9

Design Considerations

9.1 Introduction

To maximise the fuel efficiency of any vehicle the mass, aerodynamic drag and rolling resistance have to be minimised, while at the same time maximising engine/motor and transmission efficiencies. It is particularly important to design battery electric vehicles with high efficiencies in order to reduce the mass of expensive batteries required.

This chapter builds on the previous chapter on vehicle modelling. The various parameters that went into the model are examined individually, together with their effect on vehicle performance. Various choices available to designers to optimise their vehicle design are discussed, as is the greater flexibility to place components in electrical vehicles with a view to optimising weight positioning and minimising aerodynamic drag.

9.2 Aerodynamic Considerations

9.2.1 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. As seen in Chapter 8, the drag force F_{ad} on a vehicle is

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

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

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

Electric Vehicle Technology Explained, Second Edition. James Larminie and John Lowry.

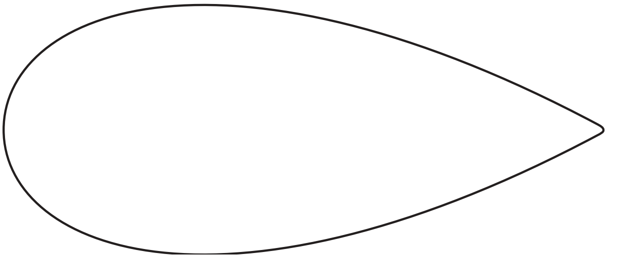

Figure 9.1 Aerodynamic ideal shape, a 'teardrop' of aspect ratio 2.4

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 $1.23\,\text{kg m}^{-3}$, the power required to drive a teardrop-shaped body with $C_d = 0.04$ of cross-section $1\,\text{m}^2$ travelling at 100 kph ($27.8\,\text{m s}^{-1}$) 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 $1.9\,\text{m}^2$ 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):

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

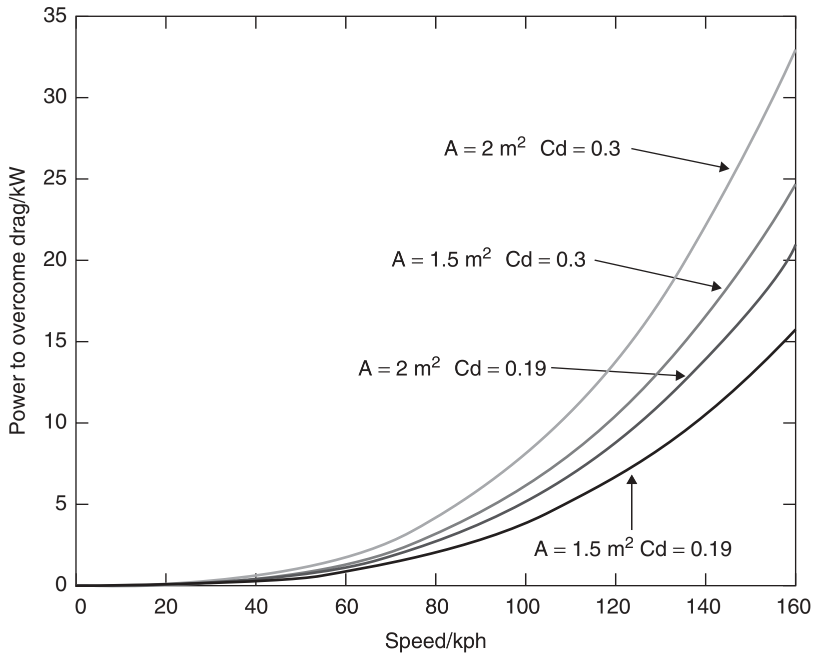

Figure 9.2 Power requirement to overcome aerodynamic drag for vehicle of different frontal areas and drag coefficients for a range of speeds up to 160 kph

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

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

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. If the MATLAB file used in Section 8.4 for the range modelling of the GM EV1 (whose results are shown in Figure 8.15) are adapted for a constant speed of 120 kph, it will be found that the predicted range is less than 80 km. However, when driving the SFUDS cycle, which has plenty of stopping and starting but no speeds over 60 kph, the range could be over 140 km in good conditions.

