Dr. Norbert Cheung's Lecture Series

Level 5 Topic no: 20

Electric Vehicles Systems

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1. EV Configurations
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Reference:

C.C. Chan and K.T. Chau, Modern Electric Vehicle Technology, London: Oxford, University Press, 2001

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1. EV Configurations

Previously, the EV was mainly converted from the ICEV, simply replacing the combustion engine by the electric motor while retaining all the other components. This converted EV has been fading out because of the drawback of heavy weight, loss of flexibility and degradation of performance. At present, the modern EV is purposely built. This purpose-built EV is based on original body and frame designs to satisfy the structural requirements unique to EVs and to make use of the greater flexibility of electric propulsion.

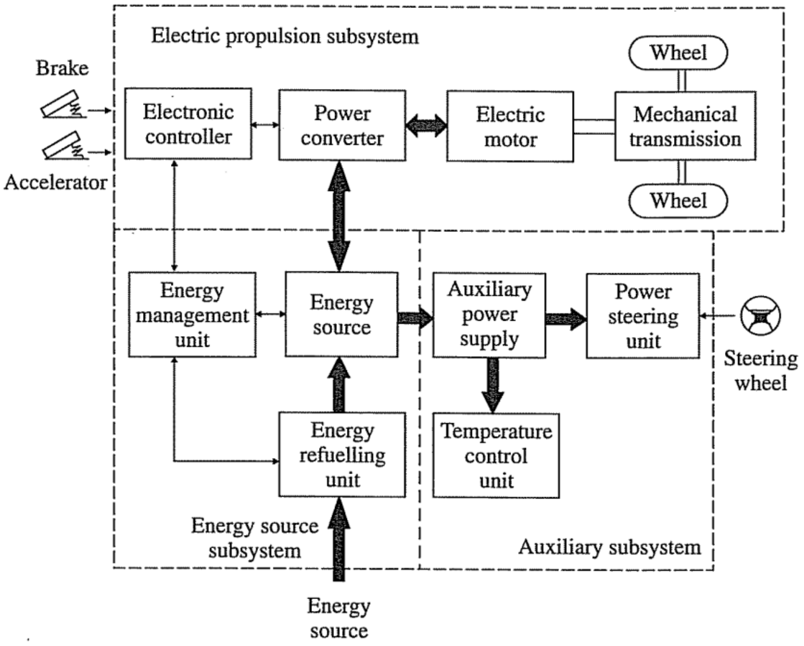


Fig. 3.1. General EV configuration.

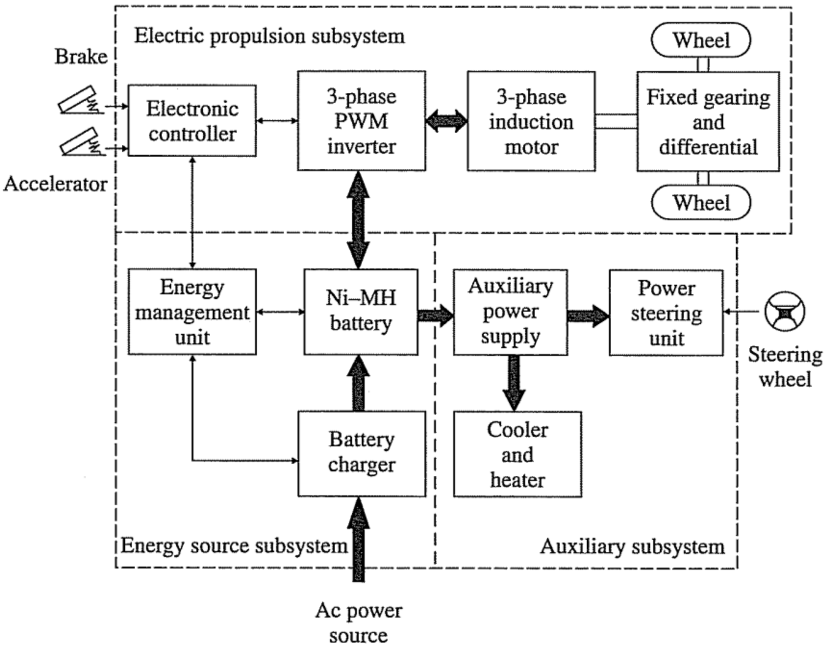
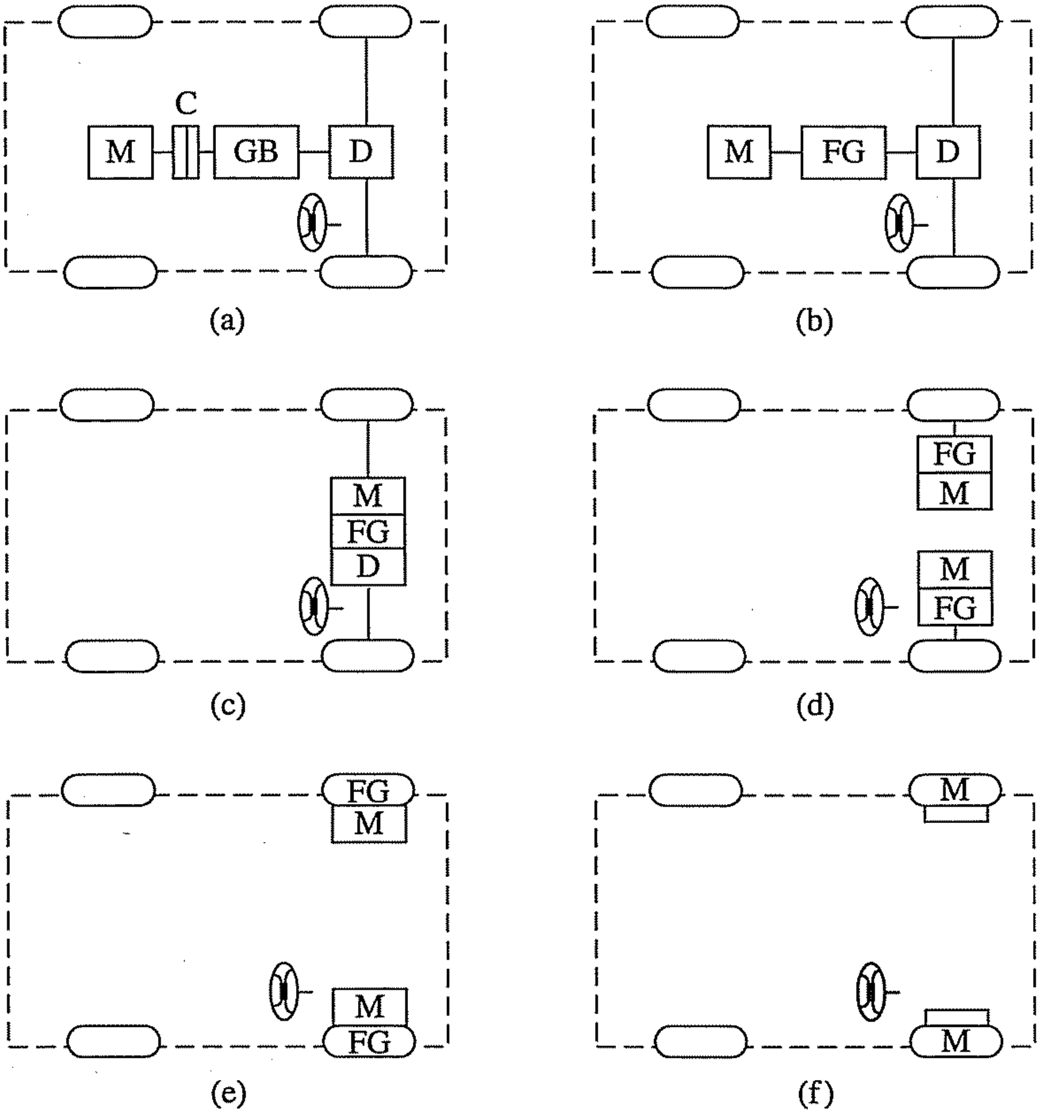


