14

Recent Electric Vehicles

14.1 Introduction

At present there are many exciting developments in electric vehicles taking place. Many of these are now commercially available or, in the case of electric buses and high-speed trains, are used competitively on commercial routes. In this chapter we examine some of these electric vehicles.

14.2 Low-Speed Rechargeable Battery Vehicles

Rechargeable battery vehicles can be divided into several different categories. Firstly there are electric bicycles, secondly there are the low-speed vehicles (LSVs) which form a class of vehicle in the USA and Canada, with maximum speeds of 40 kph (25 mph), and thirdly conventional road vehicles using rechargeable batteries. In addition there are special purpose delivery vehicles and vehicles such as fork-lift trucks. There are also the small four-wheeled carriages used by the infirm which can be ridden on the pavement and are narrow enough to fit through normal front doors. Other vehicles, such as powered wheelchairs, could also be mentioned.

14.2.1 Electric Bicycles

Electric bicycles are probably the most popular type of battery electric vehicle, with thousands being used in China. There are many different manufacturers and types with a very interesting range of power methods: hub motors in the front or back wheels and drives on the pedal cranks are the most common variations. In most European and North American countries it is becoming a standard regulation that these bikes must be of the 'pedal-assist' type. This means that they cannot be powered by the electric motor alone. If they can be ridden under electrical power only, then they count as motorbikes, and attract a host of extra regulations and taxes. However, the regulatory situation is somewhat

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fluid, varied and changeable, which is something of an impediment to the development of this market.

For example, in Britain ‘electric-power’-only bicycles are still legal, but the power must cut out once the cycle reaches a speed of 15 mph (24 kph). The maximum allowed motor power is 200 W, the maximum weight is 40 kg, and the riders must be aged 14 years or over. However, this law is liable to change in the near future in favour of ‘pedal-assist’ mode only.

These regulations mean that the controllers on electric bikes nearly always include a sensor of some kind. Often there will be a torque sensor on the pedal crank. This works with the motor controller and ensures the rider is putting in some effort before allowing the motor to provide any power. Speed sensors will also often be fitted, to cut the electric power once a set speed is reached (e.g. 15 mph in Britain, as above).

Although the large cycle manufacturers, such as Giant of Taiwan, are including electric cycles, the market is currently dominated by smaller businesses supplying a fairly local region. An example is the FreeGo Hawk illustrated in Figure 14.1 with technical details given in Table 14.1.

The development of reliable electric bikes could in itself have a significant impact. It may encourage people to use bikes rather than their conventional IC engine vehicles. A survey by one manufacturer showed that the average electric bike covered 1200 miles (1920 km) per annum, replaced 3 car journeys per week, provided a journey time faster than a bus and cost less than 1.5 pence per mile to run.

Use of this type of vehicle could be increased with encouragement from governments and councils in the form of special cycle tracks. The use of electric bikes would undoubtedly lead to less vehicle traffic and decreased pollution.

14.2.2 Electric Mobility Aids

One area of application that the demographics of western countries indicates must steadily grow for the foreseeable future is mobility aids for the elderly and infirm. The sort of

Figure 14.1 FreeGo Hawk Electric bicycle (Reproduced by kind permission of FreeGo Electric Bikes)

Table 14.1 The specification for the FreeGo Hawk electric cycle

Wheels	26 in (66 cm)
Frame	18 in (46 cm)
Motor	250 W brushless hub motor
Speed control	Handlebar-mounted twist throttle
Range – pedal-assist mode	15–20 miles (24–32 km) throttle only 10 Ah, 30–40 miles (48–64 km) pedal assist for 10 Ah battery
Battery	10 Ah lithium battery weighing 4 kg
Gears (for pedalling)	Seven speed
Battery charge time	4–6 hours full charge, 2–3 hours 80% charge
Mode	Pure power, pedal assist or pedal only, switchable
Charger	36 V mains charger
Weight including battery	26 kg
Current cost	From about £900 (sterling) depending on specification

vehicle we are talking about here is shown in Figure 14.2, a ‘carriage’ for those who can take a few steps but need help from technology to retain their independence. There are a wide range in this class, from small three wheelers to larger vehicles with a claimed range of 40 miles (64 km), and tougher wheels, for people who need to get about country lanes. Table 14.2 gives the outline technical details of a middle-range machine such as that of Figure 14.2.

Figure 14.2 Mobility aid for shopping trips and similar journeys near home

Table 14.2 Details of a shopping carriage for the infirm, such as that shown in Figure 14.2

Length	1.19 m
Width	0.6 m
Height	0.91 m
Weight	65 kg, 85 kg with batteries
Batteries	2 of 12 V, 28 Ah (20 h rate)
Motor power	370 W continuous
Drive	Rear wheel drive, one motor
Maximum speed	6 kph forward, 2 kph reverse
Maximum incline	10°
Range	30 km (claimed, on level ground)

14.2.3 Low-Speed Vehicles

LSVs are an ‘environmentally friendly’ mode of transport for short trips, commuting and shopping. In the USA, for example, 75% of drivers are believed to drive round trips of less than 40 km per day. In rural areas the lower traffic density would enable these to be used fairly easily. In towns and cities it would be worthwhile for governments and local authorities to ensure that proper lanes for this type of vehicle were made available and where possible tax incentives are used to encourage their use.