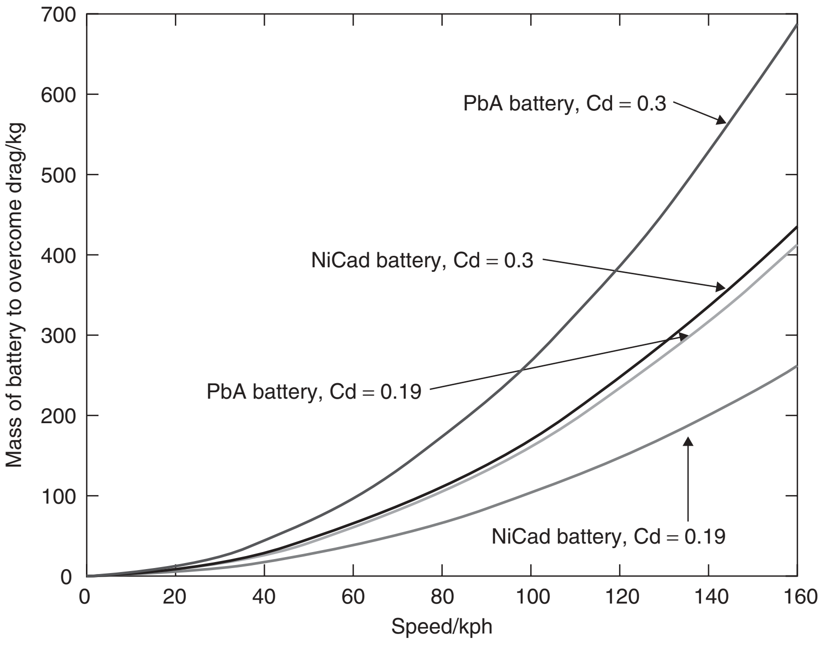

Figure 9.3 The effect of drag coefficient and speed on battery mass. The vehicles all have a frontal area of 1.5 m^2, and the range is 100 km. The mass is only for the energy required to store the energy to overcome aerodynamic drag – the actual battery mass would need to be higher

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.

9.2.2 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.

On the Honda Insight, shown in Figure 9.14, the body is tapered so that it narrows towards the back, giving it a shape approaching the teardrop. The rear wheels are placed $\sim$110 mm closer together than the front wheels, allowing the body to narrow. The cargo area above the wheel wells is narrower still and the floor under the rear portion of the car slopes upwards while the downward slope of the rear hatch window also contributes to the overall narrowing of the car at the rear.

At the back of the Insight the teardrop shape is abruptly cut off in what is called the Kamm effect. The Kamm back takes advantage of the fact that beyond a certain point there is little aerodynamic advantage of rounding off or tapering, so it might as well be truncated at this point, avoiding long, extended, fairly useless tail sections.

Another important aerodynamic feature is the careful management of under-body air flow. The Insight body features a flat under-body design that smoothes air flow under the car including three under-body covers. Areas of the under-body that must remain open to the air such as the exhaust system and the area under the fuel tank (it is a hybrid) have separate fairings to smooth the flow around them.

In order to minimise the air leakage to the underside, the lower edges of the sides and the rear of the body form a strake that functions as an air dam. At the rear the floor pan rises at a 5° angle towards the rear bumper, creating a gradual increase in the body area that smoothly feeds under-body air into the low-pressure area at the rear of the vehicle.

The GM EV1 with its exceptionally low drag adopts a similar approach. It has the advantage that as a pure electric vehicle there is no need for fuel tanks or exhaust pipes. Again the vehicle shape emulates as far as possible the teardrop shape and is as perfectly smooth as possible. The rear wheels on the EV1 are 228 mm closer together, nearly twice that on the Insight. This can clearly be seen in Figure 14.5, which shows several views of this vehicle. With both vehicles abrupt changes in body curvature are avoided, items such as the windscreen are joined smoothly into the shape, and gaps, such as those between the wheels and body, are minimised. The surface of the wheels blends in with the body shape. This all helps to keep the air flow laminar and thus reduce drag.

On very low-speed vehicles (<30 kph), such as golf buggies, where tranquillity and pure air are more important than rushing around at speed, the aerodynamic shape of the vehicle is almost irrelevant. As discussed earlier, with vehicles such as commuter cars and town delivery vehicles the aerodynamic shape is less important than on faster cars. However, it does have some significance and should not entirely be ignored. There have been attempts to produce both vans and buses with teardrop shapes, but there is a conflict between an aerodynamic shape and low frontal area and the need for maximising interior space, particularly for load carrying. There is nothing stopping commuter vehicles from being aerodynamic, but in the case of vans there needs to be a compromise between the need to slide large items into a maximum space and the desire for a teardrop tail. There is no reason why some of the features used on the Insight and the EV1, such as under-body covers, cannot be used on vans. Careful consideration of the van shape, where possible avoiding rapid changes in curvature, keeping the wheel surfaces flat, minimising gaps and rounding the corners will indeed reduce the drag coefficient, but not down to that of the EV1.

When carrying out initial calculations, as in a feasibility study, the coefficient of drag is best estimated by comparing the proposed vehicle with one of a similar shape and design. Modern computational fluid dynamics (CFD) packages will accurately predict aerodynamic characteristics of vehicles. Most motor manufacturers use wind tunnels either on scale models or more recently on full-size vehicles. Some of these now incorporate rolling roads so that an almost exact understanding of drag, lift, and so on, can be measured.