Fig. 3.2. Typical EV configuration.



(a) (b) (c) (d) (e) (f)

C : Clutch
D : Differential
FG : Fixed gearing
GB : Gearbox
M : Electric motor

Fig. 3.3. EV configuration due to variations in electric propulsion.

(1) Figure 3.3(a) shows the first alternative which is a direct extension of the existing ICEV adopting longitudinal front-engine front-wheel drive. It consists of an electric motor, a clutch, a gearbox and a differential. The clutch is a mechanical device which is used to connect or disconnect power flow from the electric motor to the wheels. The gearbox is another mechanical device which consists of a set of gears with different gear ratios. By incorporating both clutch and gearbox, the driver can shift the gear ratios and hence the torque going to the wheels. The wheels have high torque low speed in the lower gears and high speed low torque in the higher gears. The differential is a mechanical device which enables the wheels to be driven at different speeds when cornering—the outer wheel covering a greater distance than the inner wheel.

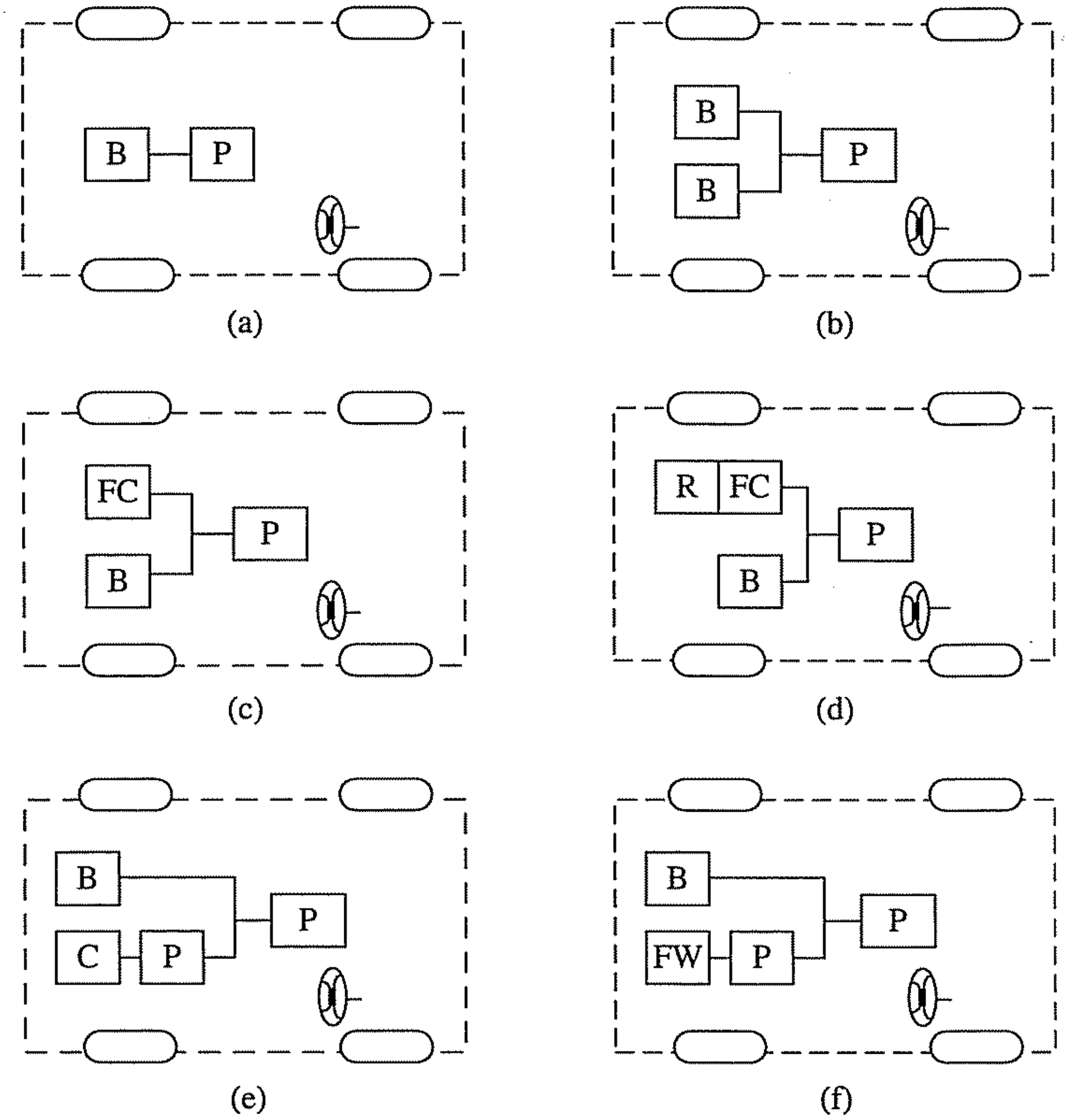
(2) By replacing the gearbox with fixed gearing and hence removing the clutch, both the weight and size of the mechanical transmission can be greatly reduced. Figure 3.3(b) shows this arrangement which consists of an electric motor, fixed gearing and a differential. Notice that this EV configuration is not suitable for the ICEV as the engine by itself, without the clutch and gearbox, cannot offer the desired torque-speed characteristics.

