given motor and gear ratio can be derived from

$$\text{Max. \% grade} = \frac{100 F_{TR}}{\sqrt{(mg)^2 - F_{TR}^2}}$$

The maximum tractive force F_{TR} available from the preliminary motor design can be plugged into the above equation to check whether the vehicle maximum gradability conditions are met or not. If the maximum electric motor power derived for acceleration or maximum vehicle velocity is not enough to meet the maximum gradability requirement of the vehicle, then either the motor power rating or the gear ratio has to be increased. Care must be taken not to violate the maximum vehicle velocity requirement when increasing the gear ratio. The gear ratio and motor power are decided in a coordinated manner to meet both requirements, while maintaining a reasonable size for both the electric motor and the gear.

10. GENERAL ISSUES IN DESIGN:

10.1 Design Specifications:

A vehicle to be used in airport buildings clearly requires much less corrosion protection than one to be used on a seaside pier and constantly subjected to saltwater spray. Obviously, where vehicles may be used in different environments, the worst case must be allowed for.

The main areas which need specifying for an electric vehicle are range, speed, acceleration, type of use, for example passenger commuter car or around town delivery van, performance uphill, legal requirements and target cost (both production and sales). Other parameters that need specifying include life, maintenance requirements, environment, emissions (in the case of a hybrid), aesthetics and comfort. The design specification must be written bearing in mind technical facts. A battery electric car with a range of 350 miles (560 km) and a mass of 500 kg and costing £1000 is clearly impossible using today's and foreseeable future technology.

10.2 Software in the use of Electric Vehicle Design:

Finite element packages have already been mentioned, and these will give accurate predictions of strength, rigidity and precisely how the body/chassis deforms under load, the dynamics of the body/chassis, and how and where it will vibrate, as well as an accurate prediction (within 1%) of how it will crumple in a crash. Likewise the aerodynamic behavior of the vehicle can be predicted reasonably

accurately using CFD analysis packages. The actual car will be designed using powerful computer-aided design (CAD) programs, and the car will be manufactured using computer-aided manufacturing (CAM). Normally, large integrated packages containing all of these and using common data from the CAD files are used. Moulds and press tools for bodywork panels, for example, will be machined from the CAD data that has defined their shape. These will previously have been analyzed for air flow using CFD and for strength, rigidity, natural vibration and behavior in a crash using finite element methods.

UNIT 3 ENERGY SOURCES

Electric Vehicle Power Source - Battery Capacity, State of Charge and Discharge, Specific Energy, Specific Power, Ragone Plot. Battery Modeling - Run Time Battery Model, First Principle Model, Battery Management System- Soc Measurement, Battery Cell Balancing. Traction Batteries - Nickel Metal Hydride Battery, Li-Ion, Li-Polymer Battery

1. ENERGY SOURCES: BATTERY

A basic requirement for electric vehicles (EVs) is a portable source of electrical energy, which is converted to mechanical energy in the electric motor for vehicle propulsion. Electrical energy is typically obtained through conversion of chemical energy stored in devices such as batteries and fuel cells. A flywheel is an alternative portable source in which energy is stored in mechanical form to be converted into electrical energy on demand for vehicle propulsion. The portable electrical energy source presents the biggest obstacle in commercialization of EVs. A near-term solution for minimizing the environmental pollution problem due to the absence of a suitable, high-energy-density energy source for EVs is perceived in the hybrid electric vehicles (HEVs) that combine propulsion efforts from gasoline engines and electric motors.

A comparison of the specific energy of the available energy sources is given in Table 3.1. The specific energy is the energy per unit mass of the energy source. The specific energies are shown without taking containment into consideration. The specific energy of hydrogen and natural gas would be significantly lower than that of gasoline when containment is considered.

Among the available choices of portable energy sources, batteries have been the most popular choice of energy source for EVs since the beginning of research and development programs in these vehicles. The EVs and HEVs commercially available today use batteries as the electrical energy source. The various batteries are usually compared in terms of descriptors, such as specific energy, specific power, operating life, etc. Similar to specific energy, specific power is the power available per unit mass from the source. The operating life of a battery is the number of deep discharge cycles obtainable in its lifetime or the number of service years expected in a certain application. The desirable features of batteries for EV and HEV applications are high specific power, high specific energy, high charge acceptance rate for recharging and

regenerative braking, and long calendar and cycle life. Additional technical issues include methods and designs to balance the battery segments or packs electrically and thermally, accurate techniques to determine a battery's state of charge, and recycling facilities of battery components. And above all, the cost of batteries must be reasonable for EVs and HEVs to be commercially viable.

Battery technology has been undergoing extensive research and development efforts over the past 30 years, yet there is currently no battery that can deliver an acceptable combination of power, energy, and life cycle for high-volume production vehicles. The small number of EVs and HEVs that were introduced in the market used batteries that were too expensive and have short calendar life, making the batteries the biggest impediment in commercializing EVs and HEVs.

TABLE 1: Nominal Energy Density of Sources

<u>Energy Source</u>	<u>Nominal Specific Energy (Wh/kg)</u>
Gasoline	12,500
Natural gas	9350
Methanol	6050
Hydrogen	33,000
Coal (bituminous)	8200
Lead-acid battery	35
Lithium-polymer battery	200

2. ELECTRIC VEHICLE POWER SOURCE:

Electric Vehicle Power Source are Battery & Engine.

3. BATTERY CAPACITY:

The amount of charge released by the energized material at an electrode associated with complete discharge of a battery is called the **BATTERY CAPACITY**. The capacity is measured in Ah (1 Ah = 3,600 C or Coulomb, where 1 C is the charge transferred in 1 s by 1 A current in the SI unit of charge).

The theoretical capacity of a battery can be obtained Faraday's law of electrolysis which states that the mass of the elemental material altered at an electrode is directly proportional to the element's equivalent weight for a given quantity of electrical charge. The equivalent weight of the

elemental material is given by the molar mass divided by the number of electrons transferred per ion for the reaction undergone by the material. This number is known as the valency number of ions for the substance. Mathematically, Faraday's law can be written as

$$m_R = \frac{Q}{F} \frac{M_m}{n}$$

where m_R is the mass of the limiting reactant material altered at an electrode, Q is the total amount of electric charge passing through the material, F is the Faraday number or Faraday constant, M_m is the molar mass and n is the number of electrons per ion produced at an electrode. M_m / n is the equivalent weight of the reactant substance. The Faraday number is given by the amount of electric charge carried by one mole of electrons. The number of molecules or atoms in a mole is given by the Avogadro number N_A which is equal to $6.022045 \times 10^{23} \text{ mol}^{-1}$. The amount of charge in one electron which is the elemental charge is equal to $e_0 = 1.6021892 \times 10^{-19} \text{ C}$. Therefore, the Faraday number is equal to $F = N_A e_0 = 96,485 \text{ C/mol}$. The number of Faradays required to produce one mole of substance at an electrode depends on the way in which the substance is oxidized or reduced.

Therefore, the theoretical capacity of a battery (in Coulomb) can be obtained as

$$Q_T = xnF \text{ C}$$

where x is the number of moles of limiting reactant associated with complete discharge of battery, and is given by

$$x = \frac{m_R}{M_m}.$$

Here m_R is the mass of the reactant material in kg and M_m is the molar mass of that material in g/mol. The theoretical capacity in Ah is

$$Q_T = 0.278F \frac{m_R n}{M_m} \text{ Ah}$$

The cells in a battery are connected in series and the capacity of the battery is dictated by the smallest cell capacity. Therefore, $Q_{\text{Tbattery}} = Q_{\text{Tcell}}$.

4. STATE OF CHARGE AND DISCHARGE:

4.1 State of Charge:

The *state of charge* (SoC) represents the present capacity of the battery. It is the amount of capacity that remains after discharge from a top-of-charge condition. The current is the rate of change of charge given by

$$i(t) = \frac{dq}{dt}$$

where q is the charge moving through the circuit. The instantaneous theoretical state of charge $SoC_T(t)$ is the amount of equivalent charge remaining at the positive electrode and ready to be released by the energized material. If the state of charge is Q_T at the initial time t_o , then $SoC_T(t_o) = Q_T$. For a time interval dt ,

$$\begin{aligned} dSoC_T &= -dq \\ &= -i(t)dt \end{aligned}$$

Integrating from the initial time t_o to the final time t , the expression for instantaneous state of charge is obtained as

$$SoC_T(t) = Q_T - \int_{t_o}^t i(\tau) d\tau \quad (5.8)$$

The state of charge is often expressed as a percentage of the capacity of the battery as follows:

$$SoC_T(t) = \frac{Q_T - \int_{t_o}^t i(\tau) d\tau}{Q_T} \times 100\%$$

The state of charge will be increasing when a battery is being charged. If the state of charge is zero initially at $t = 0$, the state of charge at time t expressed in percentage form is given by

$$SoC_T(t) = \frac{\int_0^t i(\tau) d\tau}{Q_T} \times 100\%$$

4.2 State of Discharge:

The *state of discharge* (SoD) is a measure of the charge that has been drawn from a battery during discharge. Mathematically, state of discharge is given as

$$SoD_T(t) = \Delta q = \int_{t_0}^t i(\tau) d\tau$$
$$\Rightarrow SoC_T(t) = Q_T - SoD_T(t).$$

4.3 Depth of Discharge:

The *depth of discharge* (DoD) is the percentage of battery rated capacity to which a battery is discharged. The depth of discharge is given by

$$DoD(t) = \frac{Q_T - SoC_T(t)}{Q_T} \times 100\%$$
$$= \frac{\int_{t_0}^t i(\tau) d\tau}{Q_T} \times 100\%$$

The withdrawal of at least 80% of battery (rated) capacity is referred to as deep discharge.

5. SPECIFIC ENERGY:

The *specific energy* of a battery in terms of discharge energy related to complete discharge from fully charged condition is given by

$$SE = \frac{\text{Discharge Energy}}{\text{Total Battery Mass}} = \frac{E}{M_B}$$

The unit for specific energy is Wh/kg. The theoretical specific energy of a battery using Equation 5.9 is

$$SE_T = 9.65 \times 10^7 \times \frac{nV_{bat}}{M_m} \frac{m_R}{m_B} \text{ Wh/kg}$$

If the mass of the battery M_B is proportional to the mass of the limiting reactant of the battery m_R , then SE_T is independent of mass. The specific energy of lead acid battery is 35–50 Wh/kg at C/3 rate. Since practical energy E_p varies with discharge rate, the practical specific energy SE_p is also variable.

The term ‘energy density’ is also used in the literature to quantify the quality of a battery or other energy sources. The term energy density refers to the energy per unit volume of a battery. The unit for energy density is Wh/L.

6. SPECIFIC POWER:

The *specific power* of a battery is

$$SP = \frac{P}{M_B} \text{ (units: W/kg)}$$

where P is the power delivered by battery and M_B is the mass of battery. Typically, lead acid battery’s maximum specific power is around 280 W/kg (which corresponds to P_{max}) at DoD = 80%. Similar to specific energy and energy density, the term power density is used to refer to the power of the battery per unit volume with units of W/L.

7. RAGONE PLOT:

In electrochemical batteries, there is a decrease in charge capacity (excluding voltage effects) with increasing currents. This is often referred to as the *Ragone* relationship and is described by *Ragone plots*. Ragone plots are usually obtained from constant power discharge tests or constant current discharge plots. Let us consider the experiment of Figure 5.6 again, but this time the current i is adjusted by varying R_L such that the power output at the battery terminals is kept constant. The experiment stops when the battery terminal voltage reaches the cut-off voltage, i.e., $V_t = V_{cut}$. We assume that the battery is fully charged at $t = 0$. The experiment is performed at several power levels and the following data is recorded: (i) power $p(t) = V_t i = P$, (ii) time to cut-off voltage t_{cut} and (iii) practical energy $E_p = P t_{cut}$. The plot of SP versus SE on a log-log scale is known as the Ragone plot. The Ragone plots of several batteries along with alternative energy sources and IC engines are given in Figure 5.10 to give an idea about the relative power and energy capacities of these different devices.

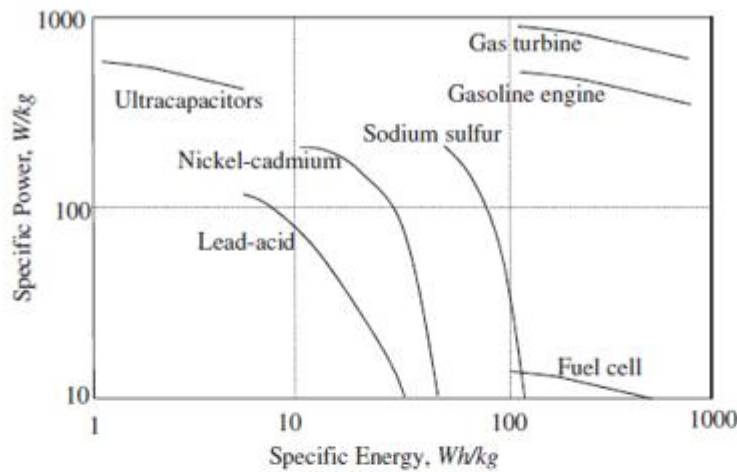


FIGURE 5.10 Specific power versus specific energy (Ragone plots) of several batteries, a gasoline engine and a fuel cell.

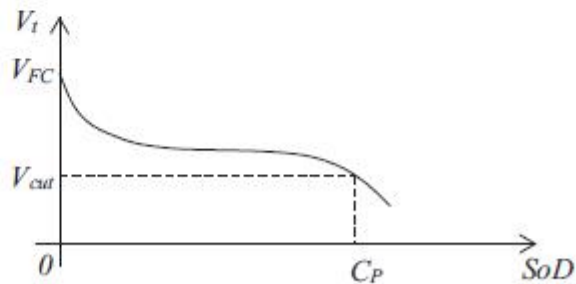


FIGURE 5.6 Battery terminal voltage.

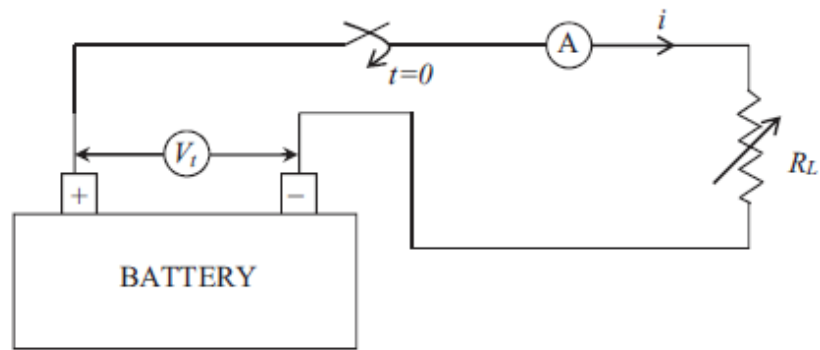


FIGURE 5.7 Battery capacity measurement.

8. BATTERY MODELING:

Batteries and other electrochemical cells can be modeled at various levels depending on the use of the model. Battery models are useful for battery design, performance evaluation and system simulation at the application level. Modeling aids research on device design, construction and materials through understanding the factors that affect the energy conversion process. Models also help research on the performance of the device in an application, which can be utilized for improved design and better utilization.

At the most complex level, the fundamental physics and chemistry-based theories are used to develop theoretical models of electrochemical cells. These models reflect material properties and design factors on the device performance. The fundamental mechanisms of electrical power generation are characterized in these models in terms of both macroscopic behavior (terminal voltage and current characteristics) and microscopic (internal material and reactant behavioral processes) information. The models are very useful for the design and performance evaluation of a particular type of battery. The strength of these models is in the information obtained on the effect of design variables on performance during the design stage. These models characterize the physical and chemical relationships applied to each element of the device. Numerical simulation techniques such as finite element analysis or computational fluid dynamics are also sometimes used to develop the analytical models. The drawbacks of the theoretical models are their

complexity; often the models cannot be used to represent the device as a component of a larger system. Device parameters are not always available to the end user. The models could be specific for a particular chemistry and design. Dynamic response such as that of the battery SoC is difficult, if not impossible to analyze with most of these models.

Battery models that emphasize the macroscopic behavior are more useful for the performance evaluation at a system level (such as the electric or hybrid vehicle systems) and for the design of these systems. For example, a simplified battery model can be used for the dynamic simulation of a hybrid vehicle to predict the powertrain characteristics as well as the range on electric only operating mode. Depending on the simulation objective, the models can be represented by a set of electrical circuit components or by a simple empirical relationship of two parameters. These two types of models are the electric circuit models and empirical models, which are presented in this section. The electric circuit-based models are somewhat more complex than the empirical models, but are extremely useful for vehicle system level analysis. On the other hand, the empirical models allow a quick evaluation on the range of a vehicle based on the capacity or energy density.

The energy storage device models presented in this section are useful not just for electric and hybrid vehicle applications, but also for utility power system applications. Distributed power systems require energy storage devices with similar features as those required for electric and hybrid vehicles.

8.1 ELECTRIC CIRCUIT MODELS:

The equivalent electrical circuit-based models use lumped parameters that make them suitable for integration in the simulation model of a larger system. The models use a combination of circuit elements (resistors, capacitors and inductors) and dependent sources to give a circuit representation of the behavior and the functionality of the electrochemical cell. The model parameters are extracted from response data of the device eliminating the need to know the chemical processes and the design details. The electric circuit models range from a simple linear resistive model to a fairly complex one that characterizes the

chemical processes in terms of lumped parameters. The accuracy of these models is in between those of the theoretical models and the empirical models; yet the circuit models are very useful for both simulation and design of a system. The application aspects of the battery can be evaluated effectively with insights into operation of the device as well as that of the system. Some of the more complex circuit models can be used to study the dynamic response such as the effect of pulse discharge which is a characteristic of hybrid and electric vehicles.

The primary electrochemical activities in the electrochemical cell are governed by two fundamental relationships: (i) Butler-Volmer relationship characterizing the electron exchange at the electrode-electrolyte interface and (ii) Faraday's law of electrolysis which states that current controls the reaction. Relating these relationships with the stored charge and the diffusing charge in the electrochemical cell enables us to develop an electric circuit model whose parameters can be obtained from experimental data.

In developing the battery models, it is more convenient to consider the stored and diffusion charges at a surface rather than the effective species concentration or surface activities. Let $q_s(t)$ and $q_d(t)$ be the instantaneous stored charge and the instantaneous diffusion charge in the vicinity of the electrode representing surface activities. If Q is the total capacity of a cell, then the charge in the non-energized species can be represented as $Q - q_s(t)$.

As was mentioned previously, the difficulty is in finding an inverse for the Butler-Volmer equation so that terminal voltage can be represented in terms of electrode current. The Nernst and Tafel equations are approximations with limitations on the terminal current. One simplified approximation is the Unnewehr universal model [11] given by

$$E(t) = E_0 + R_\Omega i(t) + k_1 q_s(t)$$

where E_0 is the initial voltage of the cell, R_Ω is the series resistance and k_1 is a constant parameter. A generalized form to represent the solution to the Butler-Volmer equation is presented by Hartley and Jannette [12]:

$$E(t) = E_0 + R_\Omega i(t) + k_1 \ln(1 + |i|) \operatorname{sgn}(i) + k_2 \ln(1 + |q_d|) \operatorname{sgn}(i) + k_3 \ln(1 - q_s)$$

The constants E_0 , R_Ω , k_1 , k_2 and k_3 depend on the properties of the electrochemical cell and can be determined from experimental data. While the Hartley model gives a mathematical representation of the terminal voltage, it is often convenient to find an equivalent electric circuit model for simulation and analysis of a battery cell. In the following, several such electric circuit models representing an electrochemical cell is given starting with a basic model derived from the Hartley model.

8.2. Basic Battery Model:

Let us begin with a simple electrical equivalent circuit model that incorporates the fundamental principles, yet simple enough for characterization based on cell discharge data is shown in Figure 5.11. One of the key dynamics that has to be modeled is the diffusion process. While complex representations using a CPE or Warburg impedance can be used, an approximate solution to the change in diffusing charge has the same form as that of a voltage across an RC circuit element. Therefore, the effect on the terminal voltage due to diffusion charge will be represented by the following first-order differential equation.

$$\frac{dv_d(t)}{dt} = \frac{1}{C_d} i(t) - \frac{1}{C_d R_d} v_d(t)$$

where $v_d(t)$ is the voltage dropped across the $R_d C_d$ parallel circuit that is proportional to the diffusion charge $q_d(t)$. Additional RC circuit elements can be added to represent the diffusion charge, but we will keep it as a single RC time constant for our simple model shown in Figure 5.11.