9.3 Consideration of Rolling Resistance

As discussed in Chapter 8, the rolling drag on a vehicle F_{rr} is given by

$$F_{rr} = \mu_{rr} m g \tag{9.5}$$

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

$$P_{rr} = F_{rr} \times v = \mu_{rr} m g v \tag{9.6}$$

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,

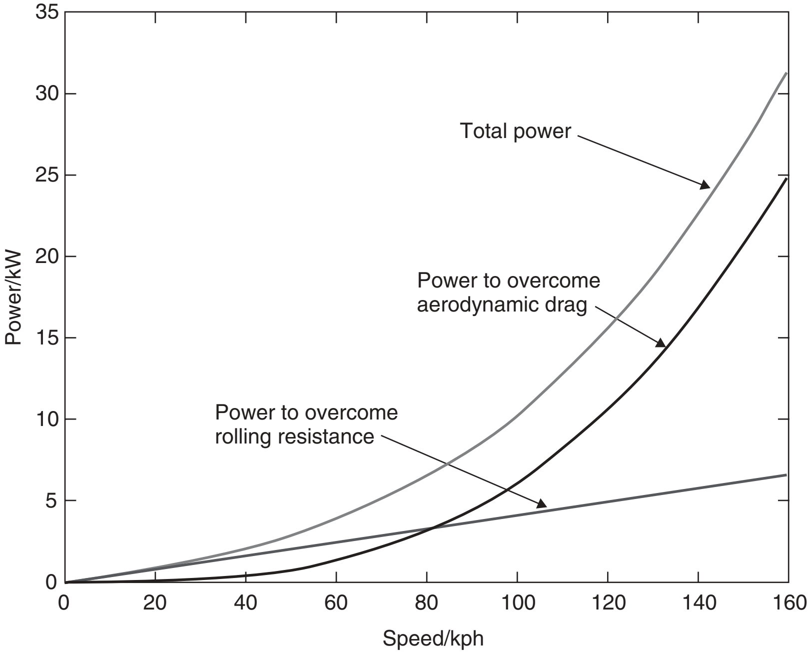

Figure 9.4 The power requirements to overcome rolling resistance and aerodynamic drag at different speeds. This is for a fairly ordinary small car, with $C_d = 0.3$, frontal area 1.5m^2, mass = 1000 kg and $\mu_{rr} = 0.015$

frontal areas of 2 m^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.

9.4 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 equalising 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.

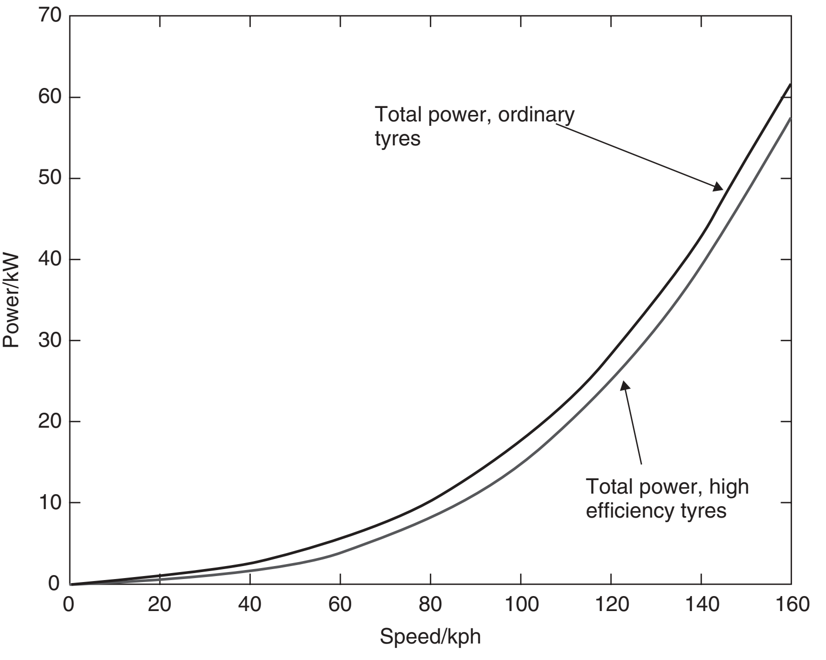

Figure 9.5 Power requirements for aerodynamic drag and rolling resistance at a range of speeds. This is for two vans, both of mass 1000 kg, frontal area 2 m^2 and $C_d = 0.5$. However, one has low-resistance tyres with $\mu_{rr} = 0.005$, whereas the other has ordinary tyres for which $\mu_{rr} = 0.015$

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 utilised. An example of a motor and differential fitted to an experimental battery-powered vehicle is shown in Figure 9.7. In this system the motor is transversal, but otherwise it is similar to Figure 9.7. This arrangement can also be seen in the diagram of the electric bus in Figure 14.7.

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. An example of a small motor connected via a simple gearbox to an axle, which would be suitable for this sort of application, is shown in Figure 9.8.

