22

PRIME MOVERS FOR MOTOR VEHICLES

The motion of all vehicles requires the expenditure of a certain quantity of mechanical energy, and in motor vehicles the system that supplies such energy (in most cases an internal combustion engine) is on board. The lack of an adequate prime mover is the main reason that mechanical vehicles could be built only at the end of the industrial revolution, and enter mass production only in the Twentieth Century, in spite of attempts dating back to ancient times.

For a mechanical vehicle to be built, a prime mover able to move not only itself, but the vehicle structure and payload as well, was needed. Remembering that the power needed to move the mass m at the speed V on a level surface with coefficient of friction (sliding or rolling) f is equal to $P = mgfV$, it is easy to conclude that the minimum value of the power/mass ratio of a prime mover able to move itself is

$$\frac{P}{m} = \frac{gfV}{\eta\alpha} , \tag{22.1}$$

where α is the ratio between the mass of the engine and the total mass of the vehicle and η is the total efficiency of the mechanism which transfers the power and propels the vehicle.

Prime movers with an adequate power/mass ratio and transmission devices with a power rating and an efficiency high enough to allow the motion of the vehicle were not practical until the Nineteenth Century.

The engine must obtain the energy required for motion from an energy source that is usually on board the vehicle. Rail vehicles often receive such energy from outside, but the only road vehicles in which this occurs are trolleybusses.

In most cases, the energy is stored as the chemical energy of a fuel, but it can be stored in the form of electrochemical energy (electrical batteries) or,

G. Genta, L. Morello, *The Automotive Chassis, Volume 2: System Design*, Mechanical Engineering Series,

TABLE 22.1. Onboard energy storage. Energy density e/m, power density P/m and general characteristics (data for electrochemical energy refer to lead-acid batteries).

Energy stored	Chemical	Electrochemical	Elastic	Kinetic
e/m [Wh/kg]	10,000 – 12,000	10 – 40	2 – 10	6 – 20
P/m [W/kg]	Engine dependent	10 – 100	High	Very high
Efficiency	0.2 – 0.3	0.6 – 0.85	0.7 – 0.9	0.7 – 0.95
Reversibility	None	Possible		
Pollution	In the site of utilization	In the site of generation		
Dependence on liquid hydrocarbons	Almost complete	The primary source can be different		

even if few attempts in this direction have been made, and even fewer vehicles of this type have a practical use, as kinetic energy (flywheels) or elastic energy (springs).

These forms of energy storage are compared in Table 22.1.

When two or more different types of energy are stored or supplied to a vehicle that can work either with energy supplied from the outside or with energy stored on board, and if the two modes of operation are used independently, the vehicle is said to be *bimodal*. A trolleybus with batteries that allow it to go on a part of its route where there is no power distribution is an example of a bimodal vehicle.

Vehicles with two or more methods of energy storage, in which one is used not only to supply energy but also to store energy coming from one of the other sources, are said to be *hybrid*. An example is a bus with an internal combustion engine and batteries, in which the electric energy is also used to transform the energy from the engine with greater efficiency and to recover braking energy.

It is also possible to have a bimodal hybrid vehicle if, in the previous example, the energy to charge the batteries is supplied not only by the thermal engine but also by the mains.

In vehicles there are huge quantities of energy that may be recovered. Theoretically, all energy not dissipated (by aerodynamic drag and rolling resistance, losses in the transmission and energy conversion) can be recovered.

If the kinetic energy or the gravitational potential energy of the vehicle is recovered when slowing down or travelling downhill, *regenerative braking* occurs.

When the only form of energy storage on board is chemical energy, regenerative braking is not possible, while it may be implemented in the other cases of Table 22.1. Energy recovery can, however, be only partial, not only due to the intrinsic losses of all energy transformations, but also because of the peculiar characteristics of braking.