Another key cell dynamic that needs to be modeled is the effect of state of charge on the terminal voltage of the cell. Figure 5.6 showed how the battery terminal voltage decreases as the cell is being discharged. In the middle of the characteristics, the terminal voltage decrease is approximately linear which can be modeled by a series capacitor C_s to represent the stored charge in the cell. The voltage across this storage capacitor C_s is proportional to the stored charge $q_s(t)$. As the state of charge of the cell increases or decreases during charging or discharging, the voltage across the capacitor will increase or decrease, respectively. Additionally, an electrochemical cell losses charge while it is at rest. A resistor can be added in parallel to the storage capacitor to account for this loss of charge. This resistor R_{sd} represents the self-discharge of the cell. The $C_s R_{sd}$ circuit elements representing the storage capacitor and self-discharge resistor is shown in Figure 5.11 in series with the diffusion parameters. The mathematical representation of this segment of the circuit model in relation to the terminal current is

$$\frac{dq_s(t)}{dt} = i(t) - \frac{1}{R_{sd}} q_s(t)$$

The two other parameters that need to be added to complete the electrochemical cell equivalent circuit is a voltage source in series with a resistor representing the ohmic resistance drop described

The voltage source is taken to be the open-circuit voltage of the cell E_0 , and R_Ω is the ohmic resistance both of which are shown in Figure 5.11 in series with the storage and diffusion parameters. This completes the simple equivalent circuit model of an electrochemical cell. The values of these circuit elements can be determined experimentally by applying a step change in battery current. The procedure for obtaining the parameters of this cell is given in Example .

Example

A step discharge current of 15 A is applied to a three-cell generic battery to calculate its parameters for the model shown in Figure 5.11. The data collected from the experiment is shown graphically in Figure 5.12. The step command of 15 A constant current discharge is applied at 3,150 s and removed at 4,370 s. After the discharge, the battery terminal voltage settles to a lower voltage level of 5.873 V compared to its initial no-load voltage due to the reduction in the state of charge. ΔV_d , ΔV_{Cs} , $\Delta V_{R\Omega}$ are the voltage differences that need to be calculated from the test data to obtain the diffusion, storage and series resistance parameters, respectively. The time to reach 63% of ΔV_d is 100 s. Neglecting the self-discharge of the cells, calculate the battery equivalent circuit parameters.

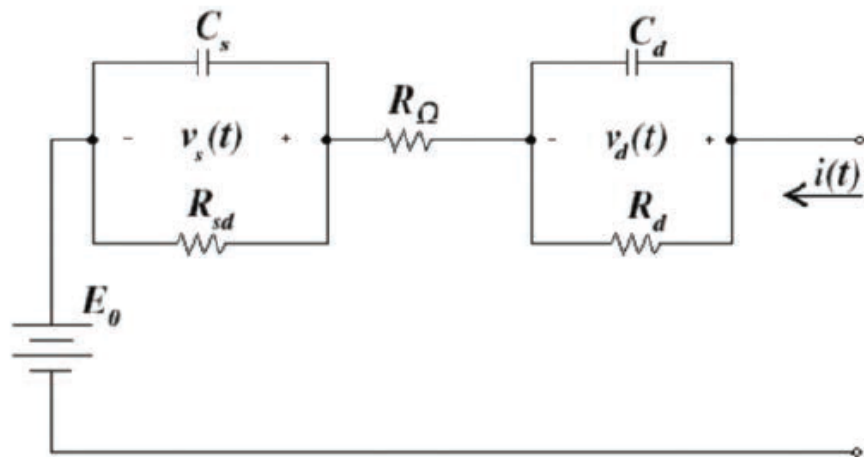


FIGURE 5.11 Electric equivalent circuit battery model.

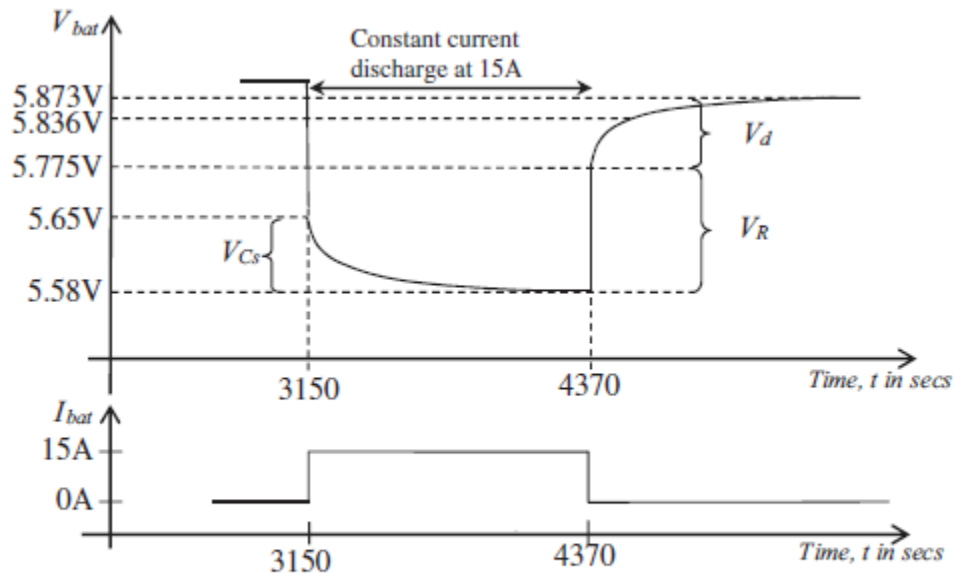


FIGURE 5.12 Test data for a battery to calculate equivalent circuit parameters.

Solution

Let us first calculate the equivalent series resistance of the battery. The voltage drop for the series resistance shows up in the output voltage characteristics as an instantaneous increase or decrease of the terminal voltage due to the step change in current. The voltage increase due to the 15 A step change in current is $\Delta V_{R\Omega} = 5.775 - 5.58 = 0.195$ V. Therefore, the series resistance value is

$$R_{\Omega} = \frac{\Delta V_{R\Omega}}{\Delta I} = \frac{0.195}{15} = 0.013 \Omega$$

The resistance for the diffusion component R_d is

$$R_d = \frac{\Delta V_d}{\Delta I} = \frac{0.098}{15} = 0.00653 \Omega$$

The RC time constant for the diffusion parameters is 100 s. Therefore, the diffusion capacitor C_d can be calculated as

$$C_d = \frac{100}{0.00653} = 15,306 \text{ F}$$

The storage capacitor C_s can be calculated from the voltage change due to the constant current discharge ΔV_{Cs} and the change in stored charge. This is calculated as follows:

$$C_s = \frac{\Delta Q}{\Delta V_{Cs}} = \frac{15(4,370 - 3,150)}{5.894 - 5.873} = 871,428.6 \text{ F}$$

9. RUN TIME BATTERY MODEL:

The Thevenin-type circuit model shown in Figure 5.11 with a constant open-circuit voltage does not allow prediction of the battery terminal voltage V_t variations (i.e., DC response) and runtime information. Prediction of SoC, transient response, terminal voltage, runtime and temperature effects is possible with run-time models. A run-time model capable of predicting the capacity of battery has been developed by Chen and Rincon-Mora [13]. The circuit model, shown in Figure 5.13, has dependent current and voltage sources in addition to several passive components. The terminal voltage-current characteristics segment of the model is similar to that of Figure 5.11 except that the open-circuit voltage depends on the capacity or SoC of the battery.

The capacitor $C_{capacity}$ and a current-controlled current source model the capacity, SoC and run-time of the battery. The two RC networks simulate the voltage-current transient response characteristics. The SoC is calculated based on the current drawn out of the cell and the initial capacity in the run-time segment of the model. The value of the capacitor $C_{capacity}$ is given by

$$C_{capacity} = 3,600 \cdot Q_c \cdot k_1 \cdot k_2$$

where Q_c is the battery capacity in Ah, and k_1 and k_2 are cycle number and temperature-dependent correction parameters, respectively. The initial voltage across $C_{capacity}$ is set to 1 or lower depending

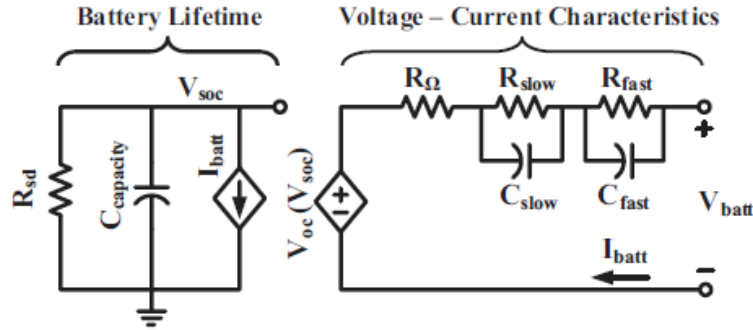


FIGURE 5.13 Run-time battery model proposed by Chen and Rincon-Mora [13].

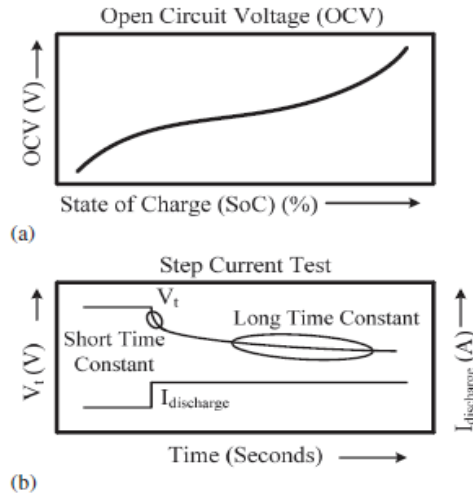


FIGURE 5.14 Example experimental curves to obtain run-time model parameters: (a) SoC versus open-circuit voltage characteristics and (b) discharge plot for calculating RC time constants.

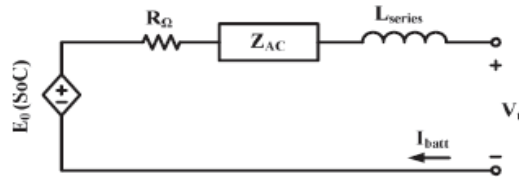


FIGURE 5.15 Impedance-based equivalent electric circuit battery model.

on whether the battery is initially fully charged or not. A value of '1' represents 100% SoC. Similarly, a value of '0' would indicate that the battery is fully discharged, i.e., SoC is 0%.

SoC is bridged to the open-circuit voltage through a voltage-controlled voltage source. The relationship between SoC and open-circuit voltage is non-linear and has to be represented from experimentally obtained data for this model. However, the collection of the open-circuit voltage versus SoC data is extremely time consuming. An example SoC versus open-circuit voltage characteristic and the discharge profile to calculate the RC time constants are shown in Figure 5.14.

10.FIRST PRINCIPLE MODEL:

An interesting equivalent circuit model based on the fundamental electrochemical principles has been developed by Lei Xia the model is called the first principle model. While this is not one of the simpler electric equivalent circuit models, it isolates and relates the physical and chemical fundamentals of an electrochemical cell to an equivalent circuit parameter. The model has discrete, lumped parameter representation of all the electrochemical processes within the cell. The first principle model, shown in Figure 5.16, incorporates the following phenomenon within an electrochemical cell:

- Electrochemical energy conversion
- Diffusion process
- Charge transfer polarization
- Concentration polarization
- Electrical double layer
- Ohmic resistance
- Self-discharge

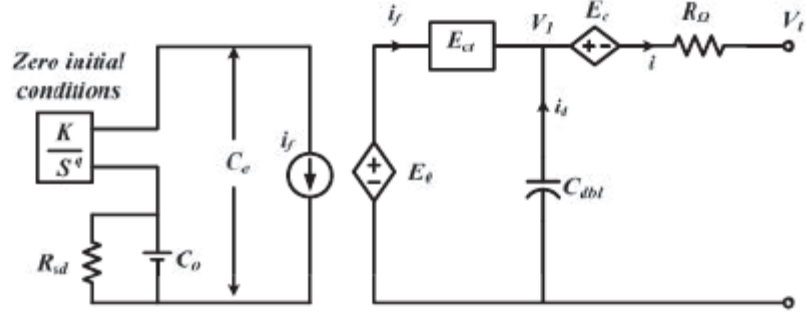


FIGURE 5.16 First principle battery model with constant current source

In the equivalent circuit, the diffusion process has been described by a general CPE; open-circuit voltage and concentration polarization have been represented by the Nernst equations; charge transfer polarization has been represented by the Tafel equation; ohmic voltage drop has been represented by resistance R_O ; electric double layer has been represented by capacitance C_{dbl} ; and resistance R_{sd} represents self-discharge of the cell.

The first principle model is construction and chemistry independent. Parameters of the model can be derived from experimental response data of the device, which eliminates the need for the knowledge of electrochemical properties and the design details. The model is based on the fact that before the discharge of any current, the internal voltage E_0 , the double-layer capacitor voltage V_1 and the terminal voltage V_t (the variables are shown in Figure 5.16) are all the same. The charge transfer potential and the concentration polarization potential are zeroes for this condition. When a load is connected to the terminals, initially the discharge current is almost entirely supplied by the double-layer capacitor. As the double-layer capacitor discharges and the V_1 decreases, the charge transfer potential is established and the faradaic current i_f starts to increase. When current i_f increases to a point where E_{ct} does not change appreciably, i_d becomes minimal. In this situation, the faradaic current i_f supplies the majority of the load current. The potential drop in this region is primarily due to the ohmic resistance.

As an example, the parameters for a generic battery cell are given below [7]:

Bulk electrolyte concentration: $C_0 = 2.616$ (dimensionless, but represents numerical value of the concentration)

Diffusion process parameters: $C_d(t) = C_0 - Ki_f(t)t^q$; $K = \frac{1}{227.5}$; $q = 0.68$

Open-circuit voltage (Nernst equation): $E(t) = 1.95 + 0.052 \ln C_d(t)$

Charge transfer polarization (Tafel equation): $E_{ct} = 0.118 + 0.28 \ln(i_f)$

Ohmic resistance: $R_O = 0.05 \Omega$

Double-layer capacitor: $C_{dbl} = 50 \text{ F}$

Concentration polarization: $E_c(t) = 0.04 \ln \frac{C_d(t)}{C_0}$

11.BATTERY MANAGEMENT SYSTEM:

The battery management system (BMS) consists of a set of algorithms based on voltage, current and temperature measurements to calculate essential battery parameters and determine charge/discharge power limits at a given time. Depending on the level of sophistication in the BMS, measurements can be from individual cells or group of cells or from the entire pack. The BMS is also responsible for generating command signals for cell equalization circuits if used in a battery pack. BMS ensures reliability and protection against overcharge, over discharge, short circuits and thermal abuse. The BMS for an energy storage system are designed to have all or some of the following features:

- State of charge (SoC) estimation
- State of health (SoH) monitoring for cell and pack protection
- Temperature control
- Charge/discharge power control
- Cell equalization
- Data logging.

The measurements, parameter estimations and outputs generated in a BMS are shown in Figure 5.26. The BMS initializes once the system is powered, which happens when with key on in a hybrid electric vehicle. The only function during initialization is to record the self-discharge during the system off period. If the self-discharge is excessive, then it is reported to the SoH monitoring algorithm. The other parameters for battery management are estimated during each measurement cycle while the pack is on.

SoC provides information on the available capacity of a battery. This is necessary not only for the protection of the battery pack, but also for vehicle powertrain controls. The SoC should also be maintained within a certain band to enhance the life of the battery. In sophisticated management systems, SoC of individual cells or group of cells in a pack are determined to verify the uniform distribution of SoC among the cells. The SoC is typically expressed as a percentage of the rated capacity instead of the maximum available capacity which could be less due to aging and environmental effects. However, the SoC could also be calculated based on the maximum available capacity. This SoC

calculation can be used for cell equalization, since all cells in the series-string generally experience the same environment.

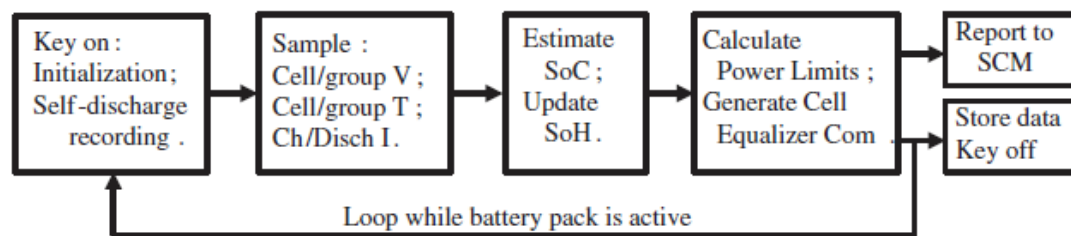


FIGURE 5.26 Parameter estimations and pack management in a BMS.

SoH is the working condition of the pack and measures the pack's ability to deliver power compared to a new pack. The fading of a cell capacity and power compared to other cells in the pack with aging indicates the deteriorating health of the cell. The cell capacity and other parameters are used in an algorithm to estimate the state of health (SoH) of a battery pack. The SoH information is useful for battery safety and for delivering power up to its maximum capability. The SoH estimation algorithms are based on comparing measured and estimated cell parameters with references or neighboring cells. The voltages and SoC anomalies of one cell compared to the nearby cells is indicative of poor health of that cell. Similarly, excessive self-discharge of the pack raises a flag, and is compared with preset limits to estimate the pack SoH. The SoH information can be used to replace damaged cells in a pack instead of replacing the entire pack.

The temperature is the primary environmental factor that affects the SoC of an energy storage system. Imbalances in temperature among the various cells in a pack will result in imbalances in the SoC. Additionally, temperature affects the self-discharge rates. The thermal management in a pack is part of the cooling system design for the pack, but the temperature information of the cells should be effectively utilized for protection and health monitoring of the cells.

The maximum power available from the battery at a given time is calculated in the BMS based on the SoC and terminal voltages ensuring that operating voltage, current, SoC and other design limits are not violated. The BMS sets the power

limits during charging and discharging for battery protection. Batteries could get severely damaged due to inappropriate charging. The limits are reported to the supervisory controller for powertrain controls in electric and hybrid vehicles.

There are three levels of management systems: pack level management, modular-pack level management and cell level management. Pack level management is the most basic one where overall pack voltage and SoC is monitored, whereas the most complete cell equalization and balancing is possible when individual cell parameters of voltage, current and temperature are monitored. The charging and discharging power managements at the pack level leaves individual cells vulnerable to damage. In modular-pack level management, groups of cells are treated as a module for cell balancing and equalization; the BMS algorithms depend on group voltage, current and temperature measurements rather than pack or individual cell measurements. For packs employing cell equalizer circuits, the BMS generates command signals for cell voltage equalization based on its measurements and estimations. The circuits act on these signals to balance the cells or groups of cells.

Data logging is another important function of the energy storage management system. The data for voltage, current, temperature, SoC, and number of charge-discharge cycles could be stored as a function of time for SoH monitoring, diagnostics and fault analysis.

12.SOC MEASUREMENT:

The SoC of the energy storage system is calculated using measurements of a physical parameter that varies with the SoC. The SoC varies with voltage, charge/discharge rate, self-discharge rate, temperature and aging. Depending on the parameters monitored, the SoC calculation can be either a voltage-based method or a current-based method. The more accurate SoC calculations use both voltage and current measurements in an observer-based method. The voltage-based SoC measurement is applicable to cell chemistries where the voltages are directly related to the SoC. The relation between open-circuit voltage and SoC must be known a priori for a good estimation of the SoC. The

voltage-based measurement is not at all suitable for lithium-ion cells, since the voltage for these cells is fairly steady over most of the charge-discharge cycle.

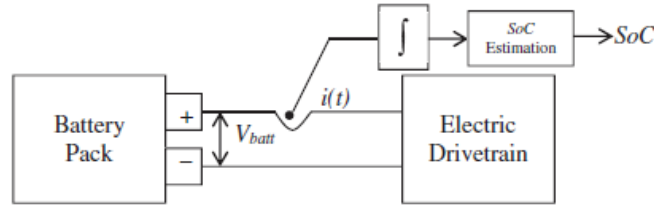


FIGURE 5.27 Battery SoC measurement.