(3) Similar to the concept of transverse front-engine front-wheel drive of the existing ICEV, the electric motor, fixed gearing and differential are integrated into a single assembly, while both axles point at both driving wheels. Figure 3.3(c) show this configuration which is in fact most commonly adopted by modern EVs.

(4) Besides the mechanical means, the differential action of an EV when cornering can be electronically provided by two electric motors operating at different speeds. Figure 3.3(d) shows this dual-motor configuration in which two electric motors separately drive the driving wheels via fixed gearing.

(5) In order to further shorten the mechanical transmission path from the electric motor to the driving wheel, the electric motor can be placed inside a wheel. This arrangement is the so-called in-wheel drive. Figure 3.3(e) shows this configuration in which fixed planetary gearing is employed to reduce the motor speed to the desired wheel speed. It should be noted that planetary gearing offers the advantages of a high speed-reduction ratio as well as an inline arrangement of input and output shafts.

(6) By fully abandoning any mechanical gearing, the in-wheel drive can be realized by installing a low-speed outer-rotor electric motor inside a wheel. Figure 3.3(f) shows this gearless arrangement in which the outer rotor is directly mounted on the wheel rim. Thus, speed control of the electric motor is equivalent to the control of the wheel speed and hence the vehicle speed.



B : Battery
C : Capacitor
FC : Fuel cell
FW : Flywheel
P : Power converter
R : Reformer

Fig. 3.4. EV configuration due to variations in energy sources.

(1) Figure 3.4(a) shows a basic battery-powered configuration that is almost exclusively adopted by existing EVs. The battery may be distributed around the vehicle, packed together at the vehicle back or located beneath the vehicle chassis. This battery should be able to offer reasonable specific energy and specific power as well as being able to accept regenerative energy during braking. Notice that both high specific energy and high specific power are desirable for EV applications as the former governs the driving range while the latter dictates the acceleration rate and hill-climbing capability. A battery having a design compromised between specific energy and specific power is generally adopted in this configuration.

(2) Instead of using a compromised battery design, two different batteries (one is optimized for high specific energy while another for high specific power) can be used simultaneously in an EV. Figure 3.4(b) shows the basic arrangement of this battery & battery hybrid energy source. This arrangement not only decouples the requirements on energy and power but also affords an opportunity to use those mechanically rechargeable batteries which cannot accept regenerative energy during braking or downhill.

(3) Differing from the battery which is an energy storage device, the fuel cell is an energy generation device. The operating principle of fuel cells is a reverse process of electrolysis—combining hydrogen and oxygen gases to form electricity and water. Hydrogen gas can be stored in an on-board tank whereas oxygen gas is simply extracted from air. Since the fuel cell can offer high specific energy but cannot accept regenerative energy, it is preferable to combine it with a battery with high specific power and high energy receptivity. Figure 3.4(c) shows this arrangement which is denoted as a fuel cell & battery hybrid energy source.

(4) Rather than storing it as a compressed gas, a liquid or a metal hydride, hydrogen can be on-board generated from ambient-temperature liquid fuels such as methanol or even petrol. As shown in Fig. 3.4(d), a mini reformer is installed in the EV to produce on line the necessary hydrogen gas for the fuel cell.

(5) In contrast to the fuel cell & battery hybrid in which the battery is purposely selected to offer high specific power and high energy receptivity, the battery in the battery & capacitor hybrid is aimed to have high specific energy. This is because a capacitor can inherently offer a much higher specific power and energy receptivity than a battery. Since the available capacitors for EV application, usually termed as ultracapacitors, are of relatively low voltage level, an additional dc–dc power converter is needed to interface between the battery and capacitor terminals. Figure 3.4(e) shows this configuration.

(6) Similar to the capacitor, the flywheel is another emerging energy storage device which can offer high specific power and high energy receptivity. It should be noted that the flywheel for EV applications is different from the conventional design which is characterized by low speed and massive size. In contrast, it is lightweight and operates at ultrahigh speeds under a vacuum environment. This ultrahigh-speed flywheel is incorporated into the rotor of an electric machine which operates at motoring and generating modes when converting electrical energy to and from kinetic energy, respectively. The corresponding configuration is shown in Fig. 3.4(f) in which the battery is selected to offer high specific energy.