The power involved in braking is hardly manageable by the device that has to convert the energy taken from the vehicle into usable energy, except in the case of slowing down with limited deceleration. Usually, to allow regenerative braking, there must be two braking systems, with the traction motors (in the case of electric vehicles) providing regenerative braking when slowing down or travelling downhill, while a conventional braking system performs, in a non-regenerative way, emergency or sudden decelerations

22.1 VEHICULAR ENGINES

The storage of energy in a liquid, less frequently gaseous, form of fuel has so many advantages that this form of energy storage has supplanted all others since the beginning of the Twentieth Century. The advantages of easy resupply (recharging) and above all the very high energy density are overwhelming.

The chemical energy of the fuel (gasoline, diesel fuel, but also liquefied petroleum gas (LPG), methane, alcohol, methylic or ethylic, etc.) is converted into mechanical energy by a thermal engine. In spite of the low conversion efficiency that characterizes all thermal engines, the actually available energy density is about $30 \div 50$ times greater than that of other energy storage devices. The power density is also very high.

The first self-propelled road vehicles were built at the end of the Eighteenth and above all at the beginning of the Nineteenth Century owing to the development of thermal engines, in this case reciprocating steam engines. However, while steam engines were adequate for ships and railway engines, their power/weight ratio was too low for road vehicles. This issue, together with other technical and non-technical factors, made steam coaches a commercial failure.

Only at the end of the Nineteenth Century did the development of reciprocating internal combustion engines allow the diffusion of motor vehicles.

As road vehicles began to spread, three competing types of engine were available: steam engines, that in the interim had undergone drastic improvements to become adapted to lightweight vehicles, the new internal combustion engines, and DC electric motors combined with recently developed lead acid accumulators. For a time it looked as though the electric motor would become the most common alternative, owing to its reliability, cleanliness, quietness and ease of control. The various types of engine were balanced in performance, as shown by the fact that the first car able to overcome the 100 km/h barrier in 1898 was an electric vehicle.

However, then as today, the main drawback of the electric vehicle, its unsatisfactory range, prevented its diffusion.

The reciprocating internal combustion engine become the main source of power for all road vehicles, and has remained so since the first decades of the Twentiethth Century.

In the 1960s, after the great success of turbojet and turboprop engines in aeronautics, which would quickly almost completely replace reciprocating engines in aircraft and helicopters, several attempts to introduce gas turbines in motor vehicles were made. They were unsuccessful, primarily because of the strong fuel consumption at idle.

At the same time, attempts to reintroduce the steam engine were also made, primarily for reducing pollution and for the scarcity, then more supposed than actual, of fuels suitable for reciprocating engines. Even if steam engines were much different from those of the previous century, the results were not satisfactory.

A further attempt to innovate, although less radical, was the introduction of rotary internal combustion engines. Some vehicles with this innovative engine were mass produced and had a limited commercial success, but this attempt was likewise another failure.

It is likely that the greatest advantage of the reciprocating automotive engine is a century of uninterrupted development, leading to performance, low cost and reliability that could not be imagined one century ago.

Practically, every attempt to substitute a different propulsion device to solve one of its many problems was answered with industry innovations that solved, in an equally (or more) satisfactory way, the same problems.

The issues that fuel today's drive to replace the internal combustion engine with a prime mover of a different kind remain its dependence on liquid hydrocarbons as fuel and the emission of pollutants and greenhouse gases.

The dependence on fuels derived from oil is characteristic of the whole economic system, particularly in Europe and even more in Italy. Even if electric vehicles became widespread or hydrogen took over as fuel, this problem would remain essentially unchanged if the primary energy used to produce electric energy or hydrogen came from the combustion of oil derivatives. More precisely, the problem would become worse, owing to lower overall energy efficiency (*from well to wheel*, as is usually said).

Only a massive use of nuclear energy, possibly with some contribution from renewable sources including hydrocarbons derived from biomasses, can radically solve this problem.

Environmental problems due to pollutants like carbon monoxide, nitrogen oxides, particulates, etc., all substances not necessarily produced by combustion, have already been tackled with success and modern internal combustion engines are much cleaner than older ones. This trend is bound to continue in the future.