In current-based estimation, the SoC is obtained from the integration of current using the fundamental definition of charge $q = \int_0^t i(t) dt$. A simple SoC measurement diagram is shown in Figure 5.26. The charge and discharge currents out of and in to the storage device are measured directly using a current sensor. The integration of measured current gives the SoD when the initial condition is the fully charged condition of the battery. Knowing the initial capacity C_p of the battery, SoC is calculated from

$$SoC(t) = C_p - SoD(t)$$

The method is also known as Coulomb counting. The method tends to accumulate errors if it is solely based on current information. A method of improving the SoC estimation is to incorporate the directly measurable parameters (voltage and current) into a mathematical model of the storage system to implement an observer-based SoC estimation method. This is a closed loop Coulomb counting method as opposed to the open-loop method of Figure 5.27. The closed loop method is based on feedbacks that can be empirically designed or generated using Kalman filters [20].

13.BATTERY CELL BALANCING:

The individual cells in the connected string of the battery pack are the unit battery cells. The available energy stored in a battery is cell is $E_{avail} = qV$, which states that both charge and voltage need to be balanced in a series string to maximize the output of a pack. When a series-string of electrochemical cells is charged as a pack, slight parameter mismatches in individual cells and temperature differences result in charge and voltage imbalances. The imbalances adversely affect the vehicle performance by reducing the throughput of the battery pack.

The chemical reactions in an electrochemical cell depend on the temperature and pressure. The temperature differences among the

cells change the self-discharge rates causing imbalances in the charge of the cells. A low cell temperature reduces chemical activity which increases the cell's internal impedance. The increased internal resistance reduces the terminal voltage, and thus, the cell capacity. In addition, manufacturing differences and different aging characteristics result in parameter mismatches among individual cells, which cause voltage and capacity imbalances.

The charge imbalance also shows up as voltage differences. The imbalances tend to grow as the pack goes through repeated charge/discharge cycles. The weaker cells tend to charge slower and the stronger cells charge faster. The process shortens the pack life and reduces its utilization. The number of charge-discharge cycles affects some battery chemistry more than the others. For example, Li-ion batteries are highly sensitive to over voltages and under voltages. Li-ion batteries are recommended to limit the charge-discharge rates to no more than 2C, and also to keep the cells charged to at least 40% SoC to minimize aging. The maximum throughput of the pack can be ensured by balancing the voltage and charge of individual cells. The cell balancing methods utilize electronic circuits and control to even out the voltages and SoC of a series string of electrochemical cells. The simplest strategy adopted for charging a series-string of cells is to monitor the cell voltages and discontinue charging when one of the cells (strongest cell) reaches the voltage limit for individual cells. Extended charging is another option where charging is continued even after the strongest cell has reached its capacity to bring the weaker cells up to capacity. When charging continues to bring the weaker cells to the maximum voltage, overvoltage results in the stronger cells. Overcharging is not at all an option with certain battery chemistry, while in others the process vents hydrogen gas (known as gassing) and removes water from the overcharged cells. Increased gassing in the cell at elevated temperatures shortens the cell life.

The overcharging in the stronger cells can be avoided if there is a path to shunt the charging currents once they reach the voltage limit. Similarly, the simplest protection during discharging of a pack is to shut down when the first cell reaches the minimum voltage limit. This cell is consequently the weakest cell in the series-string and is limiting the

capacity of the pack. If discharging is continued to extract energy from the stronger cells, then the weaker cell voltage will fall below the minimum voltage level possibly causing damage to the cells.

The simple cell balancing strategies result in underutilization of the battery pack. Improved cell balancing circuits provide a path to bypass the weaker cells once they reach the minimum voltage provided the pack voltage level is still above the minimum voltage level of the system. Power electronic converter circuits are used to divert charging currents to boost the weaker cells or deplete charge from stronger cells for cell voltage equalization.

14. TRACTION BATTERIES:

Lead acid batteries that have served the automotive industry over the past 100 years for powering electrical accessories in conventional IC engine vehicles does not have the power and energy density required in electric vehicles and hybrid vehicles. The push for zero-emission vehicles led to numerous research and development efforts on advanced batteries activities in the United States, Europe and Japan. Desirable features sought after in alternative battery technologies are high power and energy density, faster charge time and long cycle life. The research and development progressed slowly until recent years due to the lack of market penetration of electric vehicles. In the meantime, the growth in the electronics industry over the past several decades has led to tremendous advancements in alternative batteries, such as nickel-cadmium (NiCd), nickel-metal-hydride (NiMH) and Li-based batteries technologies. The rechargeable Li-ion battery is the technology of choice for cell phones and laptop computers. Further research on scaling of these battery technologies led to the development of several battery technologies for electric and hybrid vehicle applications. NiMH battery-packs are currently used in commercially available hybrid electric vehicles, while the Li-ion battery pack is used in the electric vehicle Tesla roadster. Emerging plug-in hybrid vehicles are also likely to use the Li-ion battery technology. While the NiMH and Li-ion batteries are the frontrunners today for electric and hybrid electric vehicles applications, several other battery technologies have been used in various prototype vehicles. In this

section, we will review not only the promising battery technologies, but also those have been tried in various prototype electric vehicles.

The future of the battery technologies for electric and hybrid vehicle applications depend on factors including system cost, availability of raw materials, mass production capabilities and lifecycle characteristics. One must note that the electric and hybrid vehicles industry covers a wide spectrum and is not just limited to road vehicles. Some technologies may be more suitable for certain applications for various reasons. Representative properties of the promising batteries technologies along with that of lead acid battery are summarized below in Table 5.5 with information obtained from various literatures.

TABLE 5.5
Properties of Electric and Hybrid Electric Vehicles Batteries

Battery Type	Specific Energy, Wh/kg	Specific Power, W/kg	Energy Efficiency, %	Cycle Life
Lead acid	35–50	150–400	80	500–1,000
Nickel-cadmium	30–50	100–150	75	1,000–2,000
Nickel-metal hydride	60–80	200–400	70	1,000
Aluminum-air	200–300	100	<50	Not available
Zinc-air	100–220	30–80	60	500
Sodium-sulfur	150–240	230	85	1,000
Sodium-nickel chloride	90–120	130–160	80	1,000
Lithium-polymer	150–200	350	Not available	1,000
Lithium ion	90–160	200–350	>90	>1,000

15.NICKEL-METAL-HYDRIDE (NIMH) BATTERY:

The nickel-metal-hydride is a successor to the nickel hydrogen battery, and is already in use in production hybrid electric vehicles. The positive electrode in a NiMH battery cell is nickel hydroxide (Ni(OH)_2) and the negative electrode is metal hydride. The negative electrode consists of a compressed mass of fine metal particles. The metallic alloy can absorb large number of hydrogen molecules under certain temperature and pressure to form the metal hydride. This can be thought of as an alternative approach of storing hydrogen. The proprietary alloy formulations used in NiMH are known as AB_5 and AB_2 alloys. In the AB_5 alloy, A is the mixture of rare earth elements and B is partially

substituted nickel. In the AB_2 alloy, A is titanium and/or zirconium and B is again partially substituted nickel. The AB_2 alloy has higher capacity for hydrogen storage and less costly. The nominal cell voltage in a NiMH battery is 1.2 V, which is the same as that of NiCd; NiMH cells also have flat discharge characteristics. The capacity of the NiMH is significantly higher than that of NiCd with specific energy ranging from 60 to 80 Wh/kg. The specific power of NiMH batteries can be as high as 250 W/kg.

NiMH battery packs have the capability to operate in intermediate SoC conditions and deliver thousands of shallow discharge cycles with a 1%–2% swing of SoC. This feature is particularly suitable for charge sustaining HEVs, where it is necessary for the battery packs to survive more than 100,000 vehicle miles driven over 10 years. The cost advantages for NiMH battery packs are also favorable for battery-packs designed for high power density, but not so when designed for high specific energy required in EVs. Thus, the NiMH battery packs became the enabling technology for charge sustaining HEVs.

The components of NiMH are recyclable, but a recycling infrastructure is not yet in place. NiMH batteries have a much longer life cycle than lead acid batteries and are safe and abuse-tolerant. The disadvantages of NiMH batteries are the relatively high cost, higher self-discharge rate compared to NiCd, poor charge acceptance capability at elevated temperatures and low cell efficiency. NiMH is likely to survive as the leading rechargeable battery in the future for traction applications with strong challenge coming only from lithium-ion batteries.

16.Li-Ion BATTERY:

The lithium metal has high electrochemical reduction potential relative to that of hydrogen (3.045 V) and the lowest atomic mass (6.94), which shows promise for a battery of 3 V cell potential when combined with a suitable positive electrode. The interest in secondary lithium cells soared soon after the advent of lithium primary cells in the 1970s, but the major difficulty was the highly reactive nature of the lithium metal with moisture that restricted the use of liquid electrolytes. The discovery in the late 1970s by researchers at Oxford University that

lithium can be intercalated (absorbed) into the crystal lattice of cobalt or nickel to form LiCoO_2 or LiNiO_2 paved the way toward the development of lithium-ion batteries.

The use of metallic-Li is bypassed in Li-ion batteries by using lithium intercalated (absorbed) carbons (Li_xC) in the form of graphite or coke as the negative electrode along with the lithium metallic oxides as the positive electrode. The graphite is capable of hosting lithium up to a composition of LiC_6 . The majority of the Li-ion batteries use either a layered oxide or iron phosphates of lithium as the positive electrode. Layered positive electrodes of cobalt oxide are expensive, but proved to be the most satisfactory. Nickel oxide, which costs less can also be used, but is structurally more complex. The performance is similar to that of cobalt oxide electrodes. The manganese oxide-based positive electrodes are also used since manganese is cheaper, widely available and less toxic. Alternative positive electrode material is the lithium iron phosphate (LiFePO_4) which can deliver stable and good performance at lower costs.

The cell discharge operation in a lithium-ion cell using LiCoO_2 is illustrated in Figure 5.23. During cell discharge, lithium ions (Li^+) are released from the negative electrode that travel through an organic electrolyte toward the positive electrode. In the positive electrode, the lithium ions are quickly incorporated into the lithium compound material. The process is completely reversible. The chemical reactions at the electrodes are as follows:

At the negative electrode,

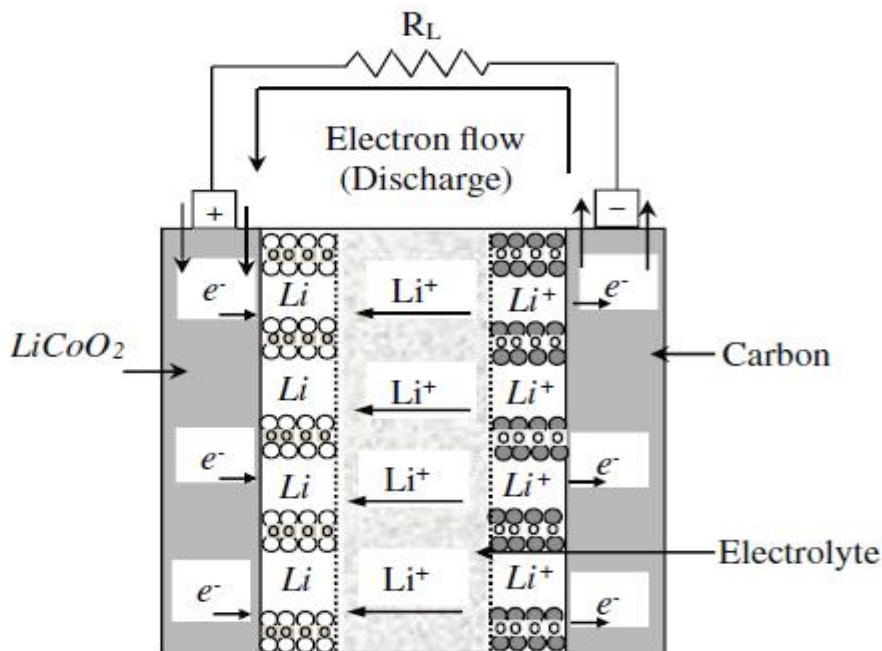
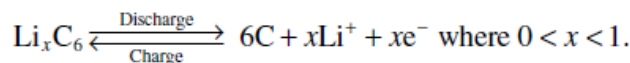
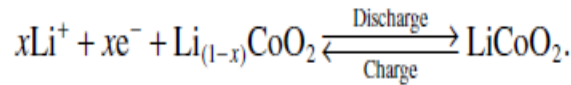


FIGURE 5.23 Lithium-ion cell. (By courtesy of Research Studies Press Ltd.)



During cell charge operation, the lithium ions move in the opposite direction from the positive electrode to the negative electrode. The nominal cell voltage for a Li-ion battery is 3.6 V, which is equivalent to 3 NiMH or NiCd battery cells.

The components of Li-ion batteries are also recyclable, but a recycling infrastructure is yet to be developed. The cost of Li-ion battery cells is now lower to that of comparable NiMH battery cells which suffer from higher material costs. Some Li-ion battery chemistries involve relatively inexpensive materials. The lower material cost does not reflect directly on the battery packs cost since more expensive management systems are necessary in Li-ion packs to address the safety concerns.

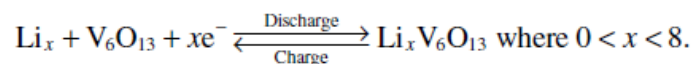
The main drawback of Li-ion batteries is that these are very sensitive to over-voltages and over-discharges. Over-voltage of Li-ion cell positive electrode results in solvent oxidation, and exothermic decomposition of the active material. Overvoltage and over-discharge can result in irreversible cell damage possibly accompanied by cell ignition [18].

The automotive industry has essentially settled on Li-ion cells using a layered cathode and a graphite anode for all types of electric and hybrid vehicles. The specific Li-ion pack chemistry varies depending on the type of BEV with the choices from LiNiCoMnO₂ (NMC), LiNiCoAlO₂ (NCA), Li₂TiO₃ (LTO) and LiFePO₄ (LFP). For BEVs, the Li-ion types of choice are the NMC and NCA ones which have the highest volumetric mass energy densities, long life and acceptable abuse tolerance, because of which they are universally used in passenger BEVs. Their cell voltages are at 3.6 V with capacity of 150–200 mAh/g. The LFPs have found applications in all-electric buses due to their lower cost although they have lower cell voltages at 3.2 V with a capacity of 150 mAh/g.

17.Li-Polymer BATTERY:

The Li-polymer evolved out of the development of solid state electrolytes, i.e., solids capable of conducting ions but are electron insulators. The solid state electrolytes resulted from the research in the 1970s on ionic conduction in polymers. These batteries are considered solid-state batteries, since their electrolytes are solids. The most common polymer electrolyte is the polyethylene oxide compounded with an appropriate electrolyte salt.

The most promising positive electrode material for Li-polymer batteries is the vanadium oxide V₆O₁₃ [16]. This oxide interlaces up to eight lithium atoms per oxide molecule with the following positive electrode reaction:



The Li-polymer batteries have the potentials for the highest specific energy and power. The solid polymers, replacing the more flammable liquid electrolytes in other type of batteries, can conduct ions at temperatures above 60°C. The use of solid polymers also has a great safety advantage in case of electric and hybrid electric vehicles accidents. Since the lithium is intercalated into carbon electrodes, the lithium is in ionic form and is less reactive than pure lithium metal. The thin Li-polymer cell gives the added advantage of forming a battery of any size or shape to suit the available space within the electric and hybrid electric vehicles chassis. The main disadvantage of the Li-polymer battery is the need to operate the battery cell in the temperature range of 80°C–120°C. Li-polymer batteries with high specific energy, initially developed for electric vehicle applications, also have the potential to provide high specific power for hybrid electric vehicle applications. The other key characteristics of the Li-polymer are good cycle and calendar life.

UNIT 4: HYBRID ELECTRIC VEHICLES

HEV Fundamentals -Architectures of HEVs- Interdisciplinary Nature of HEVs – State of the Art of HEVs – Advantages and Disadvantages – Challenges and Key Technology of HEVs – Concept of Hybridization of the Automobile-Plug-in Hybrid Electric Vehicles – Design and Control Principles of Plug-In Hybrid Electric Vehicles

1. HEV FUNDAMENTALS:

Hybrid electric vehicles (HEVs) are vehicles that combine an internal combustion engine (ICE) with an electrical traction system. It usually consists of either two or more sources of energy storage devices or two or more power sources onboard the vehicle. HEVs are synonymous with vehicles that offer high fuel economy and lower emissions when compared to conventional gasoline vehicles. Hybrid vehicles combine the ICE and electrical traction machine in an efficient way so as to utilize the most desirable characteristics of both. In HEVs, the ICE is mainly used for steady state operation while the electric machine powertrain is mainly used for dynamic operation. Some of the advantages offered by HEVs are as follows:

- Efficiency-improving technology such as regenerative braking which is not available in conventional vehicles.
- Less engine idling and efficient engine operation leading to better fuel economy.
- Better drivability since electric motor characteristics better match the road load.
- Potential to reduce the emission of greenhouse gases.
- Reduced fossil fuel consumption.

HEVs can be classified based on the configuration of the drivetrain as series hybrid, parallel hybrid, series–parallel hybrid, complex hybrid, and plug-in hybrid. In general, when we design a HEV, we need to select the ratings for the propulsion engine, traction electric motor, generator, and energy storage based on the desired vehicle performance. After the initial design, we need to verify if the vehicle performance specifications are met. The design usually requires a modeling and simulation program and may take several iterations before final design.

2. ARCHITECTURES OF HEVS:

A HEV is a combination of a conventional ICE-powered vehicle and an EV. It uses both an ICE and an electric motor/generator for propulsion. The two power devices, the ICE and the electric motor, can be connected in series or in parallel from a power flow point of view. When the ICE and motor are connected in series, the HEV is a series hybrid in which only the electric motor is providing mechanical power to the wheels. When the ICE and the electric motor are connected in parallel, the HEV is a parallel hybrid in which both the electric motor and the ICE can deliver mechanical power to the wheels.

In a HEV, liquid fuel is still the source of energy. The ICE is the main power converter that provides all the energy for the vehicle. The electric motor increases system efficiency and reduces fuel consumption by recovering kinetic energy during regenerative braking, and optimizes the operation of the ICE during normal driving by adjusting the engine torque and speed. The ICE provides the vehicle with an extended driving range therefore overcoming the disadvantages of a pure EV.

In a PHEV, in addition to the liquid fuel available on the vehicle, there is also electricity stored in the battery, which can be recharged from the electric grid. Therefore, fuel usage can be further reduced. In a series HEV or PHEV, the ICE drives a generator (referred to as the I/G set). The ICE converts energy in the liquid fuel to mechanical energy and the generator converts the mechanical energy of the engine output to electricity. An electric motor will propel the vehicle using electricity generated by the I/G set. This electric motor is also used to capture the kinetic energy during braking. There will be a battery between the generator and the electric motor to buffer the electric energy between the I/G set and the motor.

In a parallel HEV or PHEV, both the ICE and the electric motor are coupled to the final drive shaft through a mechanical coupling mechanism, such as a clutch, gears, belts, or pulleys. This parallel configuration allows both the ICE and the electric motor to drive the vehicle either in combined mode, or separately. The electric motor is also used for regenerative braking and for capturing the excess energy from the ICE during coasting.

HEVs and PHEVs can also have either the series-parallel configuration or a more complex configuration which usually contains more than one electric motor. These configurations can generally further improve the performance and fuel economy of the vehicle with added component cost.

1. Series HEVs

Figure 1.11 shows the configuration of a series HEV. In this HEV, the ICE is the main energy converter that converts the original energy in gasoline to mechanical power. The mechanical output of the ICE is then converted to electricity using a generator. The electric motor moves the final drive using electricity generated by the generator or electricity stored in the battery. The electric motor can receive electricity directly from the engine, or from the battery, or both. Since the engine is decoupled from the wheels, the engine speed can be controlled independently of vehicle speed. This not only simplifies the control of the engine, but, most importantly, can allow operation of the engine at its optimum speed to achieve the best fuel economy. It also provides flexibility in locating the engine on the vehicle. There is no need for the traditional mechanical transmission in a series HEV.