2. Fixed and Variable Gearings

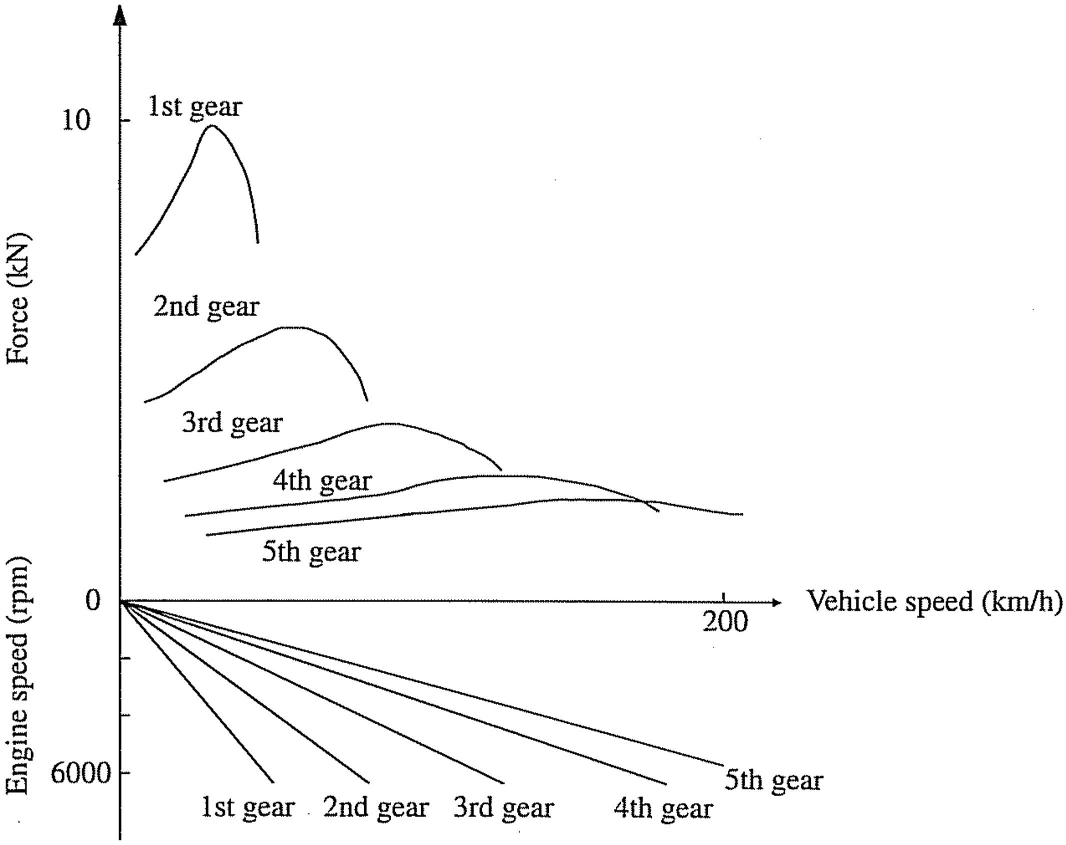


Fig. 3.5. ICEV force-speed characteristics with five-speed transmission.

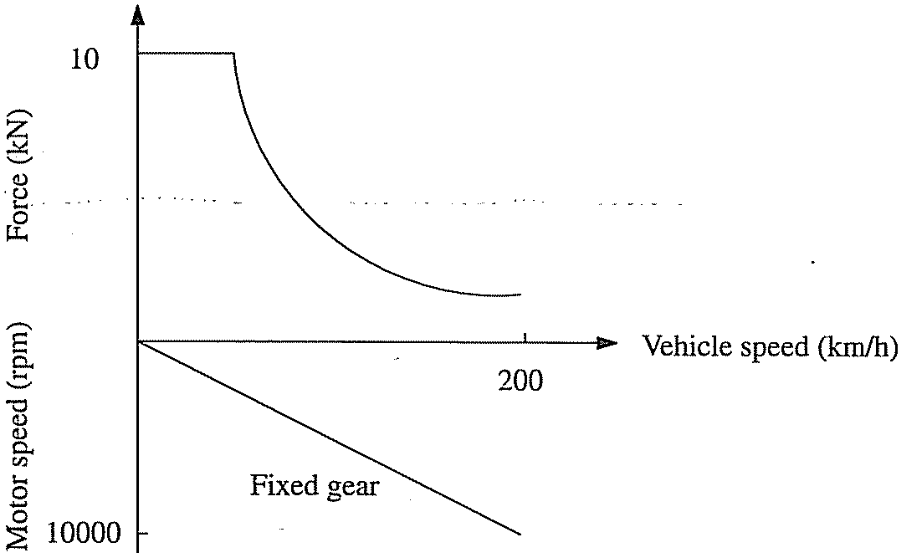


Fig. 3.6. EV force-speed characteristiscs with fixed gearing.

Figure 3.6 shows typical force-speed characteristics of an EV with fixed gearing, consisting of constant-torque operation for acceleration and hill climbing as well as constant-power operation for high-speed cruising. Moreover, the absence of gear changing (irrespective of whether it is manual or automatic) can greatly enhance smooth driving and transmission efficiency. Therefore, modern EVs almost exclusively adopt fixed gearing rather than variable gearing.

3. Single and Multiple Motor Drives

For EVs, it is possible to dispense with a mechanical differential. By separately coupling two or even four electric motors to the driving wheels, the speed of each wheel can be independently controlled in such a way that the differential action can be electronically achieved when cornering. Figure 3.8 shows a typical dual-motor drive with an electronic differential. This arrangement is smaller and lighter than the mechanical counterpart. Unlike the choice between variable gearing and fixed gearing, the selection of either a single-motor drive with a differential or a multiple-motor drive without a differential is still controversial. Positively, the removal of a mechanical differential can reduce the overall size and weight while the electronic differential can accurately control the wheel speeds so as to achieve better performance during cornering. Negatively, the use of an additional electric motor and power converter causes an increase in the initial cost while the reliability of the electronic controller to accurately control two electric motors at various driving conditions is to be observed. In recent years, the reliability of this

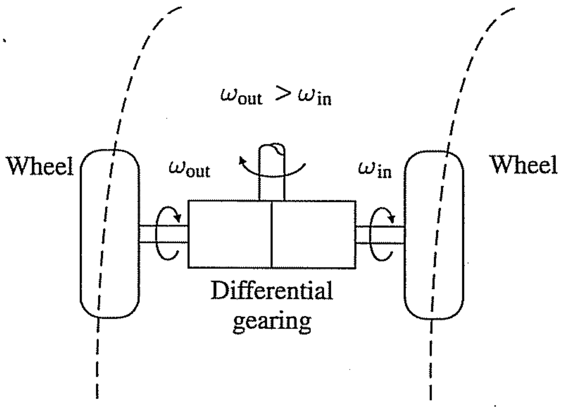


Fig. 3.7. Mechanical differential.

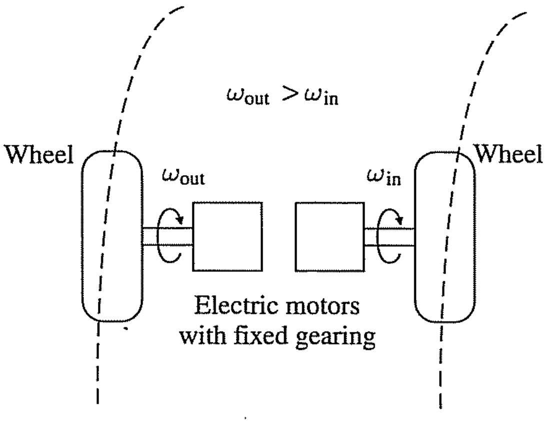


Fig. 3.8. Electronic differential.

4. In-Wheel Drives

Figure 3.9 shows these two in-wheel drives, both employing a permanent-magnet brushless motor. Although different types of electric motors can be adopted, the permanent-magnet brushless machine is most attractive because of its outstanding power density.