Carbon dioxide, on the contrary, is the result of the type of fuel used and can be reduced only by using fuels with lower carbon content, like methane, and only completely eliminated by using hydrogen. However, the production of hydrogen must use a primary source that does not produce carbon dioxide, like nuclear energy.

Hydrogen can be used both in internal combustion engines and in fuel cells.

Fuel cells are electrochemical devices able to directly convert the energy of a fuel-oxidizer pair into electric energy, without a combustion process taking place. Since in this transformation there is no intermediate stage of thermal energy, the efficiency can be, theoretically, higher than that of any thermal engine, even if it is limited by losses of various kinds.

The reactions occurring in fuel cells are electrochemical reactions of the kind typical of batteries. The choice of fuel is severely limited, since the use of molecules that may be easily ionized is mandatory. Hydrogen is the most common choice, even if methane is an interesting alternative, while the oxidizer must be, in vehicular applications, atmospheric oxygen. The energy density of fuel cells using liquid fuels like methanol or formic acid is too low for vehicular applications.

The problems linked with the use of hydrogen as a fuel primarily relate to its low volume energy density (its mass energy density is, on the contrary, quite high) and to the subsequent need to use pressurized tanks, cryogenic storage at 20 K, or to resort to technologies like those based on metal hydrides. There are also problems involved in its supply network. The technological problems are being solved, since hydrogen is used in experimental vehicles as a fuel for internal combustion engines, and in many countries there are already a number of supply points. Safety does not seem to be a problem, since hydrogen is not much more dangerous than a highly flammable and volatile liquid such as gasoline.

Hydrogen may also be stored on board as methanol or methane, from which hydrogen is then obtained by chemical dissociation. This solution has the drawback of causing poisoning of the fuel cell catalyst if impurities due to this process remain in the hydrogen.

At present there are many types of fuel cells, based on different types of membranes and catalysts. They operate at different temperatures (from less than 100°C to more than 900°C, the latter being unsuitable for vehicular use), and each has its advantages and drawbacks. The technology developed in the aerospace field (fuel cells were developed in the 1960s for the *Apollo* programme and are now used on the *Space Shuttle*) cannot be used in road vehicles. Many problems are still to be solved, from cost to reliability, with added problems linked to their use under the conditions of much variable load and reduced maintenance that are typical of motor vehicles.

Until fuel cells suitable for vehicular use are available, the only way to use electric motors is by employing accumulators. Their worst drawback is the impossibility of obtaining high energy density and power density at the same time. This is particularly true for lead-acid accumulators, whose energy density decreases fast with increasing power density, that is, with increasing current.

Also, the duration and the efficiency of batteries decrease with increasing power density. The field of batteries for vehicular propulsion has seen much research activity, and the possibility of building electric vehicles with performance not much different from that of vehicles with internal combustion engines, especially in terms of range, may yet emerge.

The possibility of using different forms of energy accumulators in a single vehicle in a hybrid configuration is particularly interesting. There are many experimental vehicles of this kind and some of them have been mass produced.

22.2 INTERNAL COMBUSTION ENGINES

As stated in the previous section, most road vehicles are powered by reciprocating internal combustion engines. The performance of an internal combustion engine is usually summarized in a single map plotted in a plane whose axes are the rotational speed Ω_e and either the power P_e or the engine torque M_e(Fig. 22.2). Often the former is reported in rpm, the power in kW and the torque in Nm.