Based on the vehicle operating conditions, the propulsion components on a series HEV can operate with different combinations:

- **Battery alone:** When the battery has sufficient energy, and the vehicle power demand is low, the I/G set is turned off, and the vehicle is powered by the battery only.
- **Combined power:** At high power demands, the I/G set is turned on and the battery also supplies power to the electric motor.
- **Engine alone:** During highway cruising and at moderately high power demands, the I/G set is turned on. The battery is neither charged nor discharged. This is mostly due to the fact that the battery's state of charge (SOC) is already at a high level but the power demand of the vehicle prevents the engine from turning, or it may not be efficient to turn the engine off.
- **Power split:** When the I/G is turned on, the vehicle power demand is below the I/G optimum power, and the battery SOC is low, then a portion of the I/G power is used to charge the battery.
- **Stationary charging:** The battery is charged from the I/G power without the vehicle being driven.
- **Regenerative braking:** The electric motor is operated as a generator to convert the vehicle's kinetic energy into electric energy and charge the battery.

A series HEV can be configured in the same way that conventional vehicles are configured, that is, the electric motor in place of the engine as shown in Figure 1.11. Other choices are also available, such as wheel hub motors. In this case, as shown in Figure 1.12, there are four electric motors, each one installed inside each wheel. Due

to the elimination of transmission and final drive, the efficiency of the vehicle system can be significantly increased. The vehicle will also have all-wheel drive (AWD) capability. However, controlling the four electric motors independently is a challenge.

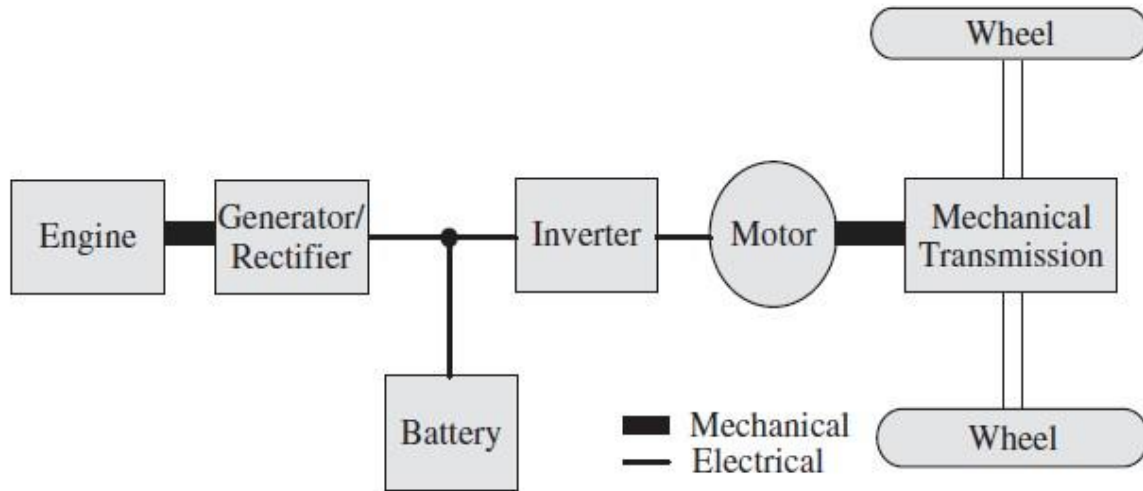


Figure 1.11 The architecture of a series HEV

2. Parallel HEVs:

Figure 1.13 shows the configuration of a parallel hybrid. In this configuration, the ICE and the electric motor can both deliver power in parallel to the wheels. The ICE and the electric motor are coupled to the final drive through a mechanism such as a clutch, belts, pulleys, and gears. Both the ICE and the motor can deliver power to the final drive, either in combined mode, or each separately. The electric motor can be used as a generator to recover the kinetic energy during braking or absorbing a portion of power from the ICE. The parallel hybrid needs only two propulsion devices, the ICE and the electric motor, which can be used in the following mode:

- **Motor-alone mode:** When the battery has sufficient energy, and the vehicle power demand is low, then the engine is turned off, and the vehicle is powered by the motor and battery only.
- **Combined power mode:** At high power demand, the engine is turned on and the motor also supplies power to the wheels.
- **Engine-alone mode:** During highway cruising and at moderately high power demands, the engine provides all the power needed to drive the vehicle. The motor remains idle. This is mostly due to the fact that the battery SOC is

already at a high level but the power demand of the vehicle prevents the engine from turning off, or it may not be efficient to turn the engine off.

- **Power split mode:** When the engine is on, but the vehicle power demand is low and the battery SOC is also low, then a portion of the engine power is converted to electricity by the motor to charge the battery.
- **Stationary charging mode:** The battery is charged by running the motor as a generator and driven by the engine, without the vehicle being driven.
- **Regenerative braking mode:** The electric motor is operated as a generator to convert the vehicle's kinetic energy into electric energy and store it in the battery. Note that, in regenerative mode, it is in principle possible to run the engine as well, and provide additional current to charge the battery more quickly (while the propulsion motor is in generator mode) and command its torque accordingly, that is, to match the total battery power input. In this case, the engine and motor controllers have to be properly coordinated.

3. Series–Parallel HEVs:

The series–parallel HEV shown in Figure 1.14 incorporates the features of both series and parallel HEVs. Therefore, it can be operated as a series or parallel HEV. In comparison to a series HEV, the series–parallel HEV adds a mechanical link between the engine and the final drive, so the engine can drive the wheels directly. When compared to a parallel HEV, the series–parallel HEV adds a second electric motor that serves primarily as a generator.

Because a series–parallel HEV can operate in both parallel and series modes, the fuel efficiency and drivability can be optimized based on the vehicle's operating condition. The increased degree of freedom in control makes the series–parallel HEV a popular choice. However, due to increased components and complexity, it is generally more expensive than series or parallel HEVs.

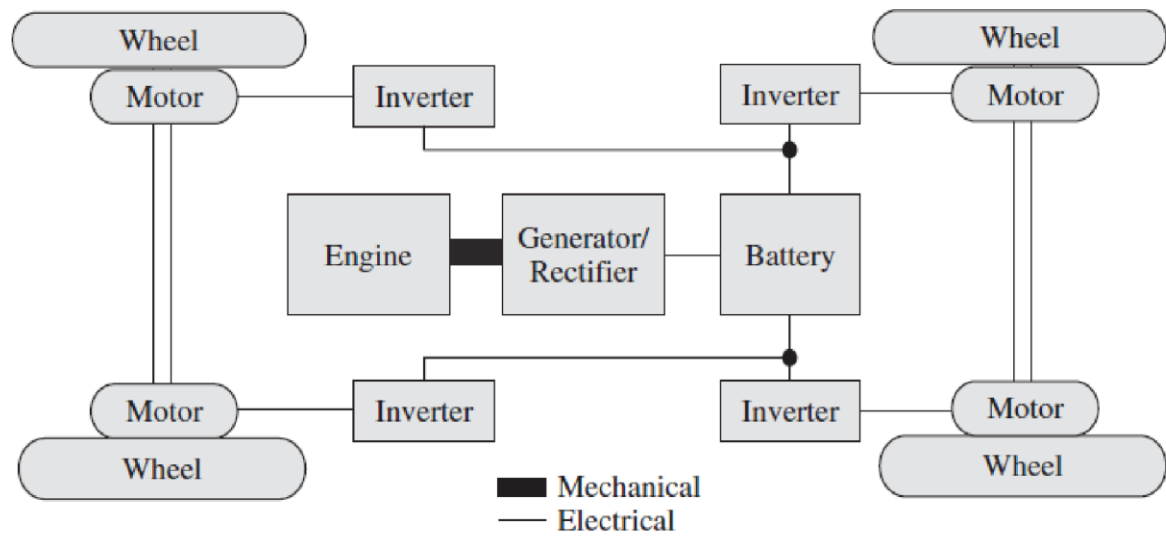


Figure 1.12 Hub motor configuration of a series HEV

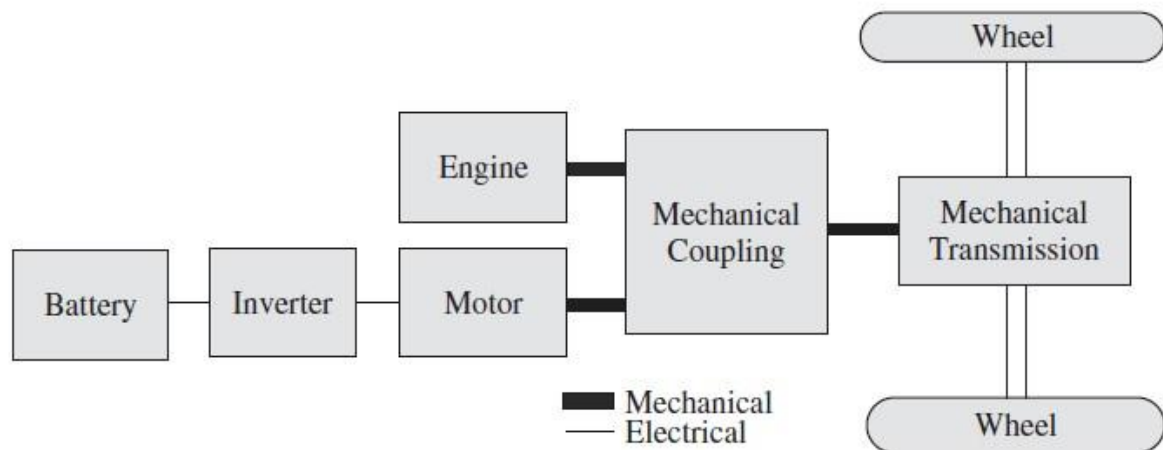


Figure 1.13 The architecture of a parallel HEV

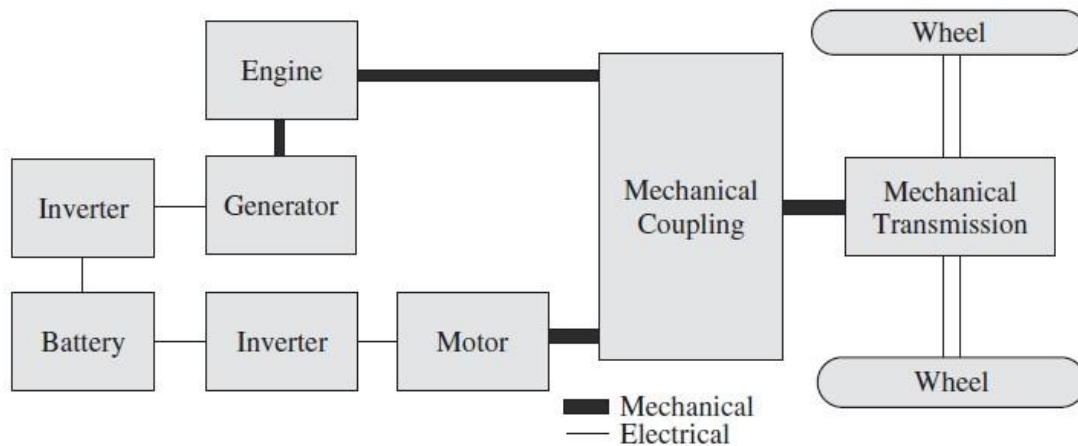


Figure 1.14 The architectures of a series-parallel HEV

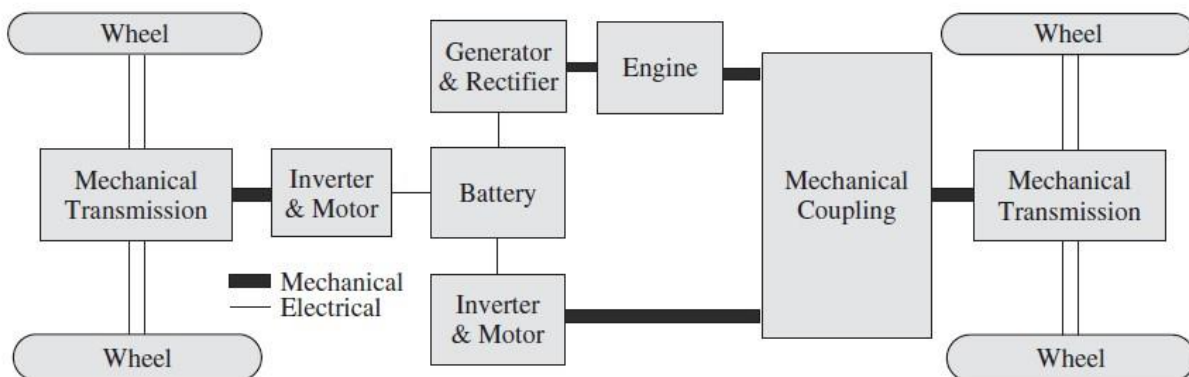


Figure 1.15 The electrical four-wheel drive system using a complex architecture

4. Complex HEVs:

Complex HEVs usually involve the use of planetary gear systems and multiple electric motors (in the case of four/all-wheel drive). One typical example is a fourwheel drive (4WD) system that is realized through the use of separate drive axles, as shown in Figure 1.15. The generator in this system is used to realize series operation as well as to control the engine operating condition for maximum efficiency. The two electric motors are used to realize all-wheel drive, and to realize better performance in regenerative braking. They may also enhance vehicle stability control and antilock braking control by their use.

5. Diesel Hybrids:

HEVs can also be built around diesel vehicles. All topologies explained earlier, such as series, parallel, series–parallel, and complex HEVs, are applicable to diesel hybrids. Due to the fact that diesel vehicles can generally achieve higher fuel economy, the fuel efficiency of hybridized diesel vehicles can be even better when compared to their gasoline counterparts.

Vehicles such as delivery trucks and buses have unique driving patterns and relatively low fuel economy. When hybridized, these vehicles can provide significant fuel savings. Hybrid trucks and buses can be series, parallel, series–parallel, or complex structured and may run on gasoline or diesel.

Diesel locomotives are a special type of hybrid. A diesel locomotive uses a diesel engine and generator set to generate electricity. It uses electric motors to drive the train. Even though a diesel locomotive can be referred to as a series hybrid, in some architectures there is no battery for the main drive system to buffer energy between the I/G set and the electric motor. This special configuration is sometimes referred to as simple hybrid. In other architectures, batteries are used and can help reduce the size of the generator, and can also be used for regenerative energy capture. The batteries, in this case, can also be utilized for short-term high current due to torque needs, without resorting to a larger generator.

3. INTERDISCIPLINARY NATURE OF HEVS:

HEVs involve the use of electric machines, power electronics converters, and batteries, in addition to conventional ICEs and mechanical and hydraulic systems. The interdisciplinary nature of HEV systems can be summarized as in Figures 1.17. The HEV field involves engineering subjects beyond traditional automotive engineering, which was mechanical engineering oriented. Power electronics, electric machines, energy storage systems, and control systems are now integral parts of the engineering of HEVs and PHEVs.

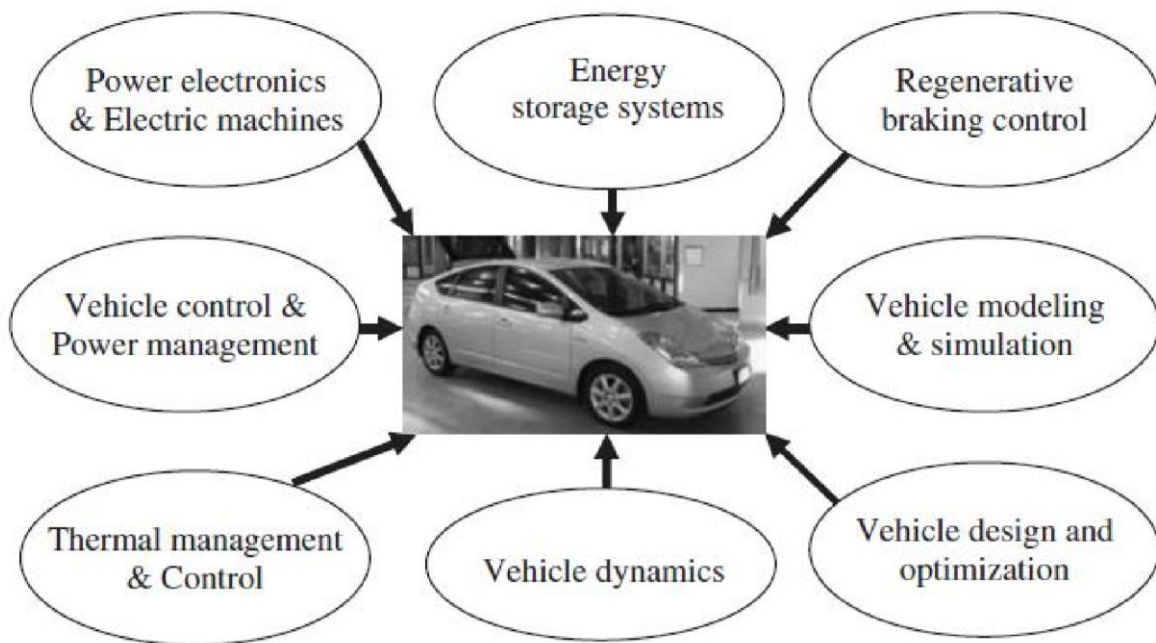


Figure 1.17 The general nature and required engineering field by HEVs

In addition, thermal management is also important in HEVs and PHEVs, where the power electronics, electric machines, and batteries all require a much lower temperature to operate properly, compared to a non-hybrid vehicle's powertrain components. Modeling and simulation, vehicle dynamics, and vehicle design and optimization also pose challenges to the traditional automotive engineering field due to the increased difficulties in packaging the components and associated thermal management systems, as well as the changes in vehicle weight, shape, and weight distribution.

4. STATE OF THE ART OF HEVS:

In the past 10 years, many HEVs have been deployed by the major automotive manufacturers. Figure 1.18 shows HEV sales in the United States from 2000 to 2009, and predictions Figure 1.19 shows the US HEV sales breakdown by manufacturer. It is clear that HEV sales have grown significantly over the last 10 years. In 2008, these sales had a downturn which is consistent with conventional car sales that dropped more than 20% in 2008 from the previous year. Another observation is that most HEV sales belong to Toyota, which manufactured the earliest modern HEV, the Prius, and also makes most of the models available (including the Lexus). Table 1.1

shows the current HEVs available in the United States, along with a comparison to the base model of gasoline-powered cars. In the case of the Toyota Prius, the comparison is made to the Toyota Corolla. It can be seen that the price of HEVs is generally 40% more than that of their base models. The increase in fuel economy in HEVs is also significant, in particular for city driving.