The high-speed inner-rotor motor has the advantages of smaller size, lighter weight and lower cost, but needs an additional planetary gearset. On the other hand, the low-speed outer-rotor motor has the definite advantage of simplicity and is gearless, but the motor suffers from the drawbacks of increased size, weight and cost because of the low-speed design. Both types of in-wheel motors have been applied to modern EVs (Shimizu, 1995).

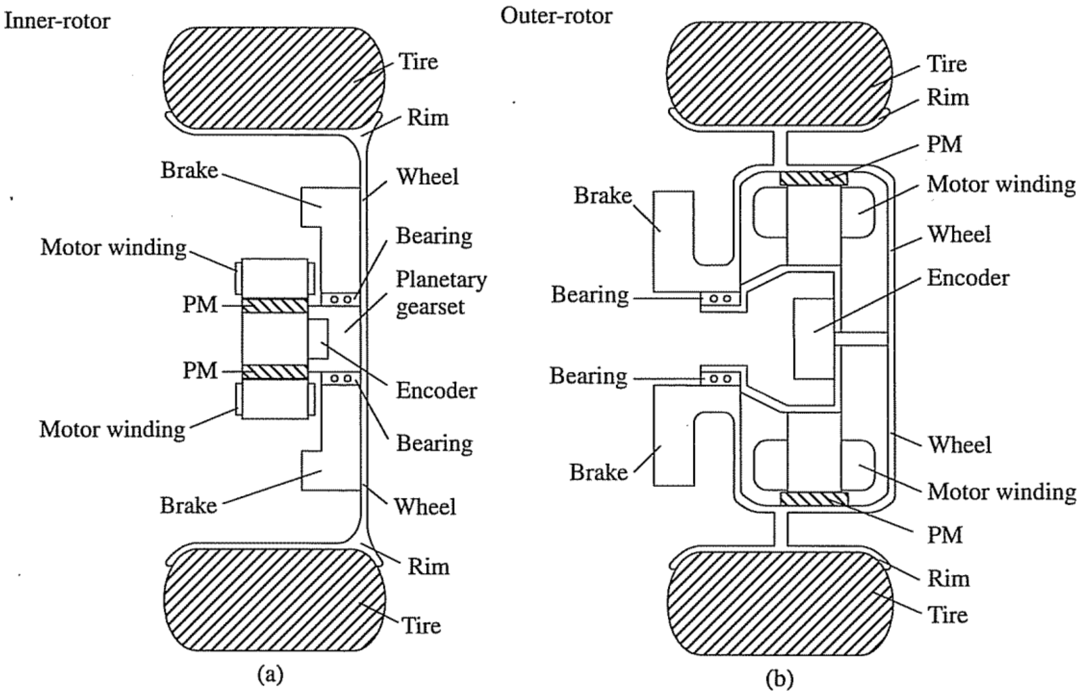


Fig. 3.9. In-wheel drives. (Courtesy of Hiroshi Shimizu.)

5. EV Parameters

WEIGHT & SIZE

Vehicle weights are key parameters in EVs because they seriously affect the driving range and vehicle performance. Their typical definitions are listed below:

- Curb weight—the weight excluding payload;
- Gross weight—the weight including payload;
- Payload—the weight of passengers and cargo;
- Inertia weight—the curb weight plus a standard payload;
- Maximum weight—the maximum gross weight for safety operation;
- Drivetrain weight—the weight of the whole drivetrain in the EV;
- Battery weight—the weight of the whole battery pack in the EV.

Another set of important parameters for EVs are the vehicle sizes which are identical to those of ICEVs. They are listed below:

- Vehicle dimensions—the length, width, height and ground clearance;
- Frontal area—the equivalent frontal area affecting the vehicle aerodynamic drag;
- Seating capacity—the number of passengers, sometimes adult or child is also specified;
- Cargo capacity—the volume of cargo.

FORCE PARAMETERS

The force that a vehicle must overcome to travel is known as road load. As shown in Fig. 3.10, this road load F_l consists of three main components—aerodynamic drag force F_d, rolling resistance force F_r and climbing force F_c as given by:

$$F_l = F_d + F_r + F_c.$$

$$F_d = 0.5\rho C_d A(v + v_0)^2,$$

where C_d is the aerodynamic drag coefficient (dimensionless), ρ is the air density in kg/m^3, A is the frontal area in m^2, v is the vehicle velocity in m/s, and v_0 is the head wind velocity in m/s. Since both v and v_0 can also be expressed in km/h, the corresponding aerodynamic force is written as:

$$F_d = 0.0386\rho C_d A(v + v_0)^2.$$

In general, ρ is taken as 1.23 kg/m^3 although it is dependent on the altitude. On the other hand, C_d varies significantly, ranging from 0.2 to 1.5. For examples, purposely streamlined cars have C_d from 0.2 to 0.3, passenger cars from 0.3 to 0.5, vans from 0.5 to 0.6, buses from 0.6 to 0.7, and trucks from 0.8 to 1.5.

The rolling resistance force is due to the work of deformation on the wheel and road surface. The deformation on the wheel heavily dominates the rolling resistance while the deformation on the road surface is generally insignificant. Factors that affecting the rolling resistance are tire types, tire pressure, tire temperature, vehicle speed, tread thickness, the number of plies, the mix of the rubber and the level of torque transmitted. Among them, the tire types and tire pressure are relatively more significant. This rolling resistance force is normally expressed as:

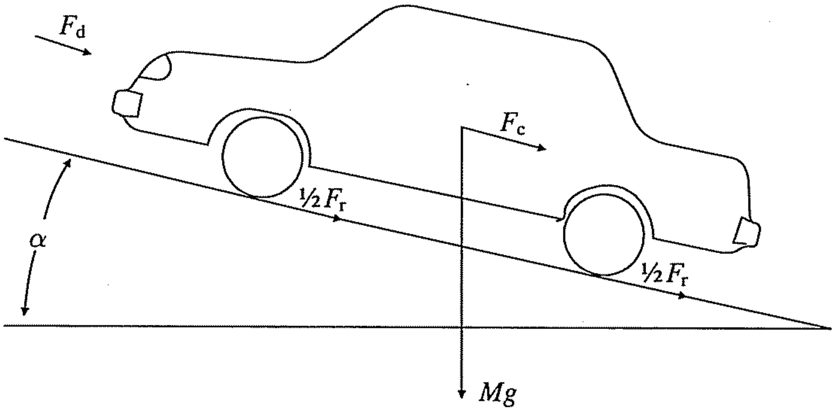


Fig. 3.10. Road load.

$$F_r = MgC_r,$$

where M is the vehicle mass in kg, g is the gravitational acceleration (9.81 m/s^2), and C_r is the rolling resistance coefficient (dimensionless). In general, the C_r of radial-ply tires (around 0.013) is lower than that of cross-ply tires (around 0.018). It also varies inversely with the tire air pressure.