If a plot of the power as a function of speed is used, the plot is limited by the curve $P_e(\Omega_e)$ expressing the maximum power the engine can supply as a function of the speed. Such a curve is typical of any particular engine and must be obtained experimentally. However, when building a simple model of the vehicle, it is possible to approximate it with a polynomial, usually with terms up to the third power,

$$P_e = \sum_{i=0}^{3} P_i \Omega_e^i \ . \tag{22.2}$$

The values of coefficients P_i can easily be obtained from experimental testing. In the literature it is possible to find some values of the coefficients which can be used as a first rough approximation. M.D. Artamonov *et al.*[1] suggest the values

$$P_0 = 0 \ , \qquad P_3 = -\frac{P_{max}}{\Omega_{max}^3}$$

for all types of internal combustion engines and

$$P_1 = \frac{P_{max}}{\Omega_{max}} \ , \qquad P_2 = \frac{P_{max}}{\Omega_{max}^2} \ ,$$

for spark ignition engines,

$$P_1 = 0.6 \ \frac{P_{max}}{\Omega_{max}} \ , \qquad P_2 = 1.4 \ \frac{P_{max}}{\Omega_{max}^2}$$

for indirect injection diesel engines and

$$P_1 = 0.87 \ \frac{P_{max}}{\Omega_{max}} \ , \qquad P_2 = 1.13 \ \frac{P_{max}}{\Omega_{max}^2}$$

for direct injection diesel engines.

In these formulae Ω_{max} is the speed at which the power reaches its maximum value P_{max}.

The driving torque of the engine is simply

$$M_e = \frac{P_e}{\Omega_e} \ , \tag{22.3}$$

or, if the cubic polynomial is used and coefficient P_0 vanishes,

$$M_e = \sum_{i=1}^{3} P_i \Omega_e^{i-1} \ . \tag{22.4}$$

At present, internal combustion engines for vehicular use are controlled by systems of increasing complexity and their performance is increasingly dependent on the control logic used. The power and torque maps are, then, not unique for a certain engine but may be changed simply by modifying the programming of

[1]M.D. Artamonov et al. *Motor vehicles, fundamentals and design*, Mir, Moscow, 1976.

the electronic control unit (ECU). If the above mentioned equations have always been just a rough approximation, today the situation is even more complex from this point of view, and in some cases the equations may supply results much different from those actually observed.

If experimental results on a similar engine are available, it is possible to obtain the maximum power curve from the power curve of that engine.

Remark 22.1 *The practice of correcting engine performance in a way proportional to the displacement is not correct, even if it is acceptable and often used for small changes of capacity. A scaling parameter that may be more correct is the area of the piston multiplied by the number of cylinders, that is, the ratio between capacity and stroke.*

The mean effective pressure p_{me}, i.e., the ratio between the work performed in a complete cycle and the capacity of the engine, is often used instead of the torque. In four-stroke engines it is defined as

$$p_{me} = \frac{4\pi M_e}{V} \ , \tag{22.5}$$

where V is the total capacity of the engine.

All points below the maximum power curve are possible working points for the engine, when it operates with the throttle partially open.

Remark 22.2 *Since the engine is seldom used at full throttle, usually only when maximum acceleration is required, the conditions of greatest statistical significance are those at much reduced throttle.*

A diagram of the specific fuel consumption of a direct injection diesel engine with a capacity of about 2 liters is shown in Fig. 22.1; on the same plot, the circles show the points at which the engine operates on the driving cycle used in Europe for computing fuel consumption for a car with a reference mass of 1600 kg.

The percentages shown close to the circles refer to the time the engine is used in the conditions related to their centers, with reference to the total time the engine is producing power (the time at idle is then not accounted for); the center of the circles represents the average of all utilization points in a rectangle with sides of 500 rpm on the speed axis and one bar on the p_{me} axis.

The curves below the one related to the maximum mean effective pressure in the plot of Fig. 22.1 are those characterized by various values of the specific fuel consumption q. The correct S.I. units for the specific fuel consumption, the ratio between the mass fuel consumption (i.e., the mass of fuel consumed in the unit time) and the power supplied, is kg/J, i.e. $\mathrm{s}^2/\mathrm{m}^2$, while the common practical units are still g/HPh or g/kWh. If the thermal value of the fuel is equal to 4.4×10^7 J/kg, it follows that