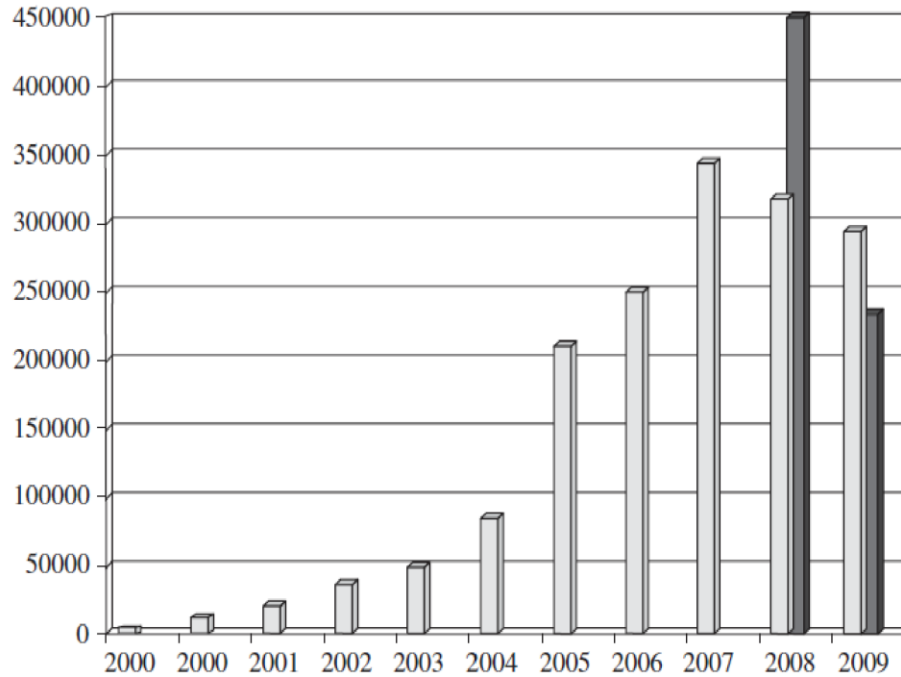


Figure 1.18 Total HEVs sold in the United States from 2000 to 2009 (in thousands): left bar, actual sales number; right bar, predicted**

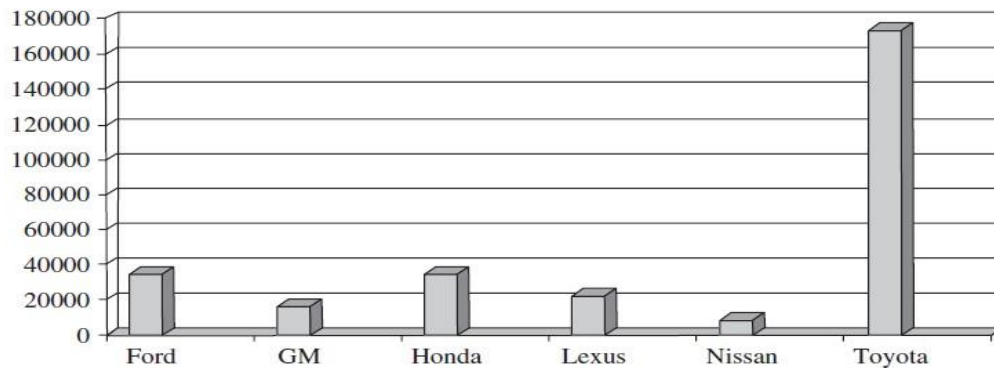


Figure 1.19 Breakdown of HEV sales by model** in the United States in 2009 (in thousands)

Table 1.1 Partial list of HEVs available in the United States

Manufacturer	Model	HEV price (US \$)	Base model price (US \$)	Price increase (%)	HEV MPG		Base MPG		Increase in MPG (%)	
					City	Hwy	City	Hwy	City	Hwy
Toyota	Prius ^a	22 800	15 450	47.6	51	48	26	35	96	37
	Camry	26 400	19 595	34.7	33	34	22	33	50	3
	Highlander	34 900	25 855	35.0	27	25	20	27	35	12
Ford/Mercury	Fusion	27 950	19 695	41.9	41	36	22	34	86	6
	Escape	29 860	21 020	42.1	34	31	22	28	55	11
	Mariner	30 105	23 560	27.8	34	31	21	28	62	11
	Milan	31 915	21 860	46.0	41	26	23	34	78	−24
Honda	Insight ^b	19 800	15 655	26.5	40	43	26	34	54	26
	Civic	23 800	15 655	52.0	40	45	26	34	54	32
Nissan	Altima	26 780	19 900	34.6	35	33	23	32	52	3
Lexus	RX 450h	42 685	37 625	13.4	32	28	18	25	78	12
	GS 450h	57 450	54 070	6.3	22	25	17	24	29	4
	LS 600h	108 800	74 450	46.1	20	22	16	23	25	−4
GM GMC, Chevrolet, and Cadillac Saturn ^c	Tahoe	50 720	37 280	36.1	21	22	15	21	40	5
	Yukon	51 185	38 020	34.6	21	22	15	21	40	5
	Sierra	38 710	20 850	85.7	21	22	15	22	40	0
	Malibu	22 800	21 825	4.5	26	34	22	33	18	3
	Escalade	73 425	62 495	17.5	21	22	13	20	62	10
	Silverado	38 340	29 400	30.4	22	21	13	17	69	24
Chrysler	Aspen ^d	44 700	40 000	11.8	18	19	15	20	38	6
Dodge	Durango ^d	45 900	40 365	13.7	18	19	15	20	38	6

^aComparison to Corolla.

^bComparison to Civic.

^cSaturn Brand vehicle including Vue and Saturn Aura are not offered.

^dChrysler Aspen uses similar platform as Durango but is no longer offered.

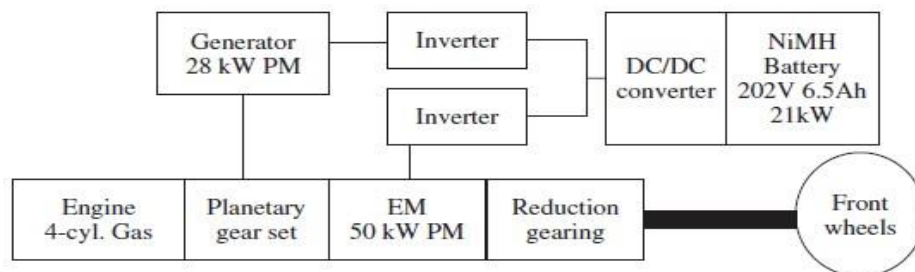


Figure 1.21 The powertrain layout of the Toyota Prius (EM, Electric Machine; PM, Permanent Magnet)

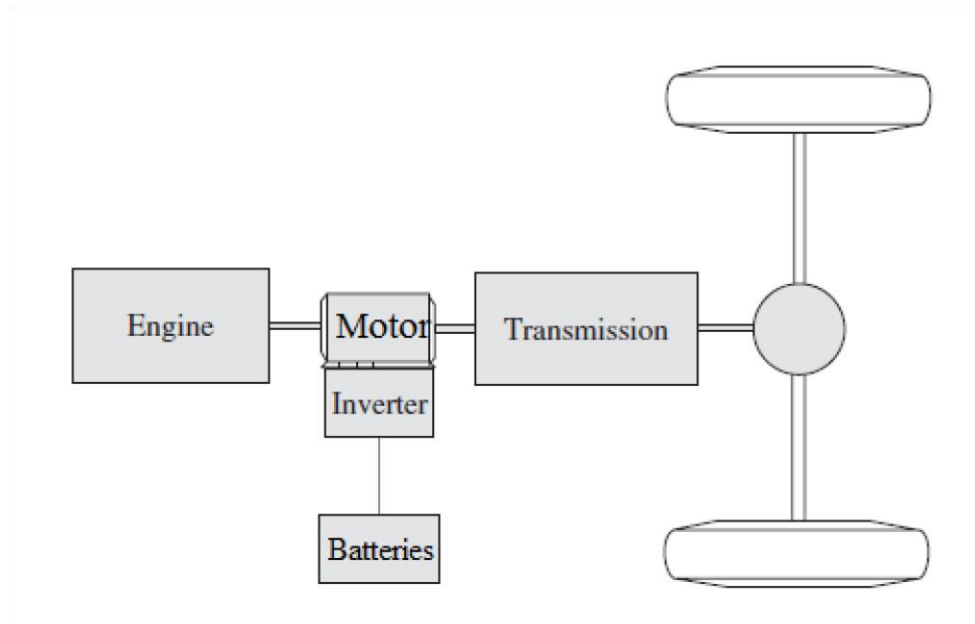


Figure 1.22 The powertrain layout of the Honda Civic hybrid

1. The Honda Civic:

The Honda Civic hybrid has an electric motor mounted between the ICE and the CVT, as shown in Figure 1.22. The electric motor either provides assistance to the engine during high power demand, or splits the engine power during low power demand.

2. The Ford Escape:

The Escape hybrid from the Ford Motor Company (Figure 1.23) is the first hybrid in the SUV category. The Escape hybrid adopted the same planetary gear concept as the Toyota system.

3. The Two-Mode Hybrid:

The GM two-mode hybrid transmission was initially developed by GM (Alison) in 1996, and later advanced by GM, Chrysler, BMW, and Mercedes-Benz with a joint venture named Global Hybrid Cooperation in 2005. The GM two-mode hybrids (Figure 1.24) use two planetary gear sets and two electric machines to realize two different operating modes, namely, high-speed mode and low-speed mode.

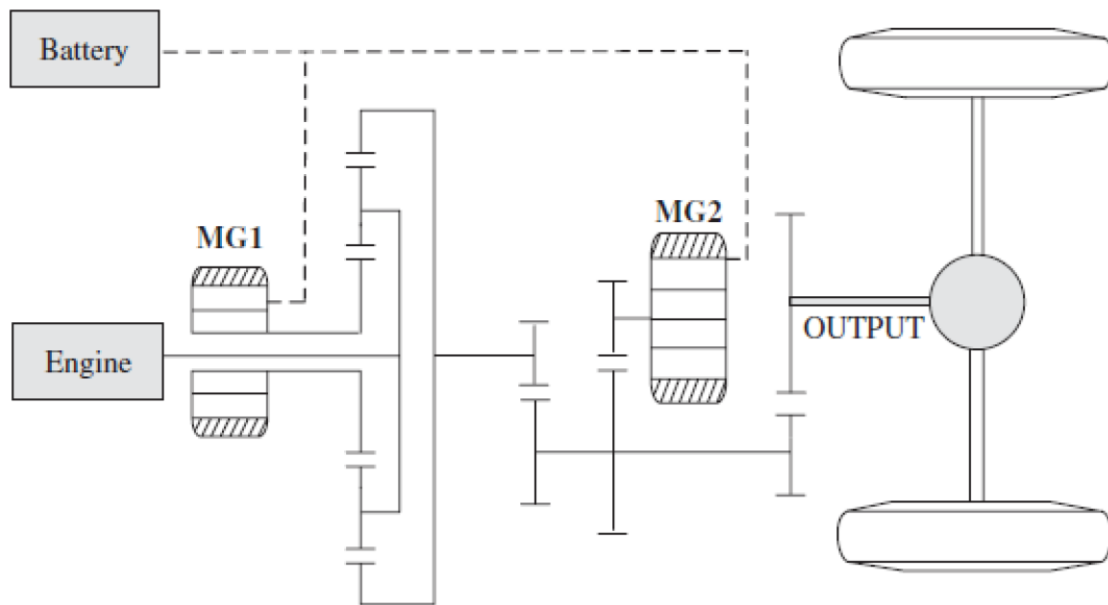


Figure 1.23 The Ford Escape hybrid SUV

5. CHALLENGES AND KEY TECHNOLOGY OF HEVS:

HEVs can overcome some of the disadvantages of battery-powered pure EVs and gasoline powered conventional vehicles. These advantages include optimized fuel economy and reduced emissions when compared to conventional vehicles, and increased range, reduced charging time, and reduced battery size (hence reduced cost) when compared to pure EVs. However, HEVs and PHEVs still face many challenges, including higher cost when compared to conventional vehicles; electromagnetic interference caused by high-power components; and safety and reliability concerns due to increased components and complexity, packaging of the system, vehicle control, and power management:

- **Power electronics and electric machines:** The subject of power electronics and electric motors is not new. However, the use of power electronics in a vehicle environment, poses significant challenges. Environmental conditions, such as extreme high and low temperatures, vibration, shock, and transient behavior are very different from what electric motors and power electronic converters have been used to. Challenges in power electronics in a HEV include packaging, size, cost, and thermal management.
- **Electromagnetic interference:** High-frequency switching and high-power operation of power electronics and electric motors will generate abundant

electromagnetic noise that will interfere with the rest of the vehicle system if not dealt with properly.

- **Energy storage systems:** Such systems are a major challenge for HEVs and PHEVs. The pulsed power behavior and energy content required for the best performance are typically difficult for conventional batteries to satisfy. Life cycle and abuse tolerance are also critical for vehicle applications. At the present time, nickel metal hydride batteries are used by most HEVs and lithium-ion batteries are targeted by PHEVs.
- **Ultra-capacitors** have also been considered in some special applications where power demand is a major concern. Flywheels have also been investigated. The limitations of the current energy storage systems are unsatisfactory power density and energy density, limited life cycle, high cost, and potential safety issues.
- **Regenerative braking control:** Recovering the kinetic energy during braking is a key feature of HEVs and PHEVs. However, coordinating regenerative braking with the hydraulic/frictional braking system presents a major challenge as far as safety and braking performance are concerned.
- **Power management and vehicle control:** HEVs involve the use of multiple propulsion components that require harmonious coordination. Hence, power management is a critical aspect of vehicle control functions in a HEV. A optimized vehicle controller can help achieve better fuel efficiency in a HEV.
- **Thermal management:** Power electronics, electric machines, and batteries all require a much lower operating temperature than a gasoline engine. A separate cooling loop is necessary in a HEV.
- **Modeling and simulation, vehicle dynamics, vehicle design, and optimization:** Due to the increased number of components in a HEV, packaging of the components in the same space is a challenge. Associated vehicle dynamics, vehicle design, and modeling and simulation all involve major challenges.

6. CONCEPT OF HYBRIDIZATION OF THE AUTOMOBILE- PLUG-IN HYBRID ELECTRIC VEHICLES:

1. PHEV:

The PHEV, as the name suggests, differs from a HEV only by the fact that it allows one to plug in a cable running from the vehicle to a household utility wall socket at home or elsewhere to charge the vehicle's battery. To extend the flexibility of the system, it is also possible in principle to use the engine and/or the battery system in the vehicle to generate AC power and feed it back to the utility grid. Since plug-in allows a fair amount of external utility system energy to drive the vehicle, it is helpful to use a larger battery than in a regular HEV. A larger battery is not a required part of the PHEV, but having one definitely benefits fuel economy and also increases the range of the vehicle when fully charged. In a HEV, using a much larger battery may not necessarily be the optimal choice in terms of design, since the ICE is always capable of kicking in, when the battery needs to be charged. People sometimes think that a large battery is mandatory for a PHEV, which may not be the case. How large the battery can be depends on the packaging space available in the vehicle. If the battery size is small, then the benefits from the PHEV will be merely incremental, whereas if it is too big then it can be very expensive and will take longer to recharge from the utility system. Note also that the household utility system may have some limitations on how much current it can sustain in charging a battery system, hence some safeguards are necessary for the plug-in. Since the cost of utility energy at present is much lower than the price of gasoline, it makes sense to use the PHEV, where possible.

2. Constituents of a PHEV:

The same diagram as before, that is, Figure 2.5, applies to a PHEV. The only difference is that it now has an extra connecting socket in the vehicle, from where a lead can be pulled out and plugged into the wall utility outlet. Obviously, when the vehicle is connected to a utility outlet, its propulsion motor is not needed and neither is the ICE, as far as turning the wheels is concerned. However, the vehicle may still need to use auxiliary loads (normally low-voltage loads at 12 V), the air-conditioner (can be low voltage as well), or the heater and some lights. Hence it is appropriate to deliver those loads at low voltage. If fast charging of the battery is necessary, it will also be appropriate to run the ICE and use the propulsion motor as a generator, or have a separate generator for this purpose. Depending on the scheme used, changes in the gear train system are called for. Even though the whole process of interconnection between the utility and the PHEV system is simple in principle, there are quite a few considerations to be taken into account, as will be obvious from the possible architecture for such a vehicle shown in Figure 2.8.

From Figure 2.8 it is apparent that in order to charge the battery, one path goes directly from the wall outlet to the battery, through a transformer isolation and a

rectifier or DC–DC converter combination. This situation is directly involved with the plug-in part of the system. The bottom part of the figure shows that the charging process is done by either driving a standalone alternator, or using the propulsion motor itself run as a generator, ultimately charging the battery. Of course, it is understood that, when plugged in, the vehicle is stationary and the wheels are not moving. Even though the process indicated in the bottom part of Figure 2.8 is not involved with directly with the plug-in, an overall power management process has to coordinate both the plug-in and the ICE, since there may be a situation when fast charging becomes necessary, and both the plug-in and the ICE (in generation mode) need to run concurrently. Finally, note the inclusion of a bidirectional converter in the plug-in part of the figure. This covers the possibility that in future the utility regulations may allow power to be fed back into the utility grid from the vehicle, assuming it has enough power to do so. This issue is not an immediate consideration within the automotive industry at present. However, the possibility may in fact help use the vehicle as an emergency generator to light a home in case there is a utility power failure.

3. Comparison between the HEV and PHEV:

Fundamentally the only difference between the HEV and PHEV is related to the upper part of Figure 2.8, where the wall outlet is used to charge the battery. The size of the battery may be substantially different. In addition, as indicated above, the plug-in system has to be properly coordinated with the rest of the charging process and the overall power management in the vehicular system.

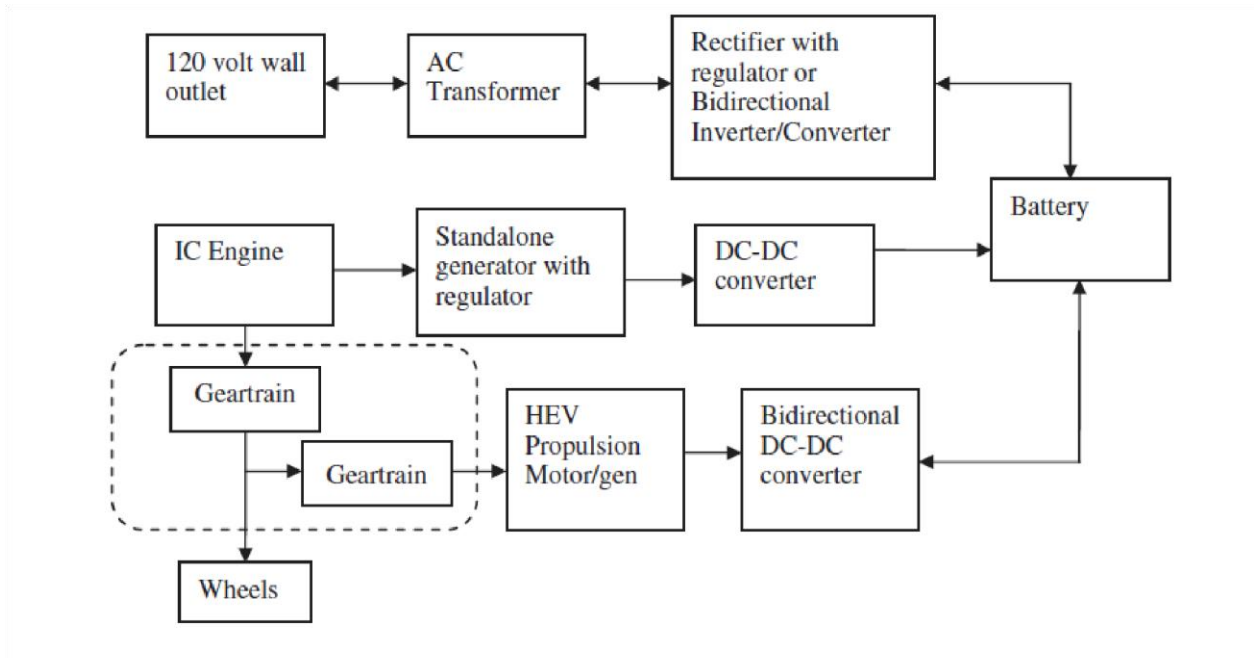


Figure 2.8 A possible architecture for the plug-in hybrid vehicle and home outlet interface

7. DESIGN AND CONTROL PRINCIPLES OF PLUG-IN HYBRID ELECTRIC VEHICLES:

PHEV Architectures:

Figure 5.3 shows the architecture of a series PHEV. In the series configuration, the gasoline engine output is connected to a generator. The electricity generated by the generator can be used to charge the battery or supply power to the powertrain motor. The electric motor is the only component driving the wheels. The motor can be an induction motor, a switched reluctance motor, or a permanent magnet motor. The motor can be mounted on the vehicle in the same way as in a conventional vehicle, without the need for transmission. In-wheel hub motors can also be chosen. In the series configuration, the motor is designed to provide the torque needed for the vehicle to drive in all conditions. The engine/generator can be designed to provide the average power demand.