These vehicles are particularly targeted at fairly active retired people who still want to get about to see their friends, but who do not travel far, are not in such a hurry and value a peaceful neighbourhood. The demographics of most western countries show there is little doubt that the market for this type of vehicle will grow steadily.

An example of LSVs is shown in Figure 14.3. The specification of a typical four-seat vehicle of this type is given in Table 14.3.

14.3 Battery-Powered Cars and Vans

There are a range of such vehicles, vans, cars and buses that have been used in recent years. Most have ranges under 100 km, and the best possible range of a rechargeable battery vehicle such as the GM EV1 is 200 km. Some of the early developments did not show huge commercial promise but with recent developments in lithium ion batteries the market is showing signs of becoming considerably active. Some of the earlier vehicles are included below and it is interesting to compare these with recent developments such as the Nissan Leaf and the Mitsubishi MiEV which are also discussed below.

14.3.1 Peugeot 106 and the Partner

Peugeot has always been very active in electric vehicles and works with vans as well as cars. Two example vans are the 106 and the Partner. The Partner van is illustrated in Figure 14.4 and the specifications of both are given in Table 14.4. There is also a 106 electric car which has a similar specification to the van.

Figure 14.3 An example of the 'low-speed vehicle' (LSV) type of electric car

Table 14.3 Specification of a typical low-speed electric vehicle

Length (mm)	3075
Width (mm)	1400
Height (mm)	1750
Wheelbase (mm)	2635
Curb weight (kg)	560
Payload (kg)	360
Ground clearance	150 mm at curb weight
Minimum turning radius (mm)	4080
Range (km)	64
Acceleration	0–40 kph in 6 s
Hill climbing capability (%)	21

The Peugeot electric vehicles are examples of conventional vehicles converted to electric vehicles. Their range is doubtless adequate for uses such as city deliveries, but is less than might have been obtained with a purpose-built electric vehicle. This is undoubtedly a trade-off of cost against range.

14.3.2 The GM EV1

When designing its EV1 vehicle, as shown in Figure 14.5, General Motors used another approach altogether. The GM EV1 is a rechargeable battery-powered two-seater car, which at the time of its introduction represented probably the most advanced electric vehicle

Figure 14.4 Peugeot ‘Partner’ battery electric van (Photograph reproduced by kind permission of Peugeot)

using rechargeable batteries. It was purposely designed through and through as an electric vehicle and is not a modified IC engine vehicle. It was introduced in 1997 initially using lead acid batteries, but more recent versions have used NiMH batteries to give an extended range. The car is summarised in Table 14.5.

We have already met this car when considering vehicle modelling in Chapter 8. It has the lowest drag coefficient of any production car ($C_d = 0.19$) and uses very low rolling resistance tyres. The vehicle was produced in limited numbers and could only be leased rather than bought. To the dismay of electric vehicle enthusiasts the EV1 was recently taken off the market. The decision of the California legislature to draw back from its requirement on manufacturers to produce fully ‘zero-emission’ vehicles has probably made this decision permanent. The existing examples will no doubt become valuable collectors’ items in the years to come, because it is a very interesting car with many exciting technical features. The EV1 is illustrated in Figure 14.5.

The EV1 is powered by a 102 kW, three-phase AC induction motor and uses a single-speed, dual-reduction gearset with a ratio of 10.946:1. The battery pack consists of 26 valve-regulated high-capacity lead acid batteries, each 12 V and 60 Ah. The EV1 can be charged safely in all weather conditions with inductive charging. Using a 220 V charger, charging from 0 to 100% takes from $5^{1/2}$; to 6 hours. The EV1 with its high-capacity lead acid pack has an estimated ‘real-world’ driving range of 50–90 miles (80–144 km), depending on terrain, driving habits and temperature. The range with the optional NiMH pack is even greater. Again, depending on terrain, driving habits, temperature and humidity, estimated real-world driving range will vary from 75 to 130 miles (120 to 208 km).

Braking is accomplished by using a blended combination of front hydraulic disc and rear electrically applied drum brakes and the electric propulsion motor. Regenerative braking is used, extending the vehicle range by partially recharging the batteries.

The vehicle’s body weighs 132 kg and is less than 10% of the total vehicle weight, which is 1400 kg, of which the battery weight is nearly 600 kg. The 162 pieces are bonded together into a unit using aerospace adhesive, spot welds and rivets.

The exterior body panels are dent and corrosion resistant. They are made out of composites and are created using two forming processes known as sheet moulding compound (SMC) and reinforced reaction injection moulding (RRIM).