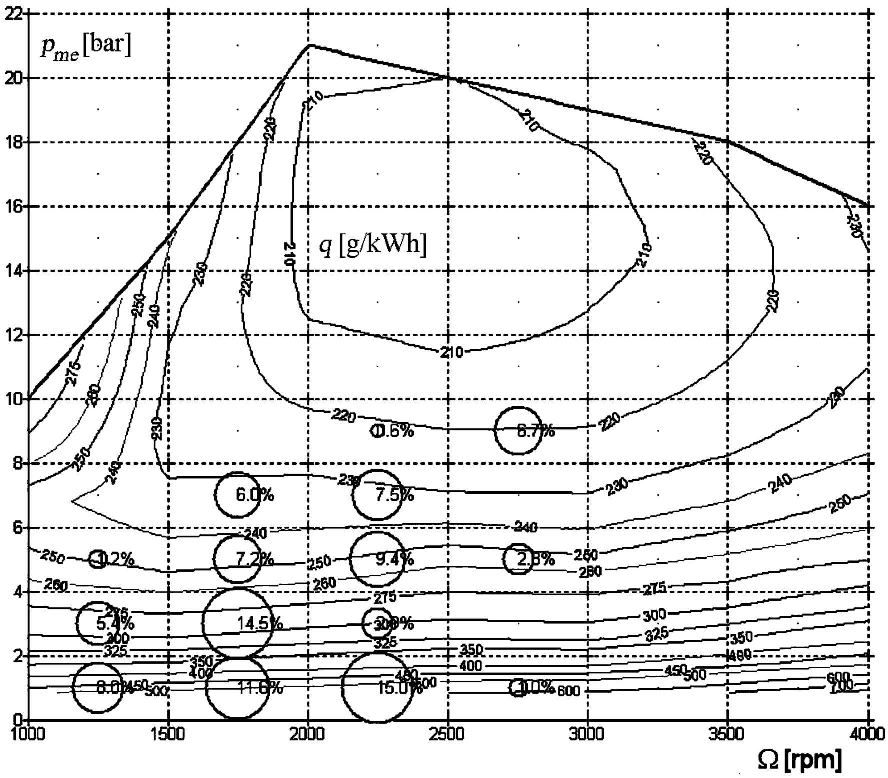

FIGURE 22.1. Map of a direct injection diesel internal combustion engine of about 2 liters capacity, with constant specific fuel consumption curves. The circles show the points where the engine operates on the driving cycle used in Europe for computing fuel consumption with a car with a reference mass of 1600 kg. The consumption of this engine at idle is about 0.62 l/h.

$$q = \frac{2.272 \times 10^{-8}}{\eta_e} \;\; \text{kg/J} = \frac{60.16}{\eta_e} \;\; \text{g/HPh} = \frac{81.79}{\eta_e} \;\; \text{g/kWh}\ ,$$

where η_e is the efficiency of the engine.

This map allows the fuel consumption of the engine to be stated in various working conditions: at far left is the minimum speed at which the engine works regularly; at far right is the maximum speed. The speed axis shows conditions at idle, where the mean effective pressure (p_{me}) vanishes together with the efficiency and the specific fuel consumption is infinite.

The map can be represented in a different way, plotting power on the ordinates and using the efficiency η_e of total energy conversion, from chemical energy of the fuel to mechanical energy at the shaft, as a parameter.

A plot of this type is shown in Fig. 22.2.