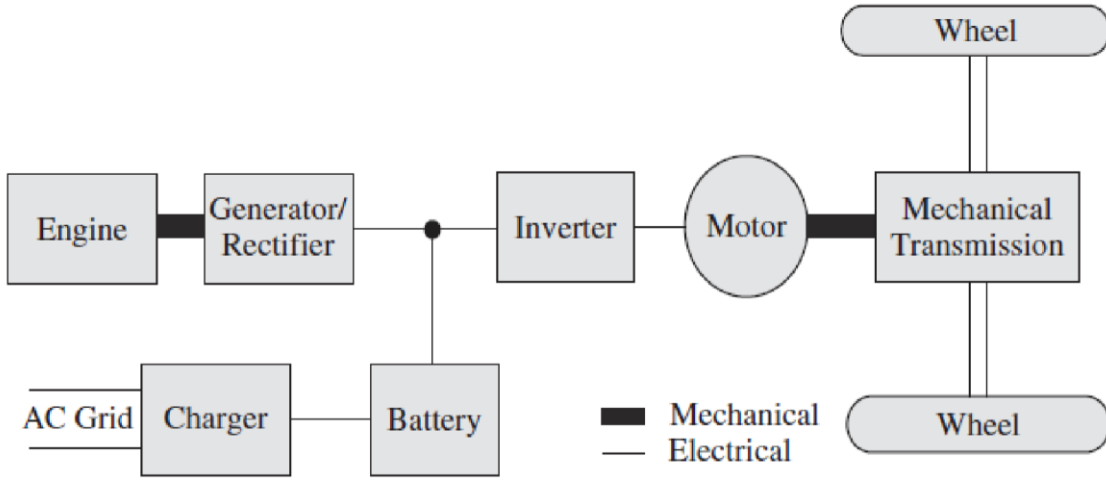


Figure 5.3 Series architecture of a PHEV

Parallel and complex hybrids can be designed as PHEVs as well. In parallel and complex configurations, the engine and the motor can both drive the wheels. Therefore, the motor size can be smaller than those in series configurations. In comparison to regular hybrid electric vehicles (HEVs), a parallel or complex PHEV will have a larger-sized battery pack that provides longer duration for extended electric drive. The engine is turned on whenever the vehicle's power demand is high.

PHEV Design and Component Sizing

The main components of a PHEV are the powertrain motor and the battery pack. Using the vehicle resistive force and acceleration requirement, the driving motor can be sized. The total vehicle force is

$$F_{TR} = mg \sin \alpha + mgC_0 + mgC_1 V^2 + \frac{1}{2} \rho C_D A_F V^2 + m \frac{dV}{dt} \quad (5.10)$$

where m is the vehicle mass, α is the road slope in radians, g is Earth's gravity, which is 9.8 m/s^2 , C_0 and C_1 are rolling coefficients, ρ is air density, C_D is the aerodynamic coefficient, A_F is frontal area in meters squared, and V is vehicle speed. The total vehicle resistance is plotted in Figure 5.10.

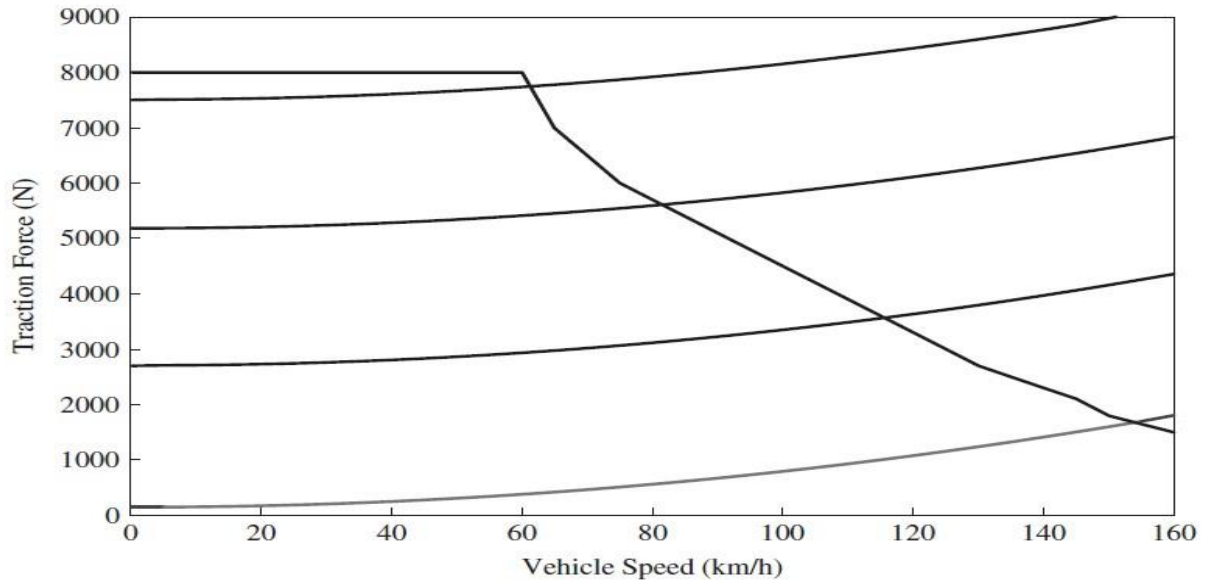


Figure 5.10 Traction force of a medium-sized passenger car

At any given vehicle speed, the power at the wheels is

$$P = F_{TR}V = \left(mg \sin \alpha + mgC_0 + mgC_1V^2 + \frac{1}{2}\rho C_D A_F V^2 + m \frac{dV}{dt} \right) V \quad (5.11)$$

UNIT 5

ELECTRIC AND HYBRID VEHICLE – CASE STUDIES

Parallel Hybrid, Series Hybrid - Charge Sustaining, Charge Depleting. Hybrid Vehicle Case Study –Toyota Prius, Honda Insight, Chevrolet Volt. 42 V System for Traction Applications. Lightly Hybridized Vehicles and Low Voltage Systems. Electric Vehicle Case Study - GM EV1, Nissan Leaf, Mitsubishi Miev. Hybrid Electric Heavy-Duty Vehicles, Fuel Cell Heavy Duty Vehicles.

1. INTRODUCTION:

The hybrid vehicles can also be classified based on the degree of hybridization into mild, power and energy hybrids. This classification is based on the powertrain size deviation from a conventional vehicle. The progression from mild to energy hybrids is related to the degree of downsizing the engine and upsizing the electrical and energy storage components.

The hybrid vehicles are also classified as charge-depleting or charge-sustaining hybrids depending on whether or not the energy storage device needs to be charged from an external source or is self-sustaining with its on-board electricity generation capability. The BEVs are an extreme example of charge-depleting vehicle, which does not have any on-board electricity generation capability. PHEVs are also examples of charge-depleting hybrids; these vehicles operate in the battery-only electric mode for certain distances and then as HEV for longer distances. The PHEVs are essentially HEVs but with a large-enough energy storage system that will get depleted of its charge and will need to be plugged in to restore operation in the electric-only mode. The charge-sustaining vehicles, such as the hybrids available commercially, have a smaller capacity energy storage system; the on-board IC engine and electric generator are sufficient to restore the charge in its energy storage device. The charge-sustaining hybrids never need to be plugged in.

2. SERIES AND PARALLEL HYBRIDS:

The HEVs evolved out of two basic configurations: Series and parallel. A series hybrid is one in which only one energy converter can provide propulsion power. The IC engine acts as a prime mover in this configuration to drive an electric generator that delivers power to the battery or energy storage link and the propulsion motor.

The components' arrangement of a series HEV is shown in Figure 3.2. A parallel hybrid is one in which more than one energy conversion device can deliver propulsion power to the wheels. The IC engine and the electric motor are configured in parallel with a mechanical coupling that blends the torque coming from the two sources. The components' arrangement of a parallel hybrid is shown in Figure 3.3.

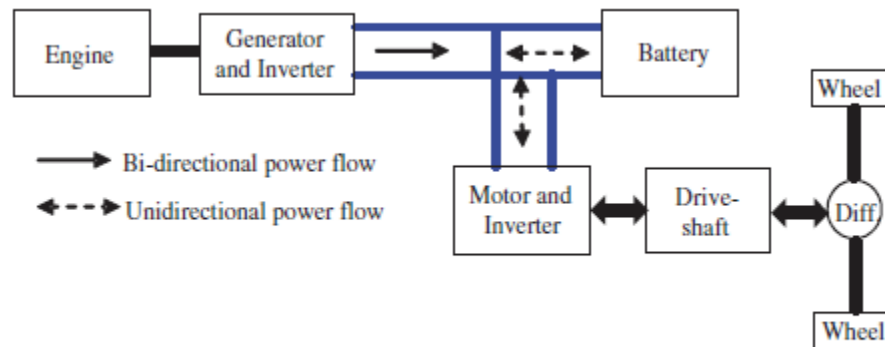


FIGURE 3.2 Series HEV powertrain.

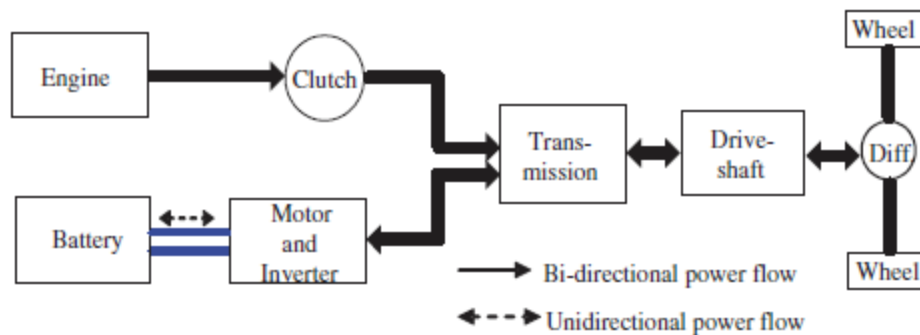


FIGURE 3.3 Parallel HEV powertrain.

Series HEV is the simpler type where only the electric motor provides all the propulsion power to the wheels. A downsized IC engine drives a generator, which supplements the batteries and can charge them when they fall below a certain state of charge (SoC). The power required to propel the vehicle is provided solely by the electric motor. Beyond the IC engine and the generator, the propulsion system is exactly the same as that in an EV; the electric motor power requirements are exactly the same as that in an EV.

The drawback of the series configuration is the size of the electrical traction motor, which has to be rated for the maximum power requirement of the vehicle.

The drawback can be removed if the engine is used in parallel with the electric machine to supply power to the wheels. This is called a parallel architecture where both the IC engine and the electric motor are connected to the driveshaft through transmission and clutch. In the parallel HEV, the power requirements of the electric motor in the parallel hybrid are lower than that of an EV or series hybrid, since the IC engine complements for the total power demand of the vehicle. The propulsion power may be supplied by the IC engine alone, by the battery-motor set, or by the two systems in combination. Both series and parallel hybrids come in a variety of types. The mission of the vehicle and the optimum design for that mission dictates the choice. If the HEV is to be basically an EV with an IC engine assist for achieving acceptable range, then the choice could be series hybrids with the IC engine ensuring that the batteries remain charged all the time. On the other hand, if the hybrid vehicle is to be basically a vehicle with almost all the performance characteristics and comforts of an IC engine vehicle but with lower emission and fuel usage standards, then the choice could be a parallel configuration. Parallel HEVs have been built with performance that is equal, in all aspects of normal operation, to a conventional car. However, some series hybrid vehicles have also been built that perform as well as the IC engine vehicles.

The advantages of a series hybrid architecture can be summarized as follows:

- Flexibility of location of engine-generator set.
- Simplicity of drivetrain.
- Suitable for short trips with stop and go traffic.

The disadvantages of a series hybrid architecture are as follows:

- It needs three propulsion components: IC engine, generator and motor.
- The motor must be designed for the maximum sustained power that the vehicle may require, such as when climbing a high grade. However, the vehicle operates below the maximum power for most of the time.
- All three drivetrain components need to be sized for maximum power for long-distance sustained, high-speed driving. This is required since the batteries will exhaust fairly quickly leaving IC engine to supply all the power through the generator.

The advantages of a parallel hybrid architecture are as follows:

- It only needs two propulsion components: IC engine and motor/generator. In parallel HEV, motor can be used as generator and vice versa.
- A smaller engine and a smaller motor can be used to get the same performance, until batteries are depleted. For short-trip missions, both can be rated at half the maximum power to provide the total power, assuming that

the batteries are never depleted. For long-distance trips, engine may be rated for the maximum power, while the motor/generator may still be rated to half the maximum power or even smaller.

The disadvantages of a parallel hybrid architecture are as follows:

- The control complexity increases significantly, since power flow has to be regulated and blended from two parallel sources.
- The power blending from the IC engine and the motor necessitates a complex mechanical device.

A simpler architecture with reduced components capable of delivering good acceleration performance is the ‘through-the-road’ parallel architecture. This architecture has one engine powering the front wheels and one electric machine powering the rear wheels. The engine is the primary propulsion unit of the vehicle, while the electric machine is used for load leveling supplying the propulsion power during acceleration and capturing vehicle kinetic energy through regeneration during deceleration. When the charge in the energy storage device falls below a set level, the engine is commanded to deliver torque in excess of what is required to meet the driver demand.

The additional energy supplied by the engine is used to charge the energy storage device by operating the rear electric machine as a generator. Power is transferred from the engine to the electric machine through the road, and hence the name *through-the-road* parallel. This charge-sustaining mechanism may not be that efficient, but the architecture offers great simplicity without the need for a coupling device to blend the torque from the engine and the electric motor. The vehicle can deliver good acceleration performance using the parallel operation of two propulsion units; the fuel efficiency can also be improved by about 20%–30% compared to a similarly sized IC engine vehicle. Additionally, the architecture gives four-wheel drive capability.

3. CHARGE-DEPLETING MODE (CD):

CD mode refers to the PHEV operation mode in which the battery SOC on an average decreases while it may fluctuate along this trend. CD mode is frequently used at the first phase of PHEV operations, in which the SOC of the battery is sufficient to power the vehicle largely by electricity for a certain range. It prioritizes the use of electricity by drawing most of the power from the battery pack as long as the battery SOC stays above the preset threshold. However, if the demanded road

power exceeds the battery power, the engine will also be running to assist the electric machine, thus enhancing the output tractive power.

CD mode is the primary operation mode in PHEV operations. In most city-driving and suburban-commuting cases, the round-trip distances are well within the PHEV battery power range. Thus, CD mode is largely utilized to take advantage of electric driving so that less fuel is used and fewer emissions are produced.

The extent of CD mode depends on the battery energy capacities and the frequencies of external battery charging. A larger battery pack with higher energy density would result in a longer CD mode range. However, this also contributes to much higher battery costs as well as vehicle weight increases. Recharging the PHEVs also helps to extend the CD range. With the installation of charging stations and the implementation of charging infrastructures at public places such as workplaces, parking lots, or in front of grocery stores, PHEVs can be readily recharged and CD ranges can be significantly increased in daily driving.

4. CHARGE-SUSTAINING MODE (CS):

CS mode refers to the PHEV operation mode in which the battery SOC on average maintains a certain level while it may frequently fluctuate above or below this level. CS mode utilizes both the engine and the electric machine to supply the vehicle power while keeping the SOC of the battery pack at a constant level. It is equivalent to the HEV operation mode in which the engine is mostly running within its optimal fuel efficiency range and the electric machines supply the power ripples. Engine power assistance and hybrid battery charging are realized in the CS mode to extend the driving range.

In PHEV operations, CS mode is more often used after the CD range when the battery power is discharged to a certain low threshold. Once the battery power is insufficient to power the vehicle on its own, the engine starts to supply the vehicle with petroleum combustion power. Both the engine and the electric machine operate together, coordinated under HEV operation mode. This takes advantage of the HEV operation benefits; so, high fuel efficiency is gained while the battery SOC is maintained at a certain level. Thus, the CS mode operation significantly increases the PHEV driving range compared with the CD mode without further increasing battery costs.

The combination of CD and CS mode enables energy use from two energy sources. The electricity works as the primary energy carrier to drive the vehicles in the preferred CD mode. The batteries can be recharged from external electric energy sources by plugging the vehicles into external power outlets. They can also be recharged by operating the vehicle in the CS mode, in which the engine utilizes the secondary energy carrier, the petroleum fuel, to generate power. In PHEVs, both energy sources are carried onboard the vehicles as they are stored in battery packs and fuel tanks. However, electricity is much preferred because it can be generated by a wide variety of cheaper energy sources, including coal, nuclear, natural gas, wind, hydro, and solar energy, and it greatly reduces vehicle tailpipe emissions. Thus, large packs of battery are normally required on PHEVs while relatively small fuel tanks are used.

5. HYBRID VEHICLE CASE STUDY

1. TOYOTA PRIUS:

PRIUS TECHNICAL SPECIFICATIONS

HYBRID SYNERGY DRIVE	
Type	Series/parallel, full hybrid
System output (bhp/kW)	121/90
ENGINE	
Engine type	2ZR-FXE (Atkinson cycle)
No. of cylinders	Four in-line
Valve mechanism	16-valve DOHC with VVT-i
Bore x stroke (mm)	80.5 x 88.3
Displacement (cc)	1,798
Compression ratio	13.0:1
Fuel system	EFI
Octane No.	95 or greater
Max. power (bhp/kW @ rpm)	97/72 @ 5,200
Max. torque (Nm @ rpm)	142 @ 3,600
Emissions level	Euro 6
ELECTRIC MOTOR	
Motor type	Permanent magnet, synchronous
Max. power (bhp/kW)	71/53
Max. torque (Nm)	163

HIGH-VOLTAGE BATTERY	
Battery type	Nickel-metal hydride
Nominal voltage (SC V)	201.6
No. of battery modules	28
Battery capacity (kWh)	1.31
TRANSMISSION	
Transmission type	Electric CVT
Differential gear ratio	2.834
PERFORMANCE	
Max. speed (mph)	112 99 AWD-i
0-62mph acceleration (sec)	10.6 10.9 AWD-i

FUEL CONSUMPTION (WLTP)			
Combined cycle (mpg)		59.6 – 68.3 58.7 – 64.7 (AWD-i)	
Fuel tank capacity (l)		43	
EMISSIONS (WLTP) & INSURANCE		15in wheel	17in wheel
CO ₂ – combined cycle (g/km)		94	104 108 - 109 (AWD-i)
Insurance groups		13E or 14E	
SUSPENSION			
Front		MacPherson strut with anti-roll bar	
Rear		Double wishbone with anti-roll bar	
BRAKES			
Front		Ventilated discs	
Rear		Solid discs	
Disc size (diameter x width, mm)	Front	255 x 25	
	Rear	259 x 9	
Parking brake		Pedal-type	

STEERING		15in wheel	17in wheel
Steering type		Electric power-assisted rack and pinion	
Steering ratio	15in wheel	13.4:1	
	17in wheel	13.6:1	
Turns lock-to-lock	15in wheel	2.84	
	17in wheel	2.85	
Turning radius – tyre (m)	15in wheel	5.1	
	17in wheel	5.4	
TYRES		15in wheel	17in wheel
		195/65 R15	215/45 R17
EXTERIOR DIMENSIONS		15in wheel	17in wheel
Overall length (mm)		4,540	
Overall width (mm)		1,760	
Overall height (mm)		1,470	
Wheelbase (mm)		2,700	
Front track (mm)		1,530	1,510
Rear track (mm)		1,520	1,540
Front overhang (mm)		950	

Rear overhang (mm)	890
Ground clearance (mm)	123
Drag coefficient (Cd)	0.24
INTERIOR DIMENSIONS	
Length (mm)	2,110
Width (mm)	1,490
Height (mm)	1,195
LUGGAGE COMPARTMENT	
VDA capacity, rear seats up (l)	457 (with temporary spare wheel) 502 with tyre repair kit
VDA, rear seats down, loaded to tonneau cover (l)	1,054
VDA, rear seats down, loaded to tonneau roof (l)	1,633
WEIGHTS	
Kerb weight (kg)	1,375 – 1,400
Gross vehicle weight (kg)	1,775
Towing capacity –unbraked/braked (kg)	725

**Economic and environmental performance comparison
among Prius family models sold in the US (model year 2001–2012)**^{[202][203]}

Vehicle	Model year	EPA city mileage (mpg)	EPA highway mileage (mpg)	Tailpipe CO ₂ emissions	EPA air pollution score Calif/others ⁽¹⁾	Annual petroleum use (barrel)
Prius 1st gen (NHW11)	2001–2003	42 mpg.us (5.6 L/100 km)	41 mpg.us (5.7 L/100 km)	217 g/mi (135 g/km)	—	8.0
Prius 2nd gen (XW20)	2004–2009	48 mpg.us (4.9 L/100 km)	45 mpg.us (5.2 L/100 km)	193 g/mi (120 g/km)	9/7 LEV-II SULEV	7.2
Prius 3rd gen (XW30)	2010–2015	51 mpg.us (4.6 L/100 km)	48 mpg.us (4.9 L/100 km)	178 g/mi (111 g/km)	9/7 SULEV II	6.6
Prius 4th gen (XW50)	2016–2021	54 mpg.us (4.4 L/100 km)	50 mpg.us (4.7 L/100 km)	170 g/mi (110 g/km)	9/7 California LEV-III SULEV30/PZEV	6.3
Prius v (ZVW41)	2012	44 mpg.us (5.3 L/100 km)	40 mpg.us (5.9 L/100 km)	212 g/mi (132 g/km)	8/7 LEV-II SULEV	7.8
Prius c (NHP10)	2012	53 mpg.us (4.4 L/100 km)	46 mpg.us (5.1 L/100 km)	178 g/mi (111 g/km)	—	6.6
Prius Plug-in Hybrid (ZVW35)	2012	Gasoline equivalent in EV mode (blended operation)	Hybrid mode (combined)	133 g/mi (83 g/km)	All-electric range (blended mode)	
		95 mpg-e (35 kW·h/100 mi)	50 mpg.us (4.7 L/100 km)		11 mi (18 km)	

Source: US Department of Energy and US Environmental Protection Agency^{[202][203]} All ratings correspond to EPA 5-cycle testing procedure (2008 and beyond).