Table 14.4 Details of Peugeot battery electric vans

	106 van	Partner van
Motor type	Leroy Somer DC separate excitation 20 kW	Leroy Somer DC separate excitation 28 kW
Max. motor torque	127 N m from 0 to 1600 rpm	180 N m from 0 to 1550 rpm
Max. motor speed (rpm)	6500	6500
Motor cooling	Forced air ventilation	
Transmission	Front wheel drive, epicyclic reduction to differential	
Steering	Rack and pinion – power assisted	
Suspension front	Independent with Macpherson-type struts	
Suspension rear	Independent with trailing arms and torsion bars	
Front brakes	Servo-assisted discs	
Rear brakes	Servo-assisted drums	
Tyres	165/70 × 13	165/60 × 14
Maximum speed (kph)	90	96
Range (urban) (km)	72	64
Restart gradient	22%	
Battery type	NiCad, 100 Ah	
Voltage (V)	120	160
Charger	3 kW integral with vehicle 240 V, 13 A AC supply	3 kW integral with vehicle 240 V, 13 A AC supply
Charging time (h)	7	9
Energy consumption (kWh per 100 km)	20	28
Length (m)	3.68	4.11
Width (m)	1.59	1.69
Height (m)	1.38	1.81
Kerb weight (kg)	1077	1450
Payload (kg)	300	500
Payload volume (m^3)	0.92	3

The EV1 is designed to be highly aerodynamic, saving energy and allowing a lower level of propulsion power that sends the vehicle further. The rear wheels are 9 in (23 cm) closer together than the front wheels, which allows for a teardrop body shape that lessens drag, as explained in Section 9.2.2.

The EV1 has an electronically regulated top speed of 80 mph (128 kph). It comes with traction control, cruise control, anti-lock brakes, airbags, power windows, power door locks and power outside mirrors, AM/FM CD/cassette and tyre inflation monitor system. The vehicle also offers programmable climate control, an electric windshield defogger/de-icer, a rear window defogger and centre-mounted instrumentation.

Figure 14.5 The groundbreaking GM EV1 battery electric car. (Reproduced by kind permission of General Motors Inc.)

Table 14.5 The GM EV1

Body style	Two-seat, two-door coupé
Electric motor	Three-phase induction motor 102 kW
Transmission	Single-speed reduction integrated with motor and differential
Battery	Release 1 lead acid 18.7 kWh
	Release 2 NiMH 26.4 kWh
Range	Release 1 70–100 miles (112–160 km)
	Release 2 100–140 miles (160–224 km)
Wheelbase (mm)	2512
Length (mm)	4310
Width (mm)	1765
Height (mm)	1283
Curb weight (kg)	1400

The EV1 does not require a conventional key to unlock the door. A five-digit personal identification code is entered on the exterior keypad to allow access. No key is needed to start the car. The same five-digit code is entered on the centre console's keypad to activate the car.

The EV1 undoubtedly has as good a performance and range as can be achieved economically using commercially available rechargeable batteries. The advanced performance clearly illustrates the benefits of designing the vehicle as an electric car rather than simply converting an existing vehicle.

The range of rechargeable battery vehicles rarely exceeds 150 km and at best 200 km. The use of batteries such as the Zebra battery or lithium chloride batteries could increase the range further by 30%. Clearly, for a very much greater range the need for a new generation of batteries became obvious.

14.3.3 *The Nissan Leaf*

With the advent of the latest lithium ion batteries there have been several battery EVs which have been released commercially or are about to be released. Two of the latest road vehicles which are currently available are discussed below.

Nissan has released a commercial five-door hatchback electric car fitted with a lithium ion battery driven by a permanent magnet synchronous motor and with a range of around 100 miles (160 km) between charges. The Leaf is illustrated in Figure 1.12 and summarised in Table 14.6. Initially the Leaf was released in Japan in 2010; however, assembly is planned for Sunderland, in Britain, from 2013 and in Smyrna, Tennessee, from 2012.

The Leaf can be charged from a home charging unit in 8 hours and can take a rapid charge to 80% of the battery capacity in 30 minutes.

14.3.4 *The Mitsubishi MiEV*

The MiEV is another battery electric vehicle which uses a lithium ion battery and also uses a permanent magnet synchronous motor. The vehicle was illustrated in Figure 1.13 and is specified in Table 14.7.

14.4 Hybrid Vehicles

Hybrid vehicles which cannot be recharged from the mains but run entirely on petrol have become well established.

Two examples are the Honda Insight and the Toyota Prius, which have really made an impact on the world of car design, and brought electric cars that people can easily use onto the market. They are discussed below. These, and a steadily increasing number of alternatives from almost all the major motor manufacturers, can be purchased now at very reasonable prices.

Table 14.6 The Nissan Leaf

Body style	Five-door hatchback
Layout	Front engine, front wheel drive
Electric motor	80 kW (110 hp) permanent magnet synchronous motor
Transmission	Single-speed direct drive
Battery	24 kWh lithium ion battery
Range	117 km (73 miles) (EPA) 175 km (109 miles) (NEDC) 76–169 km (47–105 miles) (Nissan)
Wheelbase	2700 mm (106.3 in)
Length	4445 mm (175.0 in)
Width	1770 mm (69.7 in)
Height	1550 mm (61.0 in)
Curb weight	1521 kg (3354 lb)