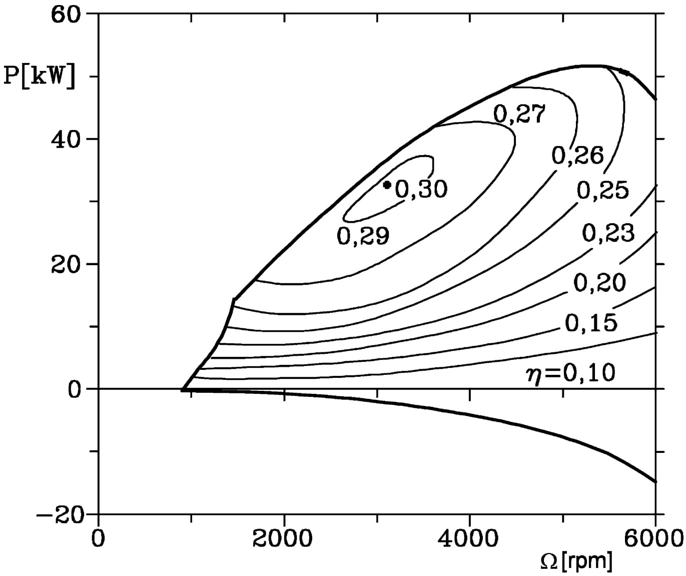

FIGURE 22.2. Map of a spark ignition internal combustion engine, with constant efficiency curves.

Remark 22.3 *The efficiency of a spark ignition engine reaches its maximum in conditions close to full throttle and at a speed close to the one where the torque is at its maximum. The efficiency decreases quickly as power is reduced at a fixed speed. This decrease is less severe in diesel engines.*

Efficiency and specific fuel consumption are linked by the relationship

$$q = \frac{1}{H\eta_e} \tag{22.6}$$

where H is the thermal value of the fuel.

Example 22.1 *Compute the coefficients of a cubic polynomial approximating the power versus speed curve of the engine of the vehicle in Appendix E.1. Compare the curve so obtained with the experimental one and that obtained from the coefficients suggested by Artamonov. Plot on the same chart the engine torque and the specific fuel consumption. By taking from the plot points spaced by 250 rpm and using a standard least squares procedure, it follows that*

$$P = -10,628 + 0,1506\Omega - 9,5436 \times 10^{-5}\Omega^2 - 5,0521 \times 10^{-8}\Omega^3 ,$$

where Ω is expressed in rad/s and P in kW. Using Artamonov's coefficients for a spark ignition engine, the equation becomes

$$P = 0,7024\Omega + 1,290 \times 10^{-4}\Omega^2 - 2,369 \times 10^{-7}\Omega^3 .$$

The two curves are plotted in Fig. 22.3. Both expressions approximate the experimental curve well, even if the coefficients are quite different.

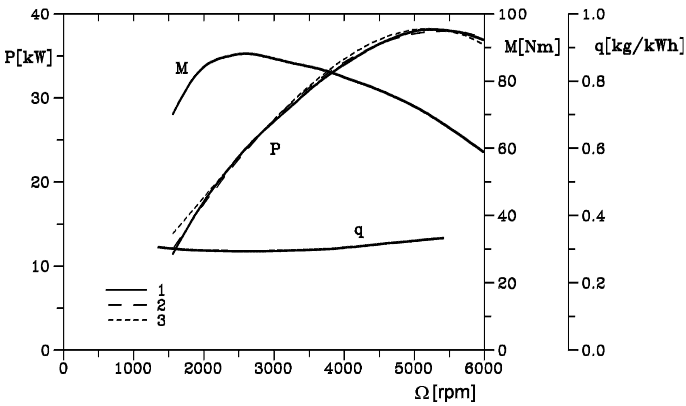

FIGURE 22.3. Engine power curve for the car of Appendix E.1. (1) Experimental curve, (2) third-power least square fit, (3) cubic polynomial with coefficients computed as suggested by Artamonov *et al.* The torque and the specific fuel consumption are also reported as functions of speed.

Two more examples of engine maps for two spark ignition engines of about 2 l capacity are reported in Figures 22.4 and 22.5. The first refers to an indirect injection engine (in the intake manifold), while the second one is for a direct injection (in the combustion chamber) engine. The latter is similar to the diesel engine shown earlier.