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. An example

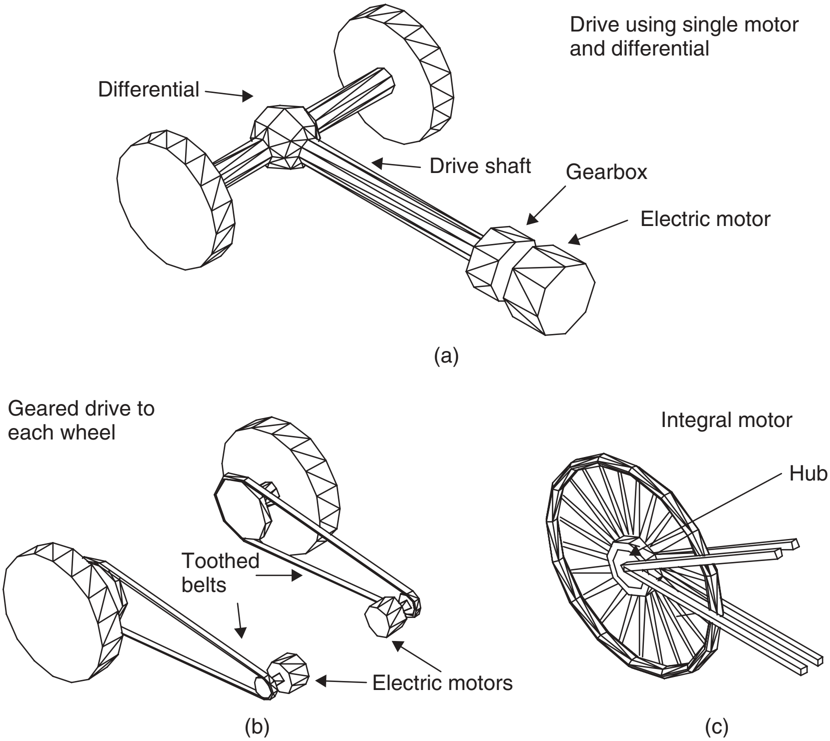

Figure 9.6 Three different arrangements for electric vehicle transmission: (a) drive using single motor and differential; (b) geared drive to each wheel; and (c) integral motor

Figure 9.7 Example of type (a) of Figure 9.6 on an experimental electric vehicle by MES-DES SA. The mounting of the motor is transverse, so there is no drive shaft

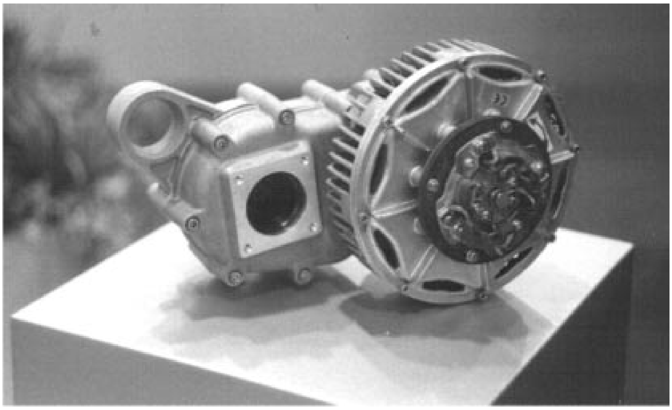

Figure 9.8 Commercial motor and single-speed gearbox to axle connection. This type of motor is designed for use in systems like that of Figure 9.6b, or on vehicles with a single drive wheel, or on vehicles like go-karts which have no differential

is shown in Figure 9.9. The General Motors Hy-wire of Figure 9.16 uses this approach, and it can also be seen in the electric bicycle of Figure 14.1. 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

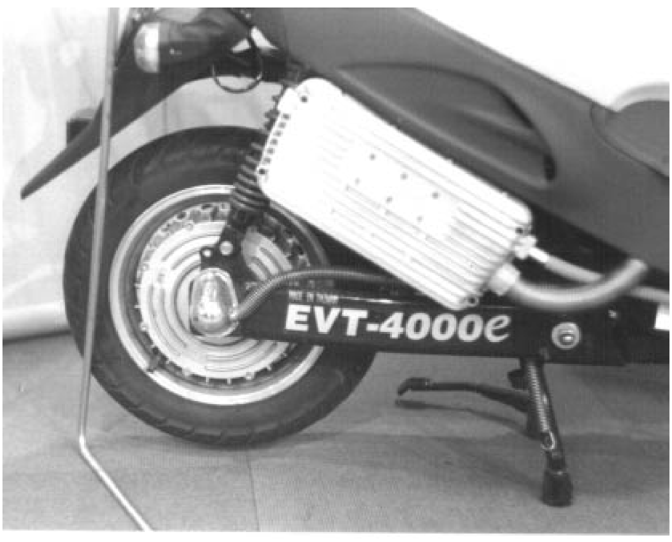

Figure 9.9 The rear wheel of an EVT electric scooter. Here there is no transmission – the wheel and motor are one. This is an example of Figure 9.6c

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.

9.5 Consideration of Vehicle Mass

The mass of an electric vehicle has a critical effect on the performance, range and cost of an electric vehicle. The first effect of the mass on rolling resistance and the power and energy to overcome this has already been discussed in Section 9.3.

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.