Table 14.7 The Mitsubishi MiEV

Body style	Five-door hatchback
Electric motor	47 kW (63 hp) permanent magnet synchronous motor mounted on rear axle, 180 N m torque
Transmission	Single-speed reduction gear
Battery	16 kWh (lithium ion battery)
Range	160 km (99 miles) (Japanese cycle) 100 km (62 miles) (US EPA cycle)
Top speed	81 mph (130 kph)
Wheelbase	2550 mm (100.4 in)
Length	3395 mm (133.7 in) 3680 mm (144.9 in) (US)
Width	1475 mm (58.1 in) 1585 mm (62.4 in) (US) (excluding side mirrors)
Height	1600 mm (63.0 in) 1615 mm (63.6 in) (US)
Curb weight	1080 kg (2400 lb)

14.4.1 The Honda Insight

The Honda Insight is a hybrid vehicle combining a conventional petrol-driven engine with an additional motor driven by a battery. The engine and motor can both be used to propel the vehicle. The Insight employs a system Honda calls the Integrated Motor Assist (IMA) system. The Insight does not get recharged from the mains in the same way as a conventional EV. Instead its benefits derive from using the IC engine in conjunction with the battery and motor/generator system to maximise energy efficiency and to minimise fuel consumption. When there is surplus power available from the engine it is used to recharge the batteries from the motor/generator. The motor/generator is also used to slow the vehicle and thus recover the kinetic energy into the battery. When the brake pedal is pressed lightly, the Insight's electric motor operates in regeneration mode, and the car begins to slow just as it would with normal brakes. Once the brake pedal is pressed further, the normal brakes come into play, slowing the car down even more.

In heavy traffic the car is driven from the batteries via the motor/generator only. Hence it can be classified as a partial zero-emission vehicle (PZEV). It is a parallel hybrid, as outlined in Figure 2.3. The electric motor/generator has a maximum power of 10 kW, and is about 6 cm thick, between the engine and the gearbox, and directly connected to the crankshaft.

The body chassis is designed for low weight while at the same time meeting crash test requirements. All structural components and most body panels are extruded or die-cast aluminium, while front fenders and rear fender skirts are a recyclable ABS/nylon composite. The car's independent front suspension uses lightweight, forged-aluminium suspension arms and aluminium front suspension knuckles. The braking system's front callipers are also aluminium alloy, as are the rear brake drums.

The rear suspension is a highly compact twist-beam design that sits completely below the Insight's flat cargo floor, along with the lightweight plastic-resin 40 l (10.6 US gallon) fuel tank and gas-pressurised rear shock absorbers. The rear suspension is also designed to help absorb the energy of a rear impact.

At the heart of the Insight's IMA system is a compact, 1 l, three-cylinder petrol IC engine. The engine uses lean-burn technology, low-friction design features and lightweight materials such as aluminium, magnesium and special plastics, in combination with a new lean-burn-compatible NOx catalyst, to achieve the levels of efficiency and low emissions in petrol engine technology. The specification for the Insight is given in Table 14.8.

14.4.2 The Toyota Prius

At about the same time as the Insight was launched, Toyota also launched its Prius vehicle. This is also a petrol IC engine/electric hybrid. It has less good fuel consumption figures, but has more luggage space and five seats. It has enjoyed considerable sales success, and has really put this type of vehicle into the public eye. This has been helped by the appeal of the car to a number of celebrities.

The car is powered by a 16-valve, four-cylinder engine of 1.5 l using variable valve timing. The engine displacement is with a bore of 75 mm and stroke of 84.7 mm. The engine also incorporates an aluminium double overhead cam (DOHC) and multi-point electronic fuel injection. This system allows the engine to maintain a high level of fuel efficiency.

Table 14.8 Details of the Honda Insight hybrid electric/IC engine car (based on Honda sales information at www.honda.com)

Engine size	1 l 3 cylinder VTEC
Electrical energy storage	NiMH battery, 144 V, 6.5 Ah
Fuel consumption	26/29 km l^{-1} city/highway[a] (EPA estimates)
Power	50 kW at 5700 rpm without assist, 56 kW at 5700 rpm with assist
Torque	91 N m at 4500 rpm without assist, 113 N m at 1500 rpm with assist
Electric motor	Permanent magnet, 'brushless DC' type, 60 mm thick
Electric motor power	10 kW maximum at 300 rpm
Front suspension	MacPherson strut with aluminium forged knuckle, aluminium lower arm
Rear suspension	Twist-beam and trailing arms
Brakes	Four-wheel ABS, front: disc, rear: drum
Launch dates	1999 (Japan, USA), 2000 (UK, Canada) and 2001 (Australia)
Length (m)	3.95
Width (m)	1.35
Weight (kg)	834
Maximum speed (kph)	166
Range	Over 1100 km, 40 l petrol tank

[a] Multiply kilometres per litre figure by 2.35 to get a result in miles per US gallon, or by 2.82 for miles per UK gallon.

The vehicle uses an electronic ignition system, which incorporates the Toyota Direct Ignition (TDI) system. With regards to performance, the engine can produce a power of 52 kW at 4500 rpm and a maximum torque of 111 N m at 4200 rpm. Further performance details are given in Table 14.9.

The hybrid element is provided by an electric motor and a separate generator, so unlike the Honda Insight it has two electrical machines, and is not a pure parallel hybrid. The motor type is a permanent magnet, as with the Insight, which is able to produce a power output of 33 kW. This motor is able to sustain a maximum torque of 350 N m at 0–400 rpm, which is enough to move the car at slow speeds. The battery provided is a nickel metal hydride (NiMH) system, consisting of 228 cells, giving 6.5 Ah at 288 V.