The climbing force is simply the climbing resistance or downward force for a vehicle to climb up an incline. This force is given by:

$$F_c = Mg\sin\alpha,$$

where α is the angle of incline in radian or degree. Usually, the incline is expressed as a percentage gradeability p:

$$p = (h/l)100\%,$$

where h is the vertical height over horizontal distance l. So, p and sin α are related by:

$$\alpha = \tan^{-1}(p/100).$$

For example, in a 20% gradeability, the angle of incline is 11.3°. The maximum gradeability denotes the maximum incline that a vehicle can climb at essentially zero speed.

The motive force F available at the wheels is required to overcome the above road load F_l and to drive the vehicle with an acceleration a. If F_l is greater than F, it becomes a deceleration and a is a negative value. It is expressed as:

$$a = \frac{(F - F_l)}{k_r M},$$

where k_r denotes a correction factor that there is an apparent increase in vehicle mass due to the inertia of rotational masses (such as wheels, gears and shafts), ranging from about 1.01 to 1.40.

ENERGY PARAMETERS

In transportation, the unit of energy is kWh rather than J because the latter is too small for such an application. To assess the energy consumption of a vehicle, the energy per unit distance in kWh/km is generally used. This unit can be applied to both ICEVs and EVs. However, an ICEV's driver generally has no idea about the kWh and prefers a physical unit of fuel volume such as the litre or gallon. So,

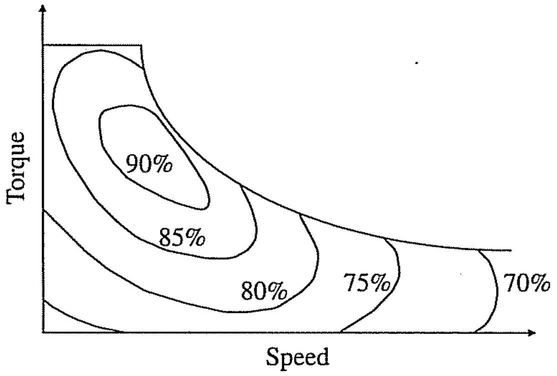


Fig. 3.11. Typical power efficiency map of an EV induction motor.

The energy efficiency η_e is the ratio of energy output to energy input, while the power efficiency η_p is the ratio of power output to power input. So, they can simply be expressed as:

$$\eta_e = \frac{E_{out}}{E_{in}}$$

$$\eta_p = \frac{P_{out}}{P_{in}}.$$

PERFORMANCE PARAMETERS

- Range per charge—the driving range in km of an EV that has been fully charged up. It can also be extended to describe the range per refuelling for those EVs adopting other energy sources such as fuel cells.
- Acceleration rate—it is usually expressed as the minimum time required to accelerate the vehicle from zero to a specified speed such as 40, 60 or 80 km/h.
- Maximum speed—it is simply the quoted maximum safe speed in km/h that a vehicle can attain.

Federal Urban Driving Schedule at 48km/h and 72 km/h

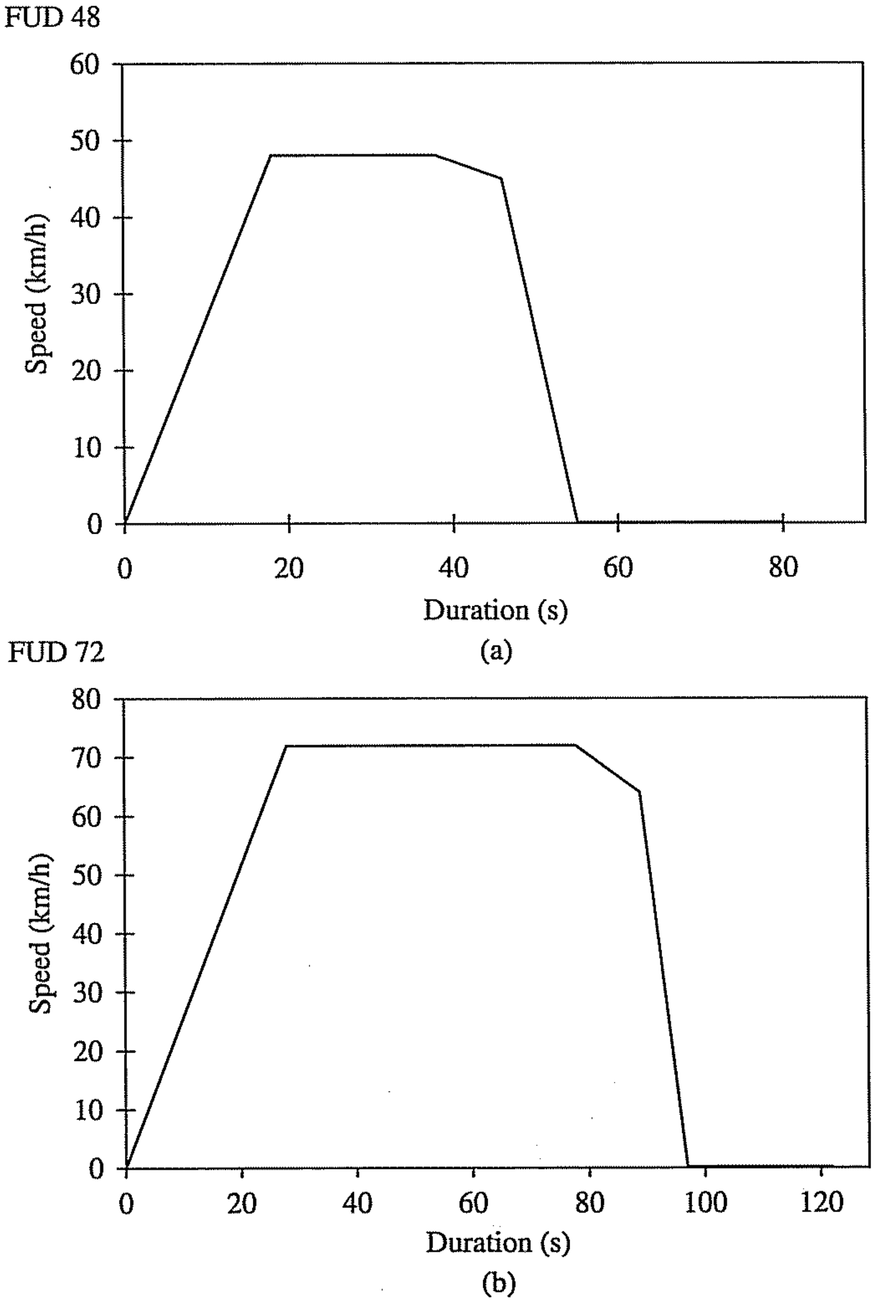


Fig. 3.13. FUD 48 and FUD 72.