In Equation (8.3) of Chapter 8 it was seen that the force F_{hc} in newtons along the slope for a car of mass m(kg) climbing a hill of angle ψ is given by

$$F_{hc} = mg \sin \psi \tag{9.7}$$

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

$$P_{hc} = F_{hc} \times v = mgv \sin \psi \tag{9.8}$$

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 studied in Chapter 8. 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 1.8 m^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.

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, as in Figure 8.16. 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. It is not too difficult, after a little experience, to add gradients to the simulation driving cycles considered in the previous chapter. This is usually done with a specific journey in mind.

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. There are a variety of simulated urban driving cycles

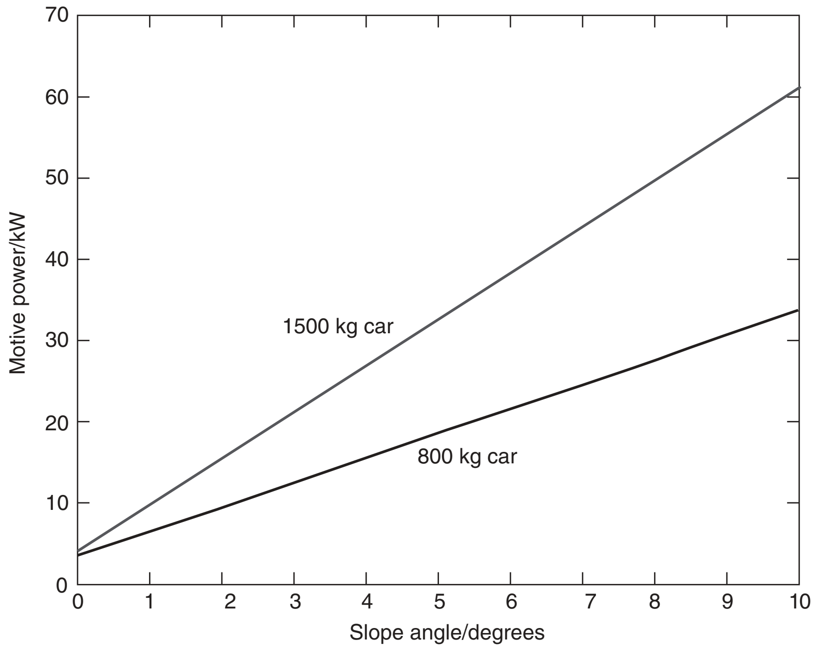

Figure 9.10 The total power requirements for two different vehicles moving at 80 kph up a hill of slope angle 0°–10°. In both cases the vehicle has good tyres with $\mu_{rr} = 0.005$, low drag as $C_d = 0.19$, and a frontal area of 1.8m^2. One car weighs 800 kg, the other 1500 kg

that have already been discussed in Chapter 8. Basically, when a vehicle of mass m(kg) is travelling at velocity v(m s^{-1}) its kinetic energy is given by

$$KE = \frac{1}{2}mv^2 \tag{9.9}$$

If the vehicle brakes this energy is converted to heat. When regenerative braking is used a certain amount of the energy is recovered. This was extensively explored in Chapter 8, including Section 8.3.3, and Table 8.3. 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 (kg m^2) rotating at ω(rad s^{-1}) is given by

$$E_r = \frac{1}{2}I\omega^2 \tag{9.10}$$

The moment of inertia I is normally expressed as

$$I = \sum_{n=1}^{n=N} m_n r_n^2 \tag{9.11}$$

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. This was addressed in Section 8.2 and Equation (8.8). In practice it is often difficult to obtain precise information about the moment of inertia of the rotating parts, and a reasonable approximation is simply to increase the mass in Equation (9.9) by 5%, and not use Equation (9.10). Notice that this does not need to be done for the mass in the hill climbing Equation (9.8)

In the next section we consider aspects of the chassis and body design, and how it might be made, and what materials used, in order to achieve this aim of reducing the weight.

9.6 Electric Vehicle Chassis and Body Design

9.6.1 Body/Chassis Requirements

This section is intended to give guidance on the design of the chassis for electric vehicles. Chassis design should be carried out in conjunction with other texts on chassis design, not to mention computer packages that specialise in this area. Nevertheless a basic understanding of what the chassis should do and other parameters related to electric vehicle chassis is needed.

In the early cars chassis and bodies were separate items. The chassis gave the basic strength of the vehicle while the body and glazing acted as a cocoon to keep the passengers and luggage protected from the outside elements.

In recent times the body and chassis have been combined as a monocoque so that every part, including the glazing, adds to the strength and stiffness, resulting in a much lighter vehicle. Either monocoques or separate chassis/body units are an acceptable basis for design. Despite the popularity of monocoques several modern electric vehicles use a separate chassis, most notably the advanced new GM ‘Hy-wire’ fuel cell vehicle, which will be discussed in more detail later.

It is worth pausing to think precisely what the chassis/body does. Ideally a chassis/body should fill the following criteria. It should be:

- strong;
- light;
- rigid;
- vibration-free, particularly at frequencies and harmonics of rotating parts and road-sourced vibration;
- aerodynamic;
- resistant to impact;
- able to crumple evenly in an accident, minimising forces on driver/passengers;
- strong enough to fix components to easily;
- impact and roll resistant;
- cheap;
- aesthetically pleasing;
- corrosion proof.