The transmission system is an electronically controlled continuously variable transmission (ECCVT) which give a better performance over the range of gears. The transmission incorporates a fairly complex system of planetary gears, called a ‘power splitter’, which directs power between the IC engine, the electric motor, the generator and the wheels, in all directions! A display on the dashboard gives a continuous indication of where energy is going. For example, when accelerating hard energy will be going from both the IC engine and the electric motor to the wheels. When at an easy steady speed, energy will go from the engine to the wheels and also from the engine through the generator back to the battery. When slowing energy will go from the wheels, through the generator and to the battery. This display is fascinating, indeed perhaps a little too interesting, to watch.

The suspension uses an independent MacPherson strut with stabiliser bar at the front of the vehicle and a torsion beam with stabiliser bar at the rear. The steering column

Table 14.9 Technical details of the Toyota Prius (based on Toyota sales information at www.toyota.com)

IC engine size	1.5 l, four cylinder, 16 valve
ICE power	52.2 kW
ICE torque	111 N m
Electric motor power	33 kW
Electric motor torque	350 N m at 0–400 rpm
Electrical energy storage	NiMH battery, 288 V, 6.5 Ah
Hybrid system net power	73 kW
Fuel consumption	22/19 km l^{-1} city/highway (EPA estimates)
Transmission	ECCVT[a]
Suspension	Independent MacPherson strut stabiliser bar and torsion beam with stabiliser bar
Steering	Rack and pinion with electro-hydraulic assist
Brakes	Front disc, rear drum, with ABS
Length (m)	4.31
Width (m)	1.69
Height (m)	1.46
Wheelbase (m)	2.55
Weight (kg)	1254
Petrol tank capacity	44.7 l, 11.8 US gallons
Tyres	P175/65R14 low rolling resistance

[a] Electronically Controlled Continuously Variable Transmission.

uses a rack and pinion system with electro-hydraulic power assist and is able to achieve a turning circle of 30.8 ft (9.4 m).

Power-assisted ventilated front discs and rear drums with standard anti-lock brake system (ABS) and regenerative braking enable the vehicle to stop in a manner which prevents skidding, even when braking heavily into a corner. Traction is provided by standard P175/65R14 low rolling resistance tyres on aluminium alloy wheels.

The car fits five people and has a good-sized luggage space not noticeably reduced in size because of the battery, which is stored under the rear passenger seat.

Toyota is due to release the Prius Alpha in 2012 which comes as a five- or seven-seater. This will use lithium batteries.

14.4.3 The Chevrolet Volt

Recently Chevrolet has introduced a hybrid which can be recharged from the mains as well as using energy from petrol.

The Chevrolet Volt, a rechargeable electric hybrid which was introduced in 2010, is illustrated in Figure 1.15. Technical aspects of the Volt are included in Table 14.10. The Volt will be released in Europe as the Vauxhall Ampera or the Opel Ampera.

The Volt is a plug-in electric hybrid manufactured by General Motors. The car runs entirely from the battery for the first 25–50 miles (40–80 km), after which it functions primarily as a series hybrid with the IC engine driving the generator to power the traction electric motor. When the initial pure EV battery capacity drops below a pre-established threshold from full charge, and while the Volt is operating as a series hybrid, the Volt's control system will select the most optimally efficient drive mode to improve performance and boost high-speed efficiency. At certain loads and speeds, 30–70 mph (48–112 kph), the IC engine may at times be engaged mechanically via a clutch to an output split planetary gearset and assist the traction motor to propel the Volt. Therefore, the Volt can

Table 14.10 The Chevrolet Volt

General description	Front engine, front wheel drive, four-passenger, five-door hatchback
Electric motor	AC permanent magnet synchronous electric motor
IC engine	1.4 l, four cylinder, 149 hp, 273 lb-ft (370 N m); DOHC 16 valve, 1.4 l inline-4, 84 hp (est.)
Transmission	Continuously variable automatic
Battery	16 kWh lithium ion
Range running from battery only	25–50 miles (40–80 km)
Total range with IC engine	379 miles (606 km)
Top speed	100 mph (160 kph)
Wheelbase	105.7 in (2.69 m)
Length	Length >177.1 in (4.5 m)
Width	70.4 in (1.79 m)
Height	56.3 in (1.43 m)
Weight	3800 lb (1720 kg)

operate as a pure EV, a series or a parallel hybrid depending on the battery's state of charge (SOC) and operating conditions.

14.5 Fuel-Cell-Powered Bus

In Chapters 1 and 4 we introduced various fuel-cell-powered vehicles. However, for a case study we will present the type of fuel cell vehicle that is most likely to make a commercial impact in the medium term, namely the fuel-cell-powered bus.

There are several important reasons why fuel cell systems are even more promising in city bus applications than for other types of vehicle. The three most important are:

1. Fuel cells are expensive, so it does not make sense to buy one and then leave it inactive and out of use for most of the day and night, which is the state of most cars. Buses, on the other hand, are in use for many hours each day.
2. The supply of hydrogen for fuel cell vehicles is such a difficult problem that we devoted a whole chapter of this book to it. Buses, on the other hand, refuel in one place, so only one refilling point needs to be supplied.
3. The advantages of zero emissions at the point of use are particularly important for city vehicles, which is exactly what this type of bus is.