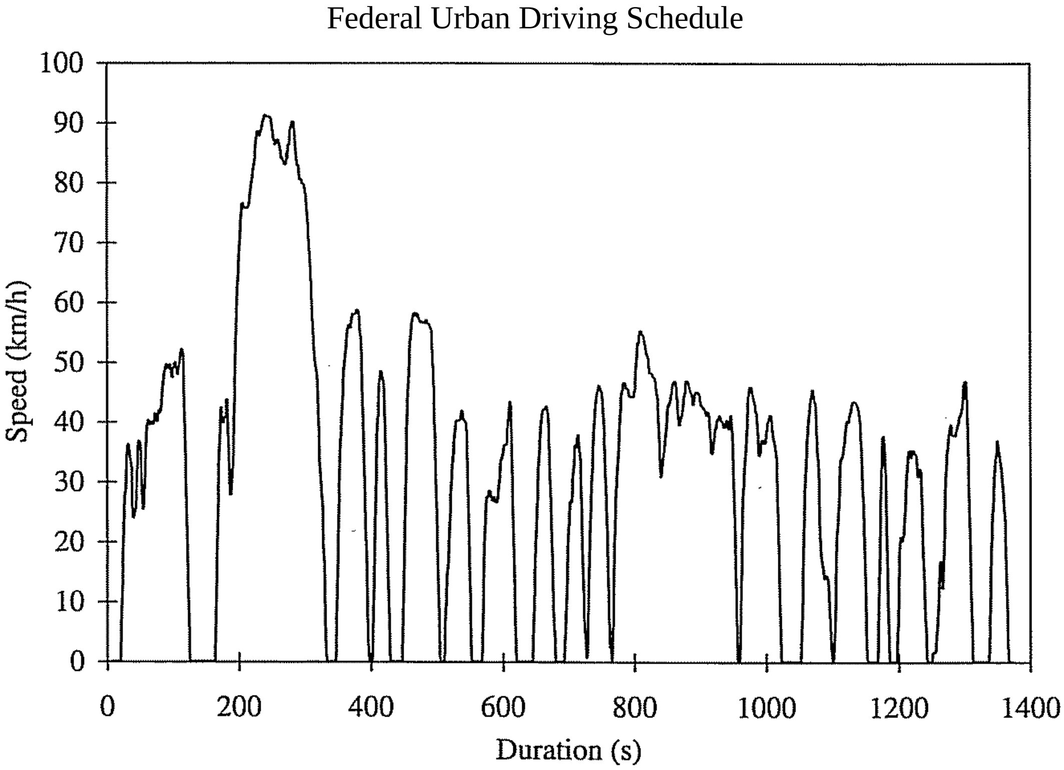


Fig. 3.12. FUDS.

Notice that the range per charge can be remarkably varied as it is claimed in many different ways. It can be based on a specified constant-speed operation on a level road, or for a specified type of driving cycle. For example, an EV can be claimed to offer a range of 200 km per charge at a constant speed of 40 km/h or a range of 120 km per charge under FUDS. Sometimes, some loose references may be used such as urban or highway situations.

In recent years, several standard driving cycles have been developed. They are basically used to characterize various driving modes in different regions or countries.

(1) Federal Urban Driving Schedule (FUDS) and Federal Highway Driving Schedule (FHDS)—the FUDS is the most common driving cycles in the USA. It was developed originally to evaluate the noxious emissions of ICEVs and was based on a cycle derived from the statistical flow of traffic patterns in Los Angeles. Subsequently, it is widely used to evaluate the fuel economy of urban or city driving. Two of its simplified versions, namely the FUD 48 and FUD 72 with their maximum speeds of 48 km/h and 72 km/h, respectively, are also widely used for computer simulation. In contrast, the FHDS was developed to typify rural or cross-country driving in the USA. Figures 3.12–3.14 show the corresponding speed–time profiles.

(2) European Driving Cycle—it is known as the ECE Cycle and is a composite of two driving modes—urban and highway. It is widely adopted in Europe to evaluate fuel economy and emissions. There is a reduced version called the ECE 15 Urban Cycle, shown in Fig. 3.15, focusing on the driving mode in urban areas.

(3) SAE J227 Cycle—in the early 1970s, the Society of Automotive Engineers (SAE) developed some standard driving cycles for EVs. The SAE J227 cycle was designed to give approximately the same road-load energy demand as the FUDS but with a lower peak road-load power. Since many EVs in the 1970s were unable to achieve the required road load power levels, the J227 Cycle was re-issued as a set of four simplified cycles, so-called J227a-A, -B, -C, and -D Cycles. The capital letters refer to four cycles with increasing power requirements and increasing maximum speed requirements. Figure 3.16 shows the J227a-C Cycle which used to be adopted in the design of EVs.

(4) Japan 10.15 Mode—Figure 3.17 shows the profile of the Japan 10.15 Mode driving cycle. As a regulation, the driving range of EVs in Japan should be evaluated by using only this driving cycle.