Chassis/body design requires optimisation of conflicting requirements such as cost and strength, or performance and energy efficiency. There are important differences when designing electric vehicles compared with their IC equivalents. For example, extra weight is not so important with an IC vehicle, where a little more power can be cheaply added to compensate for a slightly heavier chassis. The same is true for aerodynamic drag, where a slight increase in drag can be similarly compensated. Savings in weight as well as increases in efficiency contribute directly to the size of the batteries and these are both heavy and expensive.

9.6.2 Body/Chassis Layout

There is plenty of scope for designers of electric vehicles to experiment with different layouts to optimise their creation. To start with, there is no need for a bonnet housing and engine. In addition, batteries can be placed virtually anywhere along the bottom (for stability) of the vehicle and motors and gearing can be – if required – integrated with the wheel hub assemblies.

Most batteries can be varied in size. Height can be traded against length and width, and most batteries (not all) can be split up so that they can be located under seats and anywhere else required, all of which can help to use every available space and to reduce the vehicle frontal area. Batteries can also be arranged to ensure that the vehicle is perfectly balanced around the centre of gravity, giving good handling characteristics.

A picture of an interesting experimental drive system assembly is shown in Figure 9.11, consisting of one driven wheel, with batteries and controller all built into the unit. The scope for using such a device on a range of interesting vehicle layouts is considerable. It could be incorporated, for example, to drive the rear wheel in a tricycle arrangement. Interestingly, one of the most popular three-wheel electric vehicles is the 'Twike' illustrated

Figure 9.11 This power module comprises motor, controller, battery and one driven wheel in a neat unit that could be built into a wide range of vehicle designs

Figure 9.12 The famous Swiss electric 'Twike'

in Figure 9.12. Based on the previous argument the vehicle layout could be interpreted as being the 'wrong way round' – the body is like a teardrop going backwards. However, as it is a low-speed commuter vehicle based on bicycle components the aerodynamic shape is not as important as those of a high-speed vehicle. The two rear wheels with the passengers sitting side by side give stability.

The layout for an electric van also has considerable scope for new ideas. Electric motors and gearing can again, if required, be incorporated into the wheel hub assemblies, avoiding space requirements for motors, gearing and transmission. Batteries such as lead acid, NiCad or NiMH can be spread as a thin layer over the base of the vehicle leaving a large flat-floored area above – an essential requirement for vans.

9.6.3 Body/Chassis Strength, Rigidity and Crash Resistance

The days have long past, thankfully, when stress engineers regarded aircraft as hollow cylinders with beams stuck out of the side and cars as something simpler. Modern predictions of chassis/body behaviour and virtually every aspect of car design rely ultimately on analysis using complex computer packages. Nevertheless a basic understanding of the behaviour of beams and hollow cylinders does give an insight into body/chassis design.

Let us look at a hollow cylinder as shown in Figure 9.13 subjected to both bending and torsion. Bending would be caused by the weight of the vehicle, particularly when coming down after driving over a bump, and the torsion from cornering. The weight of the vehicle will cause stresses to mount in the tube and will also cause it to deflect. The torsion will likewise result in shear stresses and will cause the tube to twist.

Assuming an even weight distribution, the maximum bending stress $\sigma\,(\mathrm{N\,mm^{-2}})$ will be given by the formula

$$\sigma = \frac{wL^4 r_o}{8I} \tag{9.12}$$

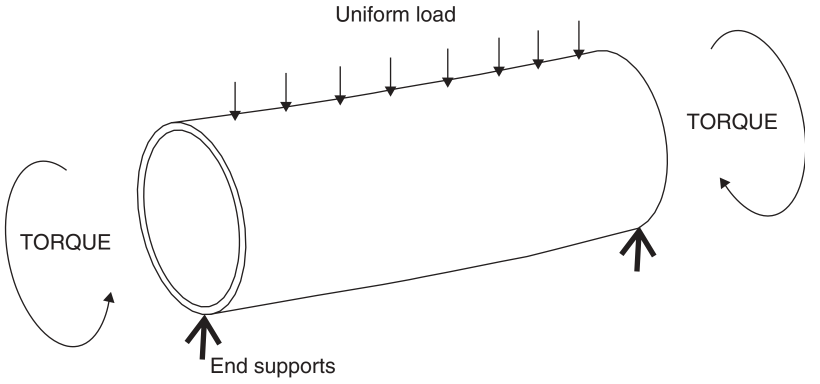

Figure 9.13 A hollow cylinder under torsion and bending loads

where w is the uniform weight/length (N mm^{-1}), L is the length (mm), r_o is the radius (mm) and I is the second moment of area (mm^4). I will be given by

$$I = \pi \frac{r_o^4 - r_i^4}{4} \tag{9.13}$$

and the maximum deflection δ(mm) in the middle of the beam will be given by

$$\delta = \frac{5wL^4}{384EI} \tag{9.14}$$

where E is Young's modulus (N mm^{-2}). Similarly, the shear stress in the cylinder wall q(N mm^{-2}) is given by

$$q = \frac{Tr_o}{J} \tag{9.15}$$

where T is the applied torque (N mm) and J is the polar second moment of area (mm^4), which will be given by

$$J = \pi \frac{r_o^4 - r_i^4}{2} \tag{9.16}$$

The angle of twist θ(rad) is given by

$$\theta = \frac{TL}{GJ} \tag{9.17}$$

where G is the rigidity modulus (N mm^{-2}).