It is not surprising then that buses feature strongly among the most exciting demonstration fuel cell vehicles. A fuel cell bus is shown in Figure 14.6, which was used between 1998 and 2000 in Vancouver and Chicago. Some high-altitude trials were also carried out in Mexico City. The layout of the fuel cell engine is shown in Figure 14.7, which had a maximum power of 260 kW. Ballard made available a good deal of data on this system, and further information can be deduced by calculations from the given data, as presented in Chapter 11 of Larminie and Dicks (2003).

Figure 14.6 Fuel-cell-powered bus, 1998 model. (Reproduced by kind permission of Ballard Power Systems.)

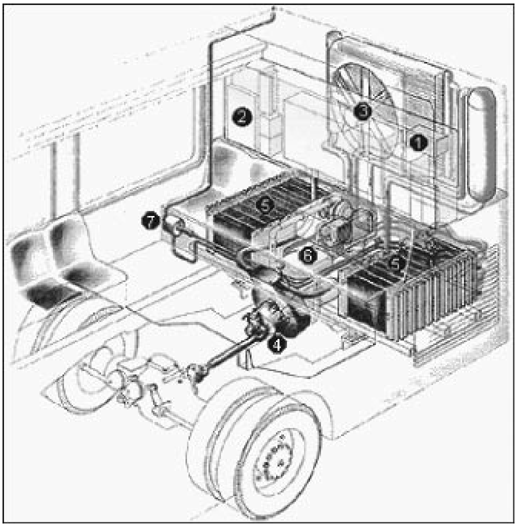

Figure 14.7 Fuel cell engine for buses based on 260 kW fuel cell. (Diagram reproduced by kind permission of Ballard Power Systems.)

Referring to Figure 14.7, the system consisted of two fuel cell units (5), each consisting of 10 stacks, each of about 40 cells in series. So the total number of cells was about 800, giving a voltage of about 750 V. In use the voltage fell to about 450 V at maximum power. The voltage was stabilised to between 650 and 750 V using a DC/DC converter as outlined in Section 7.2. There were several step-down DC/DC converters to provide lower voltages for the various subsystems, such as the controller (2), and to charge a 12 V battery used when starting the system. These voltage conversion circuits are unit (1) as shown in Figure 14.7.

The fuel cell system is water cooled, with a ‘radiator’ and electrically operated fan (3). This could dispose of heat at the rate of 380 kW. As was explained in Section 4.6, fuel cell systems need to get rid of more heat than IC engines of equivalent power. This cooling system also removes heat from the motor (4) and the power electronics (1). An ion exchange filter was used to keep the water pure, and prevent it from becoming an electrical conductor. Clearly then, no anti-freeze could be used, and so the system had to be kept from freezing, which was done using a heater connected to the mains when not in use. This is one important improvement seen on the more modern fuel cell buses. All the losses are dealt with by this cooling system, so we note that 380 kW seems an appropriate value for a 260 kW fuel cell, and suggests an efficiency for the fuel cell of about 41% at maximum power, from the calculation

$$\eta = \frac{\text{output}}{\text{output} + \text{losses}} = \frac{260}{260 + 380} = 0.41 = 41\%$$

The efficiency at lower powers will be a little higher than this. The motor (4) is rated as 160 kW continuous, which means that for short periods it could operate at about 200 kW. The motor was normally of the brushless direct current (BLDC) type explained in

Section 7.3.2. There is evidence (Spiegel, Gilchrist and House, 1999) that some models of this bus used induction motors, which illustrates very well what we said in Chapter 6 about the type of motor used being relatively unimportant. Induction motors are rugged and lower in cost, BLDC motors are slightly more efficient and compact. Dynamic braking was used to reduce wear on the friction brakes, but not regenerative braking (see Section 7.1.7). The motor is coupled to the forward-running drive shaft via a 2.42:1 fixed gear, and to the rear axle via a differential, which will have a gear ratio of about 5:1, as in Figure 8.6 and Section 9.4.

If the fuel cell output is 260 kW, and the maximum motor power is about 200 kW, where does the remaining 60 kW go? The major 'parasitic' power loss is the air compressor, which is needed as the fuel cell operates at up to about 3 bar (absolute). As was explained in Chapter 4, this increase in pressure brings performance benefits, but takes energy. Even using a turbine which extracted energy from the exhaust gas, the electrical power required to drive the compressor will have been about 47 kW. The other major power losses will have been in the power electronics equipment, about 13 kW assuming 95% efficiency, and for the fan to drive the cooling system, probably about 10 kW. These three loads explain the 'missing' 60 kW.

This bus used compressed hydrogen tanks stored on its roof. These posed no greater safety problems than those present in a normal diesel-fuelled bus. Any rupture of the tank and the hydrogen would rapidly dissipate upwards and out of harm's way. The pressure of the tanks was about 250 bar when full, which was reduced to the same pressure as the air supply, about 3 bar. Usually when the pressure of a gas is reduced greatly, there is a cooling effect, but this does not happen with hydrogen. The hydrogen behaves very differently from an ideal gas, and the so-called Joule–Thompson effect comes in to play, and there is actually a very modest temperature rise of about 7 °C in the pressure regulation system.