Note: (1) First score is for California and Northeastern states, the second score is for the other states and D.C. Super Ultra Low Emission Vehicle (SULEV) is a US classification for conventionally powered vehicles designed to produce minimal emissions of certain categories of air pollution.

2. HONDA INSIGHT: Specs Overview



2wd



Manual



Petrol/Electric
Hybrid



3dr

Power (bhp)	66 bhp
Acceleration 0-60 mph	12.1 secs
Miles per tank	730 miles
Insurance group get an insurance quote?	23
Annual road tax	£0 - £200 See all rates
Dimensions (mm)	Length 3945mm X Width 1695mm

Costs



What is the price to buy a used and new Insight 2000 and what is the overall running cost?

Fuel consumption  Pre-2017 test standard Explanation	83 mpg
Insurance group	23
Annual road tax	£0 - £200 See all rates
Price when new	£17,170
Used price range	£690 - £2,215

Dimensions



What are the dimensions of Insight 2000 and its fuel capacity and the overall weight?

Fuel Capacity	40 litres
Weight	850kg
Length	3945mm
Width	1695mm
Height	1355mm
Wheelbase	2400mm
Turning Circle	9m

Performance



What is the BHP, top speed, torque, and CO2 emissions of Insight 2000?

Power	66 bhp
Top Speed	112 mph
0-60 mph	12.1 secs
Torque	113 Nm, 83 ft-lb
CO ₂ Emissions	80 g/km
Euro Emissions Standard	4
Miles Per Tank	730 miles

Equipment list & trim options

^ Hybrid Basic equipment

- ABS
- Air conditioning
- Body coloured bumpers
- Central locking
- Climate control
- Cloth seat trim
- Driver`s airbag
- Electric mirrors
- Front electric windows
- Metallic Paint
- PAS
- Passenger`s airbag
- Remote locking
- Space saver spare wheel

Engine



What is the Engine size, fuel type, transmission, and Gearbox of Honda Insight 2000?

Engine Size	995cc
Cylinders	3
Valves	12
Fuel Type	Petrol/Electric Hybrid
Transmission	Manual
Gearbox	5 Speed
Drivetrain	Front wheel drive



Cabin & Luggage

What are the number of seats and doors in Honda Insight 2000 and its boot size?

Doors	3
Seats	2
Luggage Capacity	461 litres
Unbraked Towing Weight	-
Braked Towing Weight	-

Honda Insight	
	
Overview	
Manufacturer	Honda
Production	1999–2006 2009–2014 2018–2022
Model years	2000–2006 2010–2014 2019–2022
Body and chassis	
Class	Subcompact car (2000–2006) Compact car (2010–2022)
Body style	3-door liftback (2000–2006) 5-door liftback^[1] (2010–2014) 4-door sedan (2019–2022)
Layout	Front-engine, front-wheel-drive

First generation (ZE1)



Overview

Production	November 1999 – September 2006
Model years	2000–2006
Assembly	Japan: Tochigi (1999–2004) Japan: Suzuka, Mie (2004–2006)

Body and chassis

Class	Subcompact car
Body style	3-door liftback

Powertrain

Engine	1.0 L ECA1 I3
Electric motor	144 V 10 kW (13 hp) at 3000 rpm ULEV/SULEV
Transmission	5-speed manual CVT automatic CVT (2001–2006)
Hybrid drivetrain	Parallel hybrid (Honda Integrated Motor Assist)
Battery	6.5 AH Ni-MH 144 V (120 cells @ 1.2V)

Dimensions

Wheelbase	2,400 mm (94.5 in)
Length	3,945 mm (155.3 in)
Width	1,695 mm (66.7 in)
Height	1,355 mm (53.3 in)
Curb weight	Manual w/o AC 838 kg (1,847 lb) Manual w/ AC 852 kg (1,878 lb) CVT w/ AC 891 kg (1,964 lb)

Chronology

Predecessor	Honda CR-X Honda EV Plus
Successor	Honda Insight (second generation) Honda CR-Z

Second generation (ZE2/ZE3)



Overview

Also called	Honda Insight Hybrid
Production	2009–2014
Model years	2010–2014
Assembly	Japan: Suzuka, Mie
Designer	Tetsuji Morikawa ^[48]

Body and chassis

Class	Compact car
Body style	5-door liftback
Related	Honda Fit/Jazz (2nd gen.) Honda City (5th gen.) Honda CR-Z Honda Freed (1st gen.)

Powertrain

Engine	1.3 L LDA-MF3 I4 (gasoline hybrid)
Electric motor	DC brushless motor 13 hp (9.7 kW) @ 1500 rpm 58 lb·ft (79 N·m) @ 1000 rpm ULEV/AT-PZEV

Insight Exclusive (Japan Only):
Gasoline: 1.5 L LEA I4
1,497 cc (91.4 cu in)
SOHC 16-valve i-VTEC

· (CVT) – 111 hp (83 kW) @ 6000rpm 107 lb·ft (145 N·m) @ 4800rpm Electric: DC brushless motor – MF6 Model 14 hp (10 kW) @ 1500 rpm
58 lb·ft (79 N·m) @ 1000 rpm[2]

Transmission	CVT
Hybrid drivetrain	Parallel hybrid (Honda Integrated Motor Assist with Eco Assist)

Dimensions

Wheelbase	2,552 mm (100.5 in)
Length	4,376–4,390 mm (172.3–172.8 in)
Width	1,695 mm (66.7 in)
Height	1,425 mm (56.1 in)
Curb weight	1,237 kg (2,727 lb)

Chronology

Predecessor	Honda Fit/Aria (Japan)
Successor	Honda Grace (Japan)

3. CHEVROLET VOLT:

Chevrolet Volt	
	
2012 Chevrolet Volt	
Overview	
Manufacturer	General Motors
Also called	Buick Velite 5 Holden Volt Opel Ampera Vauxhall Ampera
Production	December 2010 – February 2019 ^[1]
Model years	2011–2019
Assembly	United States: Detroit, Michigan (Detroit/Hamtramck Assembly)
Designer	Jelani Aliyu
Body and chassis	
Class	Compact car (C)
Body style	5-door liftback
Layout	Front-engine, front-wheel drive
Platform	GM Delta II
Related	Cadillac ELR Chevrolet Malibu Hybrid
Powertrain	
Engine	1× 63 kW (84 hp) 1398 cc <i>EcoFLEX LUU I4</i> (gasoline) ^[2]
Electric motor	1× 111 kW (149 hp) 1× 55 kW (74 hp) permanent magnet motor/generators
Transmission	1-speed <i>Voltec 4ET50</i> Multi-mode electric transaxle
Hybrid drivetrain	Series hybrid/Parallel hybrid (GM Voltec) ^{[3][4]}
Battery	First generation 16.0 kWh lithium-ion (2011–2012) ^[5] 16.5 kWh lithium-ion (2013–2014) ^[6] 17.1 kWh lithium-ion (2015) ^[7] Second generation 18.4 kWh lithium-ion (2016–2019) ^[8]
Range	First generation 380 miles (610 km) EPA (2011–2015) ^[9] Second generation 420 miles (680 km) EPA (2016–2019) ^[8]
Electric range	First generation 35 miles (56 km) EPA (2011–2012) ^[10] 38 miles (61 km) EPA (2013–2015) ^[9] Second generation 53 miles (85 km) EPA (2016–2019) ^[11]
Plug-in charging	3.3 kW AC (2011–2015) 3.6 kW AC (2016–2019) 7.2 kW AC (2019 option)
Dimensions	
Wheelbase	2,685 mm (105.7 in) ^[2]
Length	4,498 mm (177.1 in)
Width	1,788 mm (70.4 in)
Height	1,438 mm (56.6 in)
Curb weight	1,721 kg (3,794 lb)

Comparison of the Volt's first and second generation EPA ratings for all-electric range and fuel economy ¹ (EPA five-cycle tests: varying driving conditions and climate controls)				
Model Year	All-electric range	Fuel economy Gasoline only	Fuel economy EV mode (MPG-e)	Comments
2011 ^{[10][122]}	35 mi (56 km)	37 mpg. _{US} (6.4 L/100 km)	93 mpg. _{US} (2.5 L/100 km) equivalent	All ratings combined city and highway Overall combined gasoline-electric fuel economy rating of 60 mpg. _{US} (3.9 L/100 km; 72 mpg. _{imp}) equivalent (MPG-e)
2012 ^[98]	35 mi (56 km)	37 mpg. _{US} (6.4 L/100 km)	94 mpg. _{US} (2.5 L/100 km) equivalent	All ratings combined city and highway EV mode city 95 mpg. _{US} (2.5 L/100 km) equivalent EV mode highway 93 mpg. _{US} (2.5 L/100 km) equivalent Energy consumption of 36 kWh per 100 miles.
2015 ^{[11][112]}	38 mi (61 km)	37 mpg. _{US} (6.4 L/100 km)	98 mpg. _{US} (2.4 L/100 km) equivalent	All ratings combined city and highway Overall combined gasoline-electric fuel economy rating of 60 mpg. _{US} (3.9 L/100 km; 72 mpg. _{imp}) equivalent (MPG-e)
2016/19 ^{[11][112][113]}	53 mi (85 km)	42 mpg. _{US} (5.6 L/100 km)	106 mpg. _{US} (2.2 L/100 km) equivalent	All ratings combined city and highway Overall combined gasoline-electric fuel economy rating of 77 mpg. _{US} (3.1 L/100 km; 92 mpg. _{imp}) equivalent (MPG-e)

4. 42 V SYSTEM FOR TRACTION APPLICATIONS:

Traction Batteries for EV and HEV Applications:

Battery Requirements for Typical Traction Applications:

Traction applications have traditionally been jobs for Lead Acid batteries but the limitations of Lead Acid batteries, together with the high cost of alternatives, have in turn limited the range of potential battery powered traction applications. A typical family car would need a battery capacity of about 40 KWh to provide a one way range of 200 miles and a 40 KWh Lead Acid battery weighs 1.5 tons. The situation is changing however as new battery chemistries and supporting technologies have brought with them new technical and economic benefits making battery power viable for traction applications that were previously uneconomic or impractical. In particular, the use of light weight Nickel Metal Hydride and Lithium batteries instead of the heavy and bulky Lead Acid batteries has made practical electric vehicles and hybrid electric vehicles possible for the first time.

General Requirements:

It goes without saying that low cost, long life (more than 1000 cycles), low self-discharge rates (less than 5% per month) and low maintenance are basic requirements for all applications. Traction batteries generally operate in very harsh operating environments and must withstand wide temperature ranges (-30°C to $+65^{\circ}\text{C}$) as well as shock, vibration and abuse. Low weight however is not always a priority since heavy weight provides stability for material handling equipment such as fork lift trucks and the grip needed by aircraft tugs for pulling heavy loads. Low weight is however essential for high capacity automotive EV and HEV batteries used in passenger vehicles and this rules out Lead Acid for these applications. Protection circuits are also essential for batteries using non-Lead Acid chemistries.

12 Volt Automotive SLI (Starting, Lighting and Ignition) Battery Operating Requirements:

- One short duration deep discharge (50% Depth of Discharge (DOD) with at least 5C rate) followed by trickle charging.
- Battery is essentially constantly fully charged.
- No prolonged operation with deep discharge.
- Typical capacity 0.4 - 1.2 kWh (33 Ah - 100Ah.)
- Peak power 2.4 -3.6 kW (200 - 300 Amps).

Power Net 36/42 Volt Battery Operating Requirements:

- One deep discharge followed by intermittent high current loads.
- No prolonged operation with deep discharge.
- High energy throughput and high cycle life essential, especially if stop/start launch assist function used.
- Tolerant to repeated high current pulses are n
- Typical capacity over 1 kWh.
- Peak power 5 to12 kW.

5. LIGHTLY HYBRIDIZED VEHICLES AND LOW VOLTAGE SYSTEMS:

HEVs can be categorized into three groups: micro hybrids, mild hybrids, and full hybrids.

MICRO HYBRIDS: Micro hybrids employ a modest electric portion in the power systems. The typical power rating for a micro hybrid sedan is between 3 and 5 kW. Micro hybrids normally refer to hybrid vehicles with the start–stop or idle–stop systems, which automatically shut down the engines when vehicles are coasting, braking, or stopped according to certain road conditions, and restart the engines when the speed is regained. The added electric power system can also be used to help supply power to driving accessories such as power steering and air conditioning. Some micro hybrids are also capable of certain levels of regenerative braking. Although micro hybrids are one of the simplest hybrids among the various hybrid configurations, they can provide up to 10% of fuel economy benefits, especially in urban driving situations, where frequent stop-and-go is inevitable.

Micro hybrids incorporate only a small portion of the electric system, normally a small motor. This results in a relatively simple structural change and cheaper re-engineering costs while significantly increasing fuel economy and cutting air emissions. Therefore, many auto manufacturers applied this technology during the initial transit from conventional petroleum-powered vehicles to HEVs.

BMW's micro hybrids incorporated the efficient dynamics technologies aimed at reducing fuel consumption and air emissions. Both start-and-stop and regenerative braking functions are available in its micro hybrids. Volkswagen also equipped its micro hybrid fleets with similar features under the name of Blue Motion Technologies. FIAT introduced the PUR-O2 in a range of its micro hybrid models, and Mercedes developed the micro hybrid drive (MHD) onto its Smart hybrid, which is reported to increase fuel economy by nearly 8%.

MILD HYBRIDS: Mild hybrids have a higher level of electric power rating, typically ranging from 7 to 15 kW for a sedan. Consequently, a higher level of fuel economy gain can be achieved, saving up to 20% in fuel compared with conventional combustion vehicles. Propulsion systems in mild hybrids normally consist of electrical motor–generators between the engine crank shafts and the transmission input shafts. The added motor–generators provide the vehicle with the start–stop function, regenerative braking function, and additional electric power to drive the accessories. Some of the mild hybrids can also provide a modest level of power assistance to the engine.

Similar to micro hybrids, mild hybrids are relatively cost-effective because they require minimal vehicle platform reconstructions and typically maintain the

fundamental manufacturing process. The high diameter-to-length ratio of the electric machine results in a high motor inertia such that the original flywheel of the engine can be replaced by the electric machine. Moreover, the electric machine can also function to start the engine and charge the battery; thus, the added costs of the electric machine and its supporting power electronics are offset by the removal of the starter motor and the alternator from the vehicle. As the manufacturing lines are largely retained and no significant changes are required, total costs essentially remain unchanged.

Mild hybrids have been developed by many auto manufacturers. Honda developed the integrated motor assist (IMA) system in 1999 and applied it onto the Honda Insight Hybrid, which was capable of stop-and-start, regenerative braking, and power assisting up to 30% of the engine power. It scored high fuel economy as well as low air emissions, and in 2000 was ranked the most efficient gasoline-fueled vehicle certified by the United States Environmental Protection Agency (EPA). The IMA system was also applied onto Honda Civic hybrid and CR-Z.

The General Motors (GM) Belt Alternator Starter (BAS) system can also be grouped in the mild hybrid category. Similarly, it took advantage of stop-and-start and regenerative braking technologies to improve fuel and driving performance. The 2007 model Chevrolet Silverado Hybrid pickup truck could achieve an overall fuel savings of 12% compared with its non-hybrid version.

Besides Japanese and American automakers, European automakers also came up with mild hybrids. Mercedes equipped its flagship S-Class with the Blue Motion Technologies as mild hybrids. BMW also released its Active Hybrid into their 7-Series mild hybrids.

FULL HYBRIDS: Full hybrids have the highest electric portion compared with micro hybrids and mild hybrids. The power rating for a full hybrid sedan is 30 kW or higher. Full hybrids are defined as those gasoline–electric vehicles that can run on either engine-only mode, battery-only mode, or a combination of the two. In addition to the functions that micro hybrids and mild hybrids are capable of, full hybrids can also operate on an all-electric range where only electric motors are used to propel the vehicle and supply all the internal power loads. However, owing to the limited size of the electric machine and the battery pack, full HEVs normally have a relatively short all-electric range with limited power output. Typically, full hybrids can achieve more than 40% of fuel economy gains in city drives and have more electric power assistance to increase driving performance.

Compared with micro and mild hybrids, full hybrids employ the largest electric power portions in the HEV powertrain systems. A larger battery pack is required to achieve the desired electric drive level. Meanwhile, since the motor is directly coupled with the output drive shaft in the electric-only mode, a robust motor with

sufficient speed and enough torque is demanded. Full hybrids also have relatively more complicated configurations. Most full hybrids integrate the electric power path with the mechanical power path by means of power split devices such as planetary gear sets. Power split devices serve to divide the power from the onboard power plants, that is, the engine and batteries, and redistribute the power flow between the electric path and the mechanical path to achieve optimal fuel efficiency and driving performance. Power split devices and other added mechanical components all add to the complexity of full hybrid systems. Therefore, though the full hybrids achieve significantly higher fuel economy and better performance, the manufacturing costs also increase as larger battery packs, more powerful electric machines, and more complicated configurations are implemented.

Full hybrids have attained the highest acceptance compared with the other two as full hybrids fulfill the demanded purpose of reducing fuel consumption and air emissions. Up to the second quarter of 2013, Toyota had achieved phenomenal success with its full hybrid models, the Toyota Prius family, which had sold more than 3 million units throughout the world. Toyota Camry Hybrid and Honda Civic Hybrids have also gained quite considerable popularities. GM, Daimler Chrysler, and BMW also released several models based on their two-mode hybrid transmission system, which is a complex full hybrid system capable of both high efficiency and high performance. Many governments around the world all released either targets or regulations to adjust the automobile industry into more hybridized forms, and large incentives were provided to compensate for the initial high costs of the full hybrid technologies. Table 12.3 summarizes the three categories of HEVs.

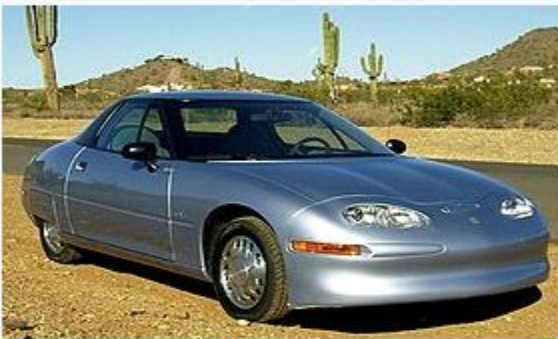
These concepts are usually related to the power rating of the main electric motor in a HEV. For example, if the HEV contains a fairly large electric motor and associated batteries, it can be considered as a full hybrid. On the other hand, if the size of the electric motor is relatively small, then it may be considered as a micro hybrid.

Typically, a full hybrid should be able to operate the vehicle using the electric motor and battery up to a certain speed limit and drive the vehicle for a certain amount of time. The speed threshold is typically the speed limit in a residential area. The typical power rating of an electric motor in a full hybrid passenger car is approximately 50–75 kW. The micro hybrid, on the other hand, does not offer the capability to drive the vehicle with the electric motor only. The electric motor is merely for starting and stopping the engine. The typical rating of electric motors used in micro hybrids is less than 10 kW. A mild hybrid is in between a full hybrid and a micro hybrid. An effective approach for evaluating HEVs is to use a hybridization ratio to reflect the degree of hybridization of a HEV. In a parallel hybrid, the hybridization ratio is defined as the ratio of electric power to the total powertrain power. For example, a HEV with a motor rated at 50kW and an engine

rated at 75kW will have a hybridization ratio of $50/(50+75)\text{kW}=40\%$. A conventional gasoline-powered vehicle will have a 0% hybridization ratio and a battery EV will have a hybridization ratio of 100%. A series HEV will also have a hybridization ratio of 100% due to the fact that the vehicle is capable of being driven in EV mode.