Certain clear conclusions can be drawn from these equations. To minimise stress due to both bending and torsion, both I and J must be kept as large as possible. For a given mass of material, the further it is spread from the centre of the tube, the larger will be both I and J, thus reducing stresses, deflection and twist.

For example, consider a solid cylinder of 200 mm diameter. I and J will be $\pi(100)^4/4 = 25\,000\,000\pi$ and $\pi(100)^4/2 = 50\,000\,000\pi$ (mm^4) respectively. The same material can be spread around the circumference of a tube of 1000 mm diameter and 10.1 mm thick. This would have values for I and J of $1.23 \times 10^9\pi$ and $2.45 \times 10^9\pi$ respectively, an increase of 49 times. The deflections and twists will also be much less for the tube – less by a factor of nearly 50 in fact, as can be seen from Equations (9.14) and (9.17).

This remains true until the material buckles, which can be predicted by modern finite element packages. Buckling can be minimised by using two layers of the material, with foam in the middle effectively creating a sandwich – hence sandwich materials. Alternatively two thin sheets of aluminium can be joined by a thin aluminium honeycomb; both of these techniques are widely used in the aircraft industry.

To keep both deflection due to bending and twist due to torque as low as possible it is necessary to use materials which are as rigid as possible, that is having high E and G values in addition to optimising the design to keep I and J as large as possible.

Due consideration must be given to material rigidity as well as strength. For example, an infinitely strong rubber would be useless as it would deform and twist far too much. Similarly a rigid but weak material would be useless.

Steel, being relatively cheap, as well as rigid, is a traditional choice for manufacturing car bodies and chassis, but it is not necessarily a good choice for electric vehicles. Firstly it has a low strength-to-weight ratio resulting in a relatively heavy structure. Secondly the manufacturing cost is low when mass produced, but relatively expensive for small-number production, which may be the initial option for electric vehicles.

Materials such as aluminium and modern composites have much better strength-to-weight ratios than steels, and both are widely used in the aircraft and racing car industries. A list of some potential materials is given in Table 9.1.

Table 9.1 Comparison of material properties

Material	Density $\rho\,(\mathrm{kg\,m^{-3}})$	Fracture stress $\sigma\,(\mathrm{MPa})$	Young's modulus $E\,(\mathrm{GPa})$	Strength to mass (σ/ρ)	Rigidity to mass (E/ρ)
Mild steel	7850	465	207	0.059	0.026
Stainless steel, FSM 1	7855	980	185	0.125	0.024
Aluminium alloy (DTD 5050B)	2810	500	71	0.178	0.025
Magnesium alloy (AX 31) (DTD 742)	1780	185	45	0.104	0.025
Carbon fibre reinforced plastic, 58% unidirectional fibres by volume in epoxy resin	1500	1050	189	0.70	0.126
Glass reinforced plastic (GRP), 80% uniaxial glass by weight in polyester resin	2000	1240	48.2	0.62	0.024

It can be seen in the table that carbon fibre has the best strength to mass (σ/ρ) as well as the best rigidity to mass (E/ρ), nearly six times the other materials, which interestingly have almost identical rigidity/mass. This accounts for its widespread use in the aerospace and racing industries. A carbon fibre Formula One chassis/body can have a mass as low as 35 kg. Glass reinforced plastic (GRP) has the next best strength-to-mass ratio, 3.5 times that of aluminium, which is next.

Before a decision is made on what the appropriate body and chassis materials are, the behaviour of a car in a crash must be considered. In a crash situation a car body and/or chassis will absorb energy. If the car is designed so that the energy is absorbed in a controlled manner the forces on the driver and passengers can be minimised. It is therefore normal to design cars with energy-absorbing crumple zones. There is national and international legislation to define a crash situation that cannot be ignored. In the late 1960s one large motor manufacturer had to strip out a brand-new production line as the cars being produced did not comply with crash legislation.

Both metals and composites absorb energy on impact, metals through plastic deformation and composites through fragmenting. The behaviour of metals in a crash can now be predicted accurately using large finite element packages, whereas it is much harder to predict the behaviour of composites. This means that if a metal structure is used, the car can be designed to deform in the optimum manner to meet legislation; this prediction would be much harder with composites.

Both carbon fibre and aluminium are considerably more expensive than steel. However, by using these materials not only is the car lighter, but for a given range a considerable amount of expensive batteries is saved, which must be accounted for in the overall costing of the vehicle.