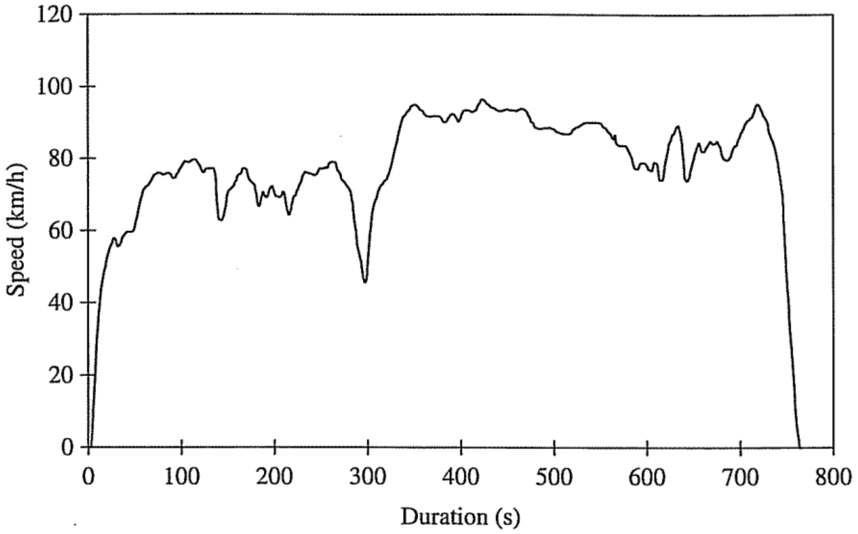


Fig. 3.14. FHDS.

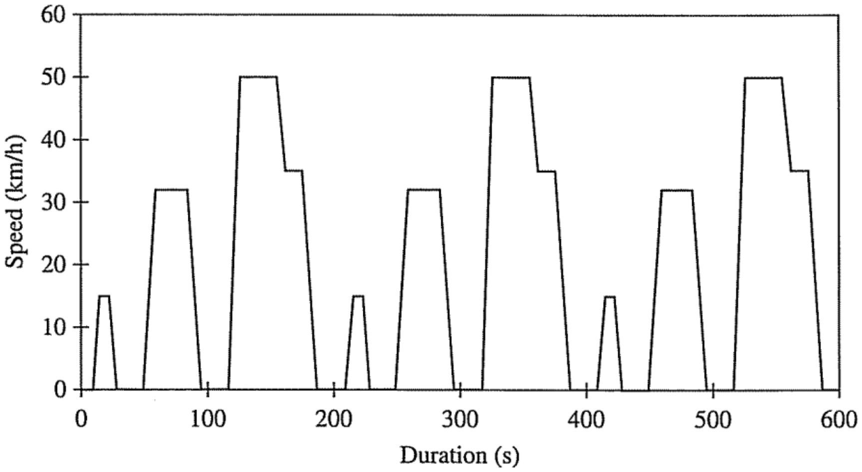


Fig. 3.15. ECE 15 Urban Cycle.

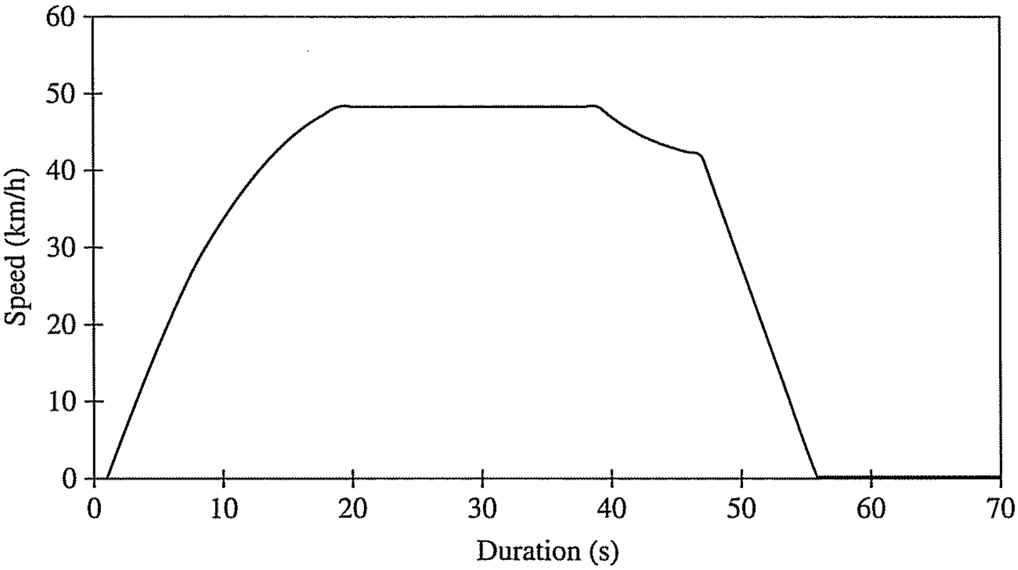


Fig. 3.16. J227a-C Cycle.

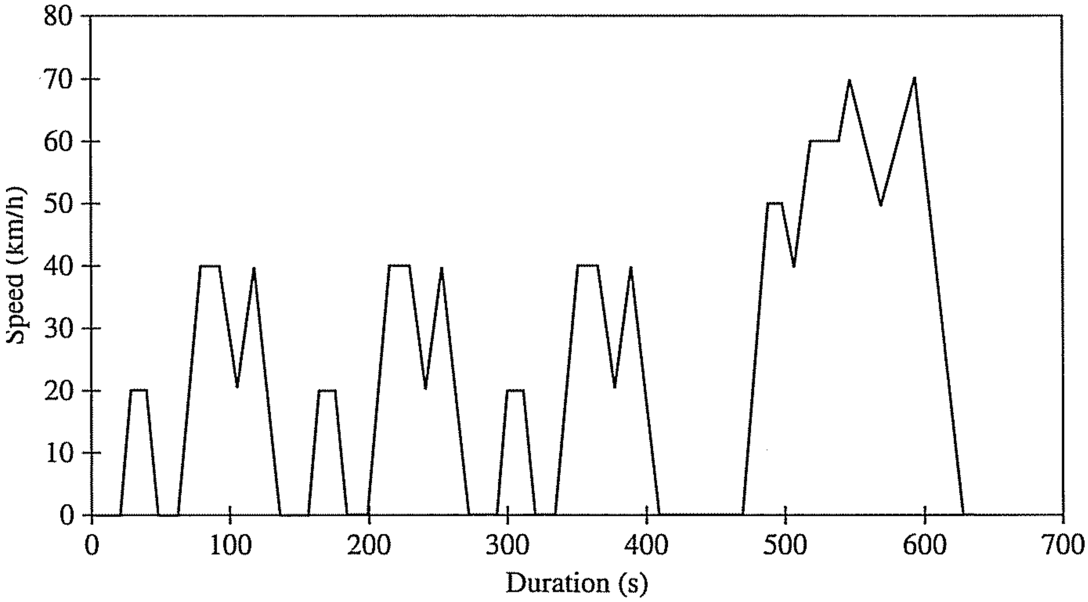


Fig. 3.17. Japan 10.15 Mode.

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