Much was learnt from the generally successful trials with these buses over several years. This information has been incorporated into the new design of buses, such as those of Figure 1.17, and those from other 'non-Ballard' companies such as the MAN bus of Figure 5.2. People are more likely to take a ride in a fuel cell bus before they go for a drive in a fuel cell car.

14.6 Conventional High-Speed Trains

14.6.1 Introduction

Electric trains have been in use throughout the twentieth century and are widely used today. Unlike electric road vehicles they have unlimited range provided that supply lines are in place. High-speed trains are often associated with the Japanese Shinkansen or bullet train which first appeared in the 1960s. Currently several countries operate high-speed networks in addition to Japan including Italy, Germany, France and China. The high-speed trains are important environmentally as they use a fraction of the energy that aircraft do. They are quicker to load and unload and do not have to taxi to a runway. For example, the ETR 500 'Frecciarossa' of the Italian Railways has a maximum speed of 300 kph (188 mph). It takes an hour and a half from Milan to Bologna including the flight and time taxiing on the runway.

The official absolute world record for conventional trains is held by the French TGV. In April 2007, a specially tuned train, reduced to three cars with higher voltage, broke the world record, reaching 574.8 kph (359.3 mph). This is about two-thirds the cruising speed of airliners. It is worth noting that the world record speed of today is often the cruising speed of the future.

While commercial high-speed trains have maximum speeds slower than jet aircraft, they have advantages over air travel for short distances. They connect city centre rail stations to each other, while air transport connects airports outside city centres. High-speed rail (HSR) is best suited for journeys of 2–3 hours (about 250–900 km or 160–560 miles), for which the train can beat air and car trip time. When travelling less than about 650 km (405 miles), the process of checking in and going through security screening at airports, as well as the journey to the airport, make the total air journey time no faster than HSR. Authorities in Europe treat HSR for city pairs as competitive with passenger air at $4 - 4^{1/2}$; hours, allowing a 1 hour flight at least 40 minutes at each point for travel to and from the airport, check-in, security, boarding, disembarkation and baggage retrieval.

Part of HSR's edge is convenience. These conveniences include the lack of a requirement to check baggage, no repeated queuing for check-in, security and boarding, as well as high on-time reliability as compared with air travel. HSR has more amenities, such as mobile (cell) phone support, booth tables, elaborate power outlets (AC mains outlet vs DC 12 V outlet), elaborate food service, no low-altitude electronics ban, self-service baggage storage areas (eliminating the need to check-in baggage) and wireless Internet broadband. Passenger comfort is normally better in trains, there is room to move around and there is no cabin depressurisation as experienced on aircraft.

There are routes where high-speed trains have beaten air transport, so that there are no longer air connections. Examples are Paris–Brussels and Cologne–Frankfurt in Europe, Nanjing–Wuhan and Chongqing–Chengdu in China, Tokyo–Nagoya, Tokyo–Sendai and Tokyo–Niigata in Japan. Statistics from Europe indicate that air traffic is more sensitive than road traffic (car and bus) to competition from HSR, at least on journeys of 400 km and more – perhaps because cars and buses are far more flexible than aircraft (on the shortest HSR journeys, like Augsburg–Munich, which is served by four ICE routes, air travel is no alternative). TGV Sud-Est reduced the travelling time from Paris to Lyons from almost 4 to about 2 hours. The rail market share of this route rose from 49 to 72%. For air and road traffic, the market shares shrunk from 31 to 7% and from 29 to 21%, respectively. On the Madrid–Sevilla relation, the AVE connection increased the rail market share from 16 to 52; air traffic shrunk from 40 to 13% and road traffic from 44 to 36%, hence the rail market amounted to 80% of the combined rail and air traffic.

Energy use and carbon emissions are considerable better on high-speed trains than that of aircraft. Shinkansen is a very energy-efficient mode of transportation. Comparing on a passenger mile basis, Shinkansen's energy consumption is only a fourth of that of air transportation, and a sixth of automobiles. Taking into account the fact that electricity is also generated by nuclear power, CO_2 emission from Shinkansen is significantly lower than other modes of transportation. Its emissions are only a fifth of that from aircraft, and an eighth from automobiles. It can be said that Shinkansen contributes to energy savings as well as the fight against global warming. In David MacKay's book *Sustainable Energy without the Hot Air*, he concludes that rail uses under 12% of the energy required for air transport, under 10% the energy used for car transport and under 33% the energy used for bus transport.

In order to benefit from HSR links ideally new tracks should be used with less sharp bends and no stoppages such as level crossings. This of course will result in heavy investment in infrastructure.

From an energy point of view, in many instances high-speed electric trains can compete with air travel over land routes with a very substantial saving of energy used during journeys. This will itself substantially reduce the amount of oil used. Where power generation is used which does not release CO_2, there will effectively be no carbon emissions.

14.6.2 The Technology of High-Speed Trains

The basic principle of a high-speed train is not dissimilar from that of an electric road EV with the exception that the train does not use a battery or a fuel cell but takes its electricity from supply lines.