9.6.4 Designing for Stability

As well as being rigid and crash resistant, a vehicle should be designed also to be clearly stable. For maximum stability, wheels should be located at the vehicle extremities and the centre of gravity should be kept as low as possible. This is one area where the weight of the batteries can be beneficial, as they can be laid along the bottom of the vehicle making it extremely stable. During a visit to look at an electric van manufacturer, one of the authors was challenged to try to turn it over while driving round roundabouts. Perhaps regrettably, he declined the offer, but it did give an indication of the manufacturer's confidence in the stability of its product. The Duke of Edinburgh drove the same model of vehicle for a while; it is not known if he received the same challenge!

9.6.5 Suspension for Electric Vehicles

Suspension has the purpose of keeping all of the wheels evenly on the ground, reducing the effects of bumps and ensuring passenger comfort. Suspension on an electric vehicle should, from the energy efficiency viewpoint, be fairly hard. As with tyres pumped to a high pressure, the energy loss is reduced but the ride tends to be less comfortable. Other than this, the suspension design for electric vehicles will not be different than that for regular vehicles of similar size.

Figure 9.14 The Honda Insight (Reproduced by kind permission of Honda Motor Co. Ltd.)

9.6.6 Examples of Chassis used in Modern Battery and Hybrid Electric Vehicles

Some electric vehicles are simply adapted from an IC engine vehicle and use an existing vehicle chassis/body. This has obvious advantages inasmuch as the whole vehicle is available and simply has to be adapted, which is obviously a cheaper option than designing a whole new vehicle. While these vehicles often have an adequate range and performance, better results are obtained if the body chassis is purpose built.

Many of the more recent electric vehicles use aluminium for the main structure despite the lower strength/mass of aluminium compared with carbon fibre composites. The vehicle panels are often made from composites.

Some examples are shown in Figures 9.14 and 9.15. The first shows the aluminium body of the Honda Insight, together with some views of the whole vehicle. The second shows the ‘Twike’, a simple elegant design using a tubular aluminium chassis. (The complete vehicle is shown in Figure 9.12.) The vehicle panels are often made from composites. Note that front crumple zones are a feature of both designs.

9.6.7 Chassis used in Modern Fuel Cell Electric Vehicles

Chassis bodies for fuel cell vehicles need to house the hydrogen fuel tanks or a hydrogen generator, the fuel cells, the motor and radiators for getting rid of excess heat. Fuel cells can be used in conventional vehicle chassis units, and some examples have been seen in earlier chapters, for example Figures 1.15 and 1.16. However, General Motors has taken the view that a modern power source required a totally new approach to the design. GM’s fuel cell vehicle, the ‘Hy-wire’, uses a ‘skateboard’ chassis illustrated in Figure 9.16.

Figure 9.15 The Twike chassis

Figure 9.16 GM's 'Hy-wire' chassis and one-body design (Reproduced by kind permission of General Motors Corp.)

This chassis unit is based on a simple aluminium ladder frame with front and rear crush zones. The chassis contains hydrogen tanks, drive-by-wire system controls for the steering, cabin heaters, radiators for dispensing with excess heat from the fuel cells and the air management system. The electric motors are built into the wheels. The whole unit is elegant and compact and allows a range of bodies simply to be attached to the chassis unit, the steering and controls being connected electrically. This allows the chassis to be used as the basis for a range of vehicles, from family saloons to sports cars.

9.7 General Issues in Design

9.7.1 Design Specifications

Before anyone sits down to design anything, including an electric vehicle, they should write a design specification outlining precisely what they want to achieve. There are books devoted to the subject of writing specifications but it is worth briefly looking at the implications.

For example, is the vehicle required for high-speed motorway driving, or is it simply for delivering people or loads about town at low speeds? This fact alone will lead to great differences in the shape of the vehicle. It was seen in the section considering aerodynamics that the vehicle which is to be used for motorway driving needs to be as aerodynamic as possible, but for the low-speed delivery van the aerodynamics are of much less importance.

Likewise, while any electric vehicle needs to be protected against corrosion, the environment in which the vehicle is likely to be used needs defining. 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 worse 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.

9.7.2 Software in the use of Electric Vehicle Design

Much of the conventional theory as presented in this book and elsewhere is satisfactory for giving first-order calculations and initial systems studies. It is an important initial stage in the design process of electric vehicles to carry out an initial study to check on the likely performance and range of the vehicle. The guidance given in the previous chapter, and in the appendices, can be used for such analysis.

However, it is usually necessary to use more sophisticated software to predict the performance of the vehicle more accurately. 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 behaviour 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 analysed for air flow using

CFD and for strength, rigidity, natural vibration and behaviour in a crash using finite element methods.

It is normal that products such as vehicles going into production will be designed by whole teams of engineers, industrial designers and analysts. Despite this, initial pilot studies for electric vehicles, prototypes and specials can still be designed by individuals or small groups of engineers and designers, and the approach to the design outlined in this chapter will help them in this task.