6. ELECTRIC VEHICLE CASE STUDY - GM EV1, NISSAN LEAF, MITSUBISHI MIEV:

1. GM EV1:

General Motors EV1	
	
Overview	
Manufacturer	General Motors
Production	1996–1999
Model years	1997 (Gen I): 660 units 1999 (Gen II): 457 units
Assembly	United States: Lansing, Michigan (Lansing Craft Center)
Body and chassis	
Class	Electric subcompact coupé
Body style	2-seat, 2-door coupé
Layout	Transverse front-motor, front-wheel drive
Powertrain	
Electric motor	Three-phase alternating current induction motor with IGBT power inverter 137 bhp (102 kW) at 7000 rpm 110 lb·ft (150 N·m) at 0–7000 rpm
Transmission	Single-speed reduction integrated with motor and differential
Battery	16.5–18.7 kWh lead–acid 26.4 kWh nickel–metal hydride (NiMH)

Electric range	EPA, revised to 2019 procedure: ^{[1][2]} Lead–acid: 55 mi (89 km) NiMH: 105 mi (169 km) EPA, original 1999 procedure: ^{[3][4]} Lead–acid: 78 mi (126 km) NiMH: 142 mi (228 km)
Plug-in charging	6.6 kW Magne Charge inductive converter
Dimensions	
Wheelbase	98.9 in (2,510 mm)
Length	169.7 in (4,310 mm) ^[5]
Width	69.5 in (1,770 mm) ^[5]
Height	50.5 in (1,280 mm)
Curb weight	3,086 lb (1,400 kg) with lead–acid batteries 2,908 lb (1,319 kg) with NiMH batteries

Specifications [\[edit \]](#)

	Gen I – lead acid	Gen II – lead acid	Gen II – NiMh
Production years	1996–1998	1999	1999
Markets	California, Arizona	California, Arizona, Georgia	
Range	79 mi (127 km)		EPA : 105 mi (169 km)
Efficiency	City: 300 Wh/mi (186 Wh/km) Highway: 250 Wh/mi (155 Wh/km)		
Battery type	Valve regulated lead acid battery	Panasonic valve regulated lead acid battery	Ovonics nickel–metal hydride battery
Battery capacity (gross)	16.3 kWh	18.7 kWh	26.4 kWh
AC charging	6.6 kW		
Motor	Single, front, three-phase induction AC motor		
Power (peak)	137 hp (102 kW)		
Torque (peak)	111 ft·lb (150 N·m)		
Curb weight	2,970 lb (1,347 kg)	2,970 lb (1,347 kg)	2,970 lb (1,347 kg)
Acceleration (0 to 60 mph)	< 9 seconds		
Top speed	80 mph (129 km/h) software limited top speed		
Drag coefficient (<i>C_d</i>)	0.19		

2. NISSAN LEAF:

Nissan Leaf



A second generation Nissan Leaf (2017-present)

Overview	
Manufacturer	Nissan
Production	December 2010–present
Model years	2011–present (Europe & North America)
Body and chassis	
Class	Compact/Small family car (C) ^[1]
Body style	5-door hatchback
Layout	Front-motor, front-wheel-drive
Chronology	
Predecessor	Nissan Altra
First generation (ZE0)	
	
Overview	
Also called	Venucia e30 (China)
Production	December 2010 – 2017
Model years	2011–2017
Assembly	- Japan: Yokosuka, Kanagawa (Oppama Plant) - United States: Smyrna, Tennessee

	United Kingdom: Sunderland (NMUK)
<u>Designer</u>	Kazuki Yamazaki and Masahide Fujiwara ^[10]
Body and chassis	
<u>Platform</u>	Nissan EV platform
Powertrain	
<u>Electric motor</u>	80 kW (107 hp), 280 N·m (210 ft·lb) Nissan EM motor , synchronous motor
<u>Transmission</u>	1-speed fixed gear ratio (7.937:1 for 2011–2012 and 8.193:1 for 2013–2017)
<u>Battery</u>	MY 2011–15 (all trims) and MY 2016 S trim 24 kWh lithium-ion battery MY 2016 (SL and SV trims) 30 kWh lithium-ion battery^[11]
Range	MY 2011/12 117 km (73 miles) EPA 175 km (109 miles) NEDC MY 2013 121 km (75 miles) EPA^[12] 200 km (124 miles) NEDC^[13] MY 2014/15 135 km (84 miles) EPA^[11] MY 2016 - with 24 kWh battery 135 km (84 miles) EPA^[11] - with 30 kWh battery 172 km (107 miles) EPA^[11]
<u>Plug-in charging</u>	3.6 kW (3.3 kW output) and optional 6.6 kW (6.0 kW output) 240 V AC ^[14] on SAE J1772-2009 inlet, max 44 kW 480 V DC on CHAdeMO inlet, adapters for domestic AC sockets (110–240 V)
Dimensions	
<u>Wheelbase</u>	2,700 mm (106.3 in) ^[15]
Length	4,445 mm (175.0 in) ^[15]
Width	1,770 mm (69.7 in) ^[15]
Height	1,550 mm (61.0 in) ^[15]

Curb weight

- **MY 2011/12**
- 1,521 kg (3,354 lb)^[16]
- **MY 2013**
- 1,493 kg (3,291 lb)^[17]
- **MY 2017**
- 1,500–1,538 kg (3,307–3,391 lb)

Second generation (ZE1)



2018 Nissan Leaf N-Connecta (UK)

Overview

Production October 2017–present

Model years 2018–present

Assembly

- Japan: [Yokosuka, Kanagawa \(Oppama Plant\)](#)
- United States: [Smyrna, Tennessee](#)
- United Kingdom: [Sunderland \(NMUK\)](#)

Designer Kazuhiko Watanabe^[87]

Powertrain

Electric motor

- 110 kW (148 hp), 320 N·m (236 lb·ft) EM57 [Nissan EM motor, synchronous motor](#)^[88]
- 160 kW (215 hp) EM57 [Nissan EM motor, synchronous motor](#)

Transmission 1-speed fixed gear ratio 8.193:1

Battery	• 40 kWh lithium-ion battery^[89] • 62 kWh lithium-ion battery
Range	• 40 kWh: • 243 km (151 miles) EPA^[89] • 274 km (170 miles) WLTP • 62 kWh: Leaf Plus or e+ • 364 km (226 miles) EPA^[90]
Plug-in charging	6.6 kW (6.0 kW output) 240 V AC on SAE J1772-2009 inlet; 50 or up to 100 kW via CHAdeMO DC fast charge
Dimensions	
Wheelbase	2,700 mm (106.3 in)
Length	4,490 mm (176.8 in)
Width	1,788 mm (70.4 in)
Height	1,530 mm (60.2 in)
Curb weight	1,580–1,640 kg (3,483–3,616 lb)

3. MITSUBISHI MIEV:

Mitsubishi i-MiEV	
	
Overview	
Manufacturer	Mitsubishi Motors
Also called	Peugeot iOn (Europe) Citroën C-Zero (Europe) Mitsuoka Like

Production	2009–2021 2009–2014 (Europe)
Assembly	Japan: Kurashiki , Okayama (Mizushima Plant)
Body and chassis	
<u>Class</u>	Kei car (Japan) City car (outside Japan)
<u>Body style</u>	5-door hatchback
<u>Layout</u>	RMR
Related	Mitsubishi i Mitsubishi Minicab MiEV
Powertrain	
<u>Electric motor</u>	47 kW (63 hp), 180 N·m (133 lbf·ft) permanent-magnet motor ^[1]
<u>Transmission</u>	Single speed reduction gear
<u>Battery</u>	16 kWh / 58 MJ (Li-ion battery)
Range	160 km (99 mi) (Japanese cycle) 100 km (62 mi) (US EPA cycle)
<u>Plug-in charging</u>	15 A 240 V AC (3.6 kW) ^[2] on the SAE J1772-2009 inlet, optional CHAdeMO DC rapid charging, adapters for domestic AC sockets (110–240 V)
Dimensions	
<u>Wheelbase</u>	2,550 mm (100.4 in)
Length	3,395 mm (133.7 in) 3,480 mm (137.0 in) (Japan 2018-2021)

	3,680 mm (144.9 in) (North America) ^[3]
Width	1,475 mm (58.1 in) 1,585 mm (62.4 in) (North America) ^[3]
Height	1,600 mm (63.0 in) 1,615 mm (63.6 in) (North America) ^[3]
<u>Curb weight</u>	1,080 kg (2,380 lb)
Chronology	
Predecessor	Mitsubishi i
Successor	Mitsubishi eK X EV (Japan) Citroën Ami (Europe)

7. HYBRID ELECTRIC HEAVY-DUTY VEHICLES, FUEL CELL HEAVY DUTY VEHICLES:

Hybrid Electric Heavy-Duty Vehicles and Fuel Cell Heavy-Duty Vehicles are two different types of technologies used in the transportation industry, particularly for large commercial vehicles such as trucks and buses. These technologies are designed to reduce emissions, improve fuel efficiency, and promote sustainability. Here's a brief overview of each:

Hybrid Electric Heavy-Duty Vehicles:

Hybrid electric heavy-duty vehicles combine traditional internal combustion engines (usually diesel or gasoline) with an electric propulsion system. These vehicles have a battery or energy storage system that stores and delivers electrical energy to support the operation of the vehicle. The electric component can be used to assist the engine during acceleration or to operate the vehicle at low speeds or in stop-and-go traffic. Regenerative braking captures and stores energy during braking, which can be used to recharge the battery and improve fuel efficiency. The combination of the internal combustion engine and the electric components can lead to reduced fuel consumption and lower emissions, making these vehicles more environmentally friendly.

Fuel Cell Heavy-Duty Vehicles:

Fuel cell heavy-duty vehicles use hydrogen as a fuel source to generate electricity through a chemical process in a fuel cell. The electricity produced in the fuel cell powers electric motors that drive the vehicle's wheels. Water vapor is the only byproduct of the chemical reaction, which makes fuel cell vehicles essentially zero-emission in terms of greenhouse gases. Fuel cell vehicles are particularly well-suited for heavy-duty applications where long-range and quick refueling are essential. Hydrogen refueling infrastructure is a challenge, but efforts are being made to expand hydrogen refueling stations to support the adoption of these vehicles. Both hybrid electric and fuel cell heavy-duty vehicles offer potential benefits for reducing greenhouse gas emissions and improving air quality in the transportation sector. However, the choice between the two technologies depends on factors such as the specific operational needs, infrastructure availability, and regional policies promoting one technology over the other. As technology continues to evolve, both hybrid electric and fuel cell heavy-duty vehicles are expected to play important roles in the transition toward more sustainable transportation options.

(OR)

Hybrid Electric Heavy-Duty Vehicles:

Hybrid Electric Heavy-Duty Vehicles, often referred to as hybrid electric trucks or buses, are commercial vehicles designed to reduce fuel consumption and emissions by integrating two or more different propulsion systems: an internal combustion engine (usually diesel or gasoline) and an electric drive system. Here's a more detailed explanation of how these vehicles work and their key components:

1. Internal Combustion Engine:

These vehicles typically feature a conventional internal combustion engine, which can be powered by diesel, gasoline, or alternative fuels like natural gas. The internal combustion engine is responsible for providing the primary source of propulsion and generating electricity to charge the vehicle's batteries.

2. Electric Drive System:

Hybrid electric heavy-duty vehicles are equipped with an electric drive system that includes an electric motor, a high-capacity battery, and power electronics. The electric motor is used to assist the internal combustion engine during various driving conditions, such as acceleration, climbing hills, or when additional power is

needed. The high-capacity battery stores electrical energy generated during regenerative braking and can also be charged from the engine when it's operating efficiently.

3. Regenerative Braking:

Regenerative braking is a key feature of hybrid electric vehicles. When the vehicle decelerates or brakes, the electric motor operates in reverse, converting the kinetic energy of the vehicle into electrical energy. This recovered energy is then used to recharge the battery, improving overall energy efficiency and reducing fuel consumption.

4. Power Management System:

A sophisticated power management system controls the operation of the internal combustion engine and electric motor to optimize fuel efficiency and reduce emissions. It determines when to use electric power, when to use the internal combustion engine, and when to switch between them for the most efficient performance.

5. Different Operating Modes:

Hybrid electric heavy-duty vehicles typically have different operating modes, such as all-electric mode (running on electricity only for short distances at low speeds), parallel hybrid mode (both engine and electric motor work together), and series hybrid mode (electric motor powers the vehicle with the engine acting as a generator to charge the battery).

Benefits of Hybrid Electric Heavy-Duty Vehicles:

1. **Reduced fuel consumption:** By using electric power for certain operations and regenerating energy during braking, these vehicles can achieve improved fuel efficiency compared to traditional heavy-duty vehicles.
2. **Lower emissions:** Hybrid electric technology can significantly reduce greenhouse gas emissions and air pollutants, contributing to better air quality.
3. **Enhanced performance:** Electric motors can provide additional torque and power when needed, making these vehicles more capable of handling heavy loads and challenging driving conditions.

Hybrid electric heavy-duty vehicles are often used in urban delivery trucks, transit buses, and other applications where frequent stops and starts are common. They offer a practical and environmentally friendly solution for reducing the environmental

impact of commercial transportation while maintaining the necessary power and range for these demanding applications.

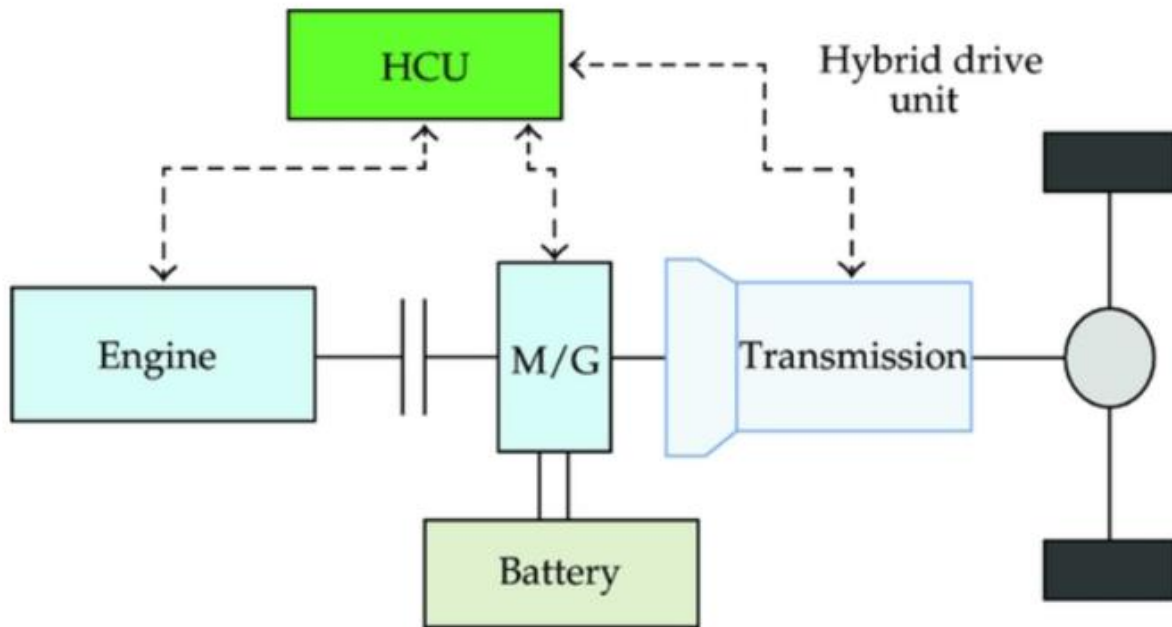


Fig: HYBRID ELECTRIC HEAVY-DUTY VEHICLES

Fuel Cell Heavy Duty Vehicles:

Fuel cell heavy-duty vehicles are commercial vehicles that use fuel cells to generate electricity for propulsion. They are often powered by hydrogen and are designed to be more environmentally friendly compared to traditional diesel or gasoline-powered heavy-duty vehicles. Here's an explanation of how these vehicles operate:

1. Fuel Cell Stack:

At the heart of a fuel cell heavy-duty vehicle is the fuel cell stack. This stack consists of multiple individual fuel cells arranged in series. Each fuel cell is a small unit that contains a proton exchange membrane (PEM), an anode, and a cathode. Hydrogen is supplied to the anode, where it undergoes a chemical reaction, breaking down the hydrogen molecules into protons and electrons.

2. Proton Exchange Membrane (PEM):

The PEM, which is typically made of a special polymer material, acts as an electrolyte that allows protons to pass through while blocking electrons. This separation of protons and electrons is crucial for the generation of electricity.

3. Electrochemical Reaction:

In the fuel cell stack, hydrogen protons (H^+) move through the PEM to the cathode side, while the electrons are forced to follow an external electrical circuit due to their inability to pass through the PEM. This movement of protons and electrons leads to an electrochemical reaction at the cathode where oxygen (usually from the air) combines with the protons to form water (H_2O).

4. Generation of Electricity:

The movement of electrons through the external electrical circuit generates electrical power, which is used to drive the electric motor of the vehicle. The only byproduct of this electrochemical process is water vapor, making fuel cell vehicles essentially zero-emission in terms of greenhouse gases.

5. Hydrogen Storage:

Fuel cell heavy-duty vehicles require a storage system for hydrogen, typically in high-pressure tanks. These tanks store compressed hydrogen gas that is then supplied to the fuel cell stack.

6. Electric Motor:

The electricity generated in the fuel cell stack powers an electric motor, which is responsible for driving the vehicle's wheels.

7. Vehicle Propulsion:

The electric motor provides the necessary torque and power to propel the vehicle. These vehicles can have impressive torque and acceleration, making them suitable for heavy-duty applications.

8. Regenerative Braking:

Like hybrid electric vehicles, fuel cell vehicles often feature regenerative braking systems to capture and store energy during braking, improving overall energy efficiency.

Fuel cell heavy-duty vehicles offer several advantages, including zero-emission operation, long-range capabilities, and rapid refueling, making them well-suited for applications where extended range and quick turnaround times are essential. While the production and distribution of hydrogen can be a challenge, efforts are being made to expand the hydrogen refueling infrastructure to support the adoption of these vehicles.

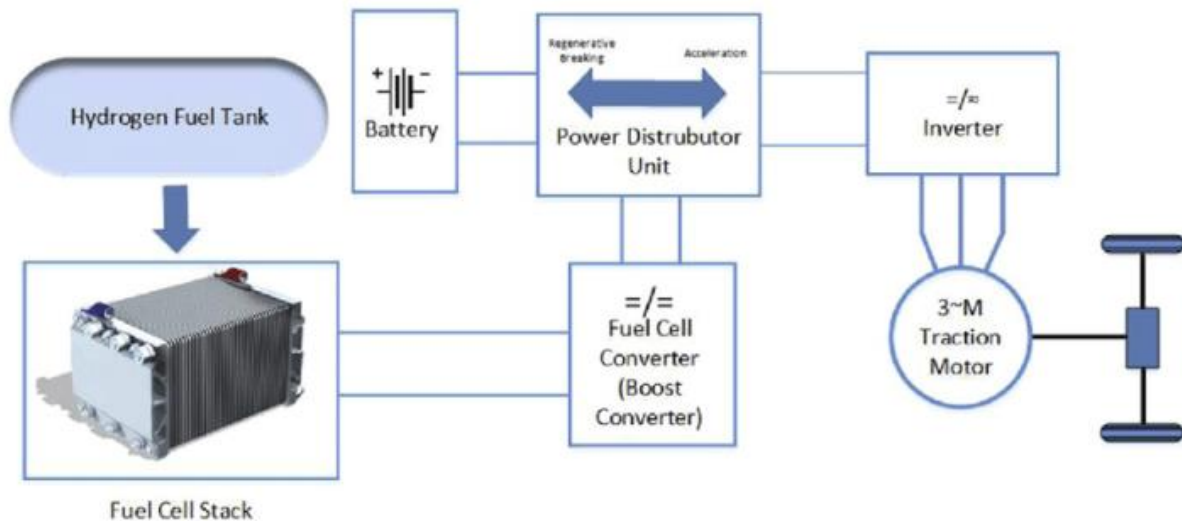


Fig: FUEL CELL HEAVY-DUTY VEHICLES