The TGV takes its electricity from a pantograph. This has a top linkage member (holding the wiper) that operates like a hydraulic damper with a short stroke to keep intimate contact with the overhead conductor and keep bouncing to a minimum. Contact wire pressure is about 70 N. The bottom linkage, which guides alignment with the contact wire, is locked at a fixed height when operating under the fixed-height overhead on high-speed trackage.

The electricity is first converted to direct current, then it is converted to AC electricity of varying frequency by an inverter supplying each motor. The speed of the train is controlled by the frequency of the alternating current from the inverter.

The inverters convert their DC input into a computer-controlled three-phase, variable frequency AC waveform, in order to control the traction motors. There is one inverter per traction motor. The inverters are thyristor based. For each truck (bogie), the two inverter/motor pairs are connected in series. The power electronics physically associated with one truck (bogie) correspond to a 'motor block' or 'power pack'. There are thus two such power packs installed in each power car.

A synchronous AC traction motor is excited at a frequency proportional to its rotational speed. In an unusual arrangement considered to be one of the TGV design's strong points, the traction motors are slung from the vehicle body, instead of being an integral part of the Y230 power truck (bogie). This substantially lightens the mass of the truck (each motor weighs 1460 kg), giving it a critical speed far higher than 300 kph (188 mph) and exceptional tracking stability. The traction motors are still located where one would expect them: in between the truck (bogie) frames, level with the axles, but just suspended differently. Each motor can develop 1100 kW (when power comes from 25 kV overhead) and can spin at a maximum rate of 4000 rpm.

The output shaft of the motor is connected to the axle gearbox by a tripod transmission, using sliding cardan (universal-joint) shafts. This allows a full decoupling of the motor and wheel dynamics; a transverse displacement of 120 mm is admissible. The final drive is a gear train that rides on the axle itself and transfers power to the wheels. This final drive assembly is restrained from rotating with the axle by a reaction linkage.

14.7 Conclusion

The future of EVs, in both the short and long term, is very exciting. It is a market which is developing and changing rapidly.

There have been considerable developments in technology, which now allow advances in EV design to be made. There are growing environmental concerns which are pressing society to find alternatives to IC engines alone as a source of power for vehicles. Environmental concerns encompass both worries about CO_2 emissions and the effect of exhaust gas emissions on health. In the largest market for personal transport, the USA, there is an increasing realisation that fuel economy is important. The Californian car market alone is about 1 million units per year, and the rules of this state will continue to give a 'technology push' to developments in this area, as they have done so strongly up to now.

There has been a proliferation of small-scale commuter vehicles, bikes, delivery vehicles, mobility aids and lightweight cars that use rechargeable batteries. These have a limited range and are normally used as second vehicles. As such they encourage people to use this form of transport for short journeys and hence are reducing the use of conventional vehicles.

With recent developments in lithium ion batteries there have been developments in rechargeable battery cars which are now being mass produced and sold commercially, such as the Nissan Leaf and the Mitsubishi MiEV. Hybrid vehicles have also developed rapidly in the last few years. The Toyota Prius has been a particular success, at least as a technology demonstration if not commercially, and nearly all major motor manufacturers are developing products in this area. Initial practice was to use engine and battery in conjunction to maximise fuel economy, rather than to charge the vehicle from an external electric charging point. However, this is starting to change, and grid-connectable hybrids such as the Chevrolet Volt are now available commercially. Clearly manufacturers see hybrid vehicles as an area where electric cars can be produced to compete with conventional IC vehicles in terms of range, flexibility and cost. Fuel cell cars are further away from commercialisation than hybrids, but fuel-cell-powered buses are closer to the market.

In addition to developing EVs close attention needs to be given to the infrastructure needed to supply power for them. While small electric commuter vehicles use household electric sockets at present, and current commercially available hybrid vehicles solely use petrol or diesel, future fuel cell vehicles are likely to need sources of hydrogen. More widespread use of rechargeable battery vehicles will require charging points to be installed.

The issue of energy sources also needs to be addressed. Introduction of EVs undoubtedly cleans up the immediate environment where the vehicle is being used. However, in the case of rechargeable vehicles the emission of CO_2 is simply being transferred to fossil-fuel-burning power stations. Introduction of more alternative energy power stations such as solar, wind and hydro to match the introduction of EVs would ensure real 'zero-emission transport'.

With current technical developments in the energy sources for EVs, coupled to the desire for less environmentally damaging transport, the future for EVs looks extremely promising. Again in the area, railway high-speed trains are starting to compete with aircraft in terms of speed. Initially this is true for short overland journeys of a few hundred kilometres. It must be noted that trains use a fraction of the energy and release a fraction of the carbon emissions that aircraft do.

Rapid development of rechargeable vehicles, electric hybrids, fuel cell EVs and high-speed trains is likely to continue over the next two decades. At the same time the infrastructure for powering EVs will develop. It is hoped that more emphasis will be placed on the provision of clean sustainable energy systems for providing electrical power for rechargeable vehicles, and for producing hydrogen for fuel cells.

The possible development of EVs in the future is considered in Chapter 15.

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