Remark 22.4 *When the fuel consumption is needed in points different from those shown in the plot, it is advisable not to interpolate in the map of specific fuel consumption, but on that of efficiency. The consumption changes in a strongly nonlinear way with both speed and mean effective pressure, and tends to infinity when the* p_{me} *tends to zero. The efficiency, on the contrary, tends to zero, when the* p_{me} *tends to zero.*

22.3 ELECTRIC VEHICLES

Batteries and electric motors are the most common alternative to internal combustion engines. As already stated, the performance obtainable is lower than that typical of vehicles with internal combustion engines, especially in terms of range, but also in terms of operating costs and vehicle availability. Studies on batteries for vehicular use are very active, and it is a common opinion that only through electric vehicles will some of the problems caused by the use of motor vehicles in urban areas be solved. The performance of some of the batteries suggested instead of the more common lead-acid batteries are reported in Table 22.2. Future progress seems to be linked more to the possibility of mass producing accumulators with sufficient performance at costs compatible with vehicular use than to an increase of performance.

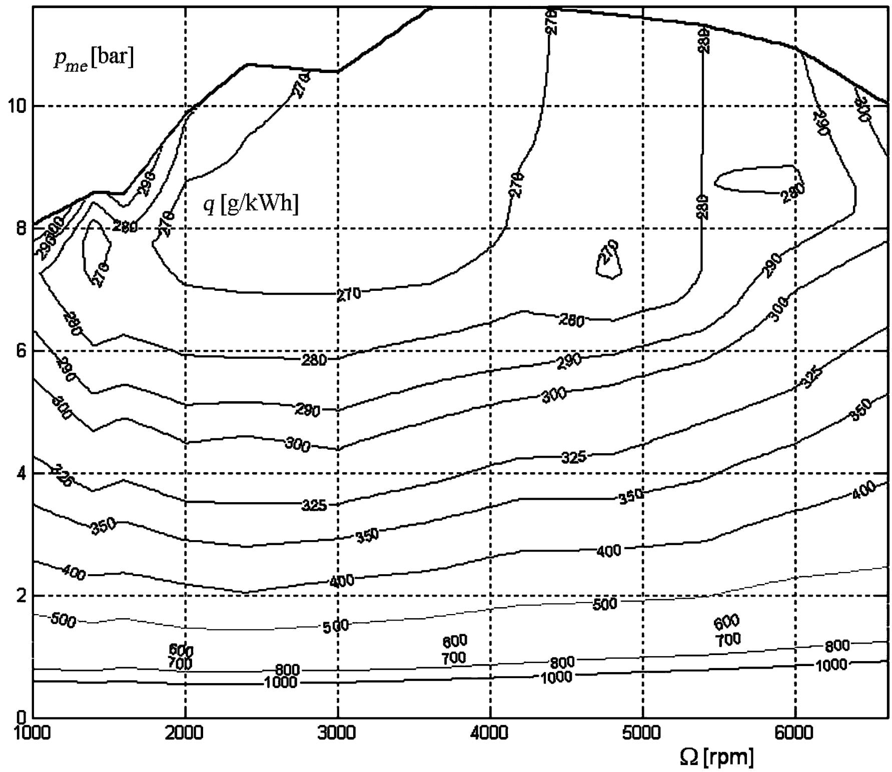

FIGURE 22.4. Map of the specific fuel consumption of an indirect injection spark ignition engine of about 2 liters capacity. The consumption of this engine at idle is about 0.92 l/h.

The advantages of electric vehicles are linked primarily to the possibility of moving the pollution from where the vehicle is used to where the power is generated, taking advantage of the better pollution control of power stations versus small engines. Another advantage is the possibility of regenerative braking. The performance of electric drives is, however, decreased by losses in both the engine and the batteries, and above all by the difficulties that batteries have in accepting the high power bursts occurring in braking. The disadvantages are also well known: The reduced range and duration of batteries and their high mass. However, even today, the performance of electric vehicles is sufficient for urban use.

From the point of view of energy the advantages of battery powered electric vehicles (BEV) are still in doubt: When the primary source is a fossil fuel, in spite of the greater efficiency of the primary conversion and regenerative braking, the overall consumption is comparable to that of internal combustion engines. The very fact that the thermo-mechanical conversion occurs far from the vehicle makes it impossible to use waste heat for heating, and this makes the energy balance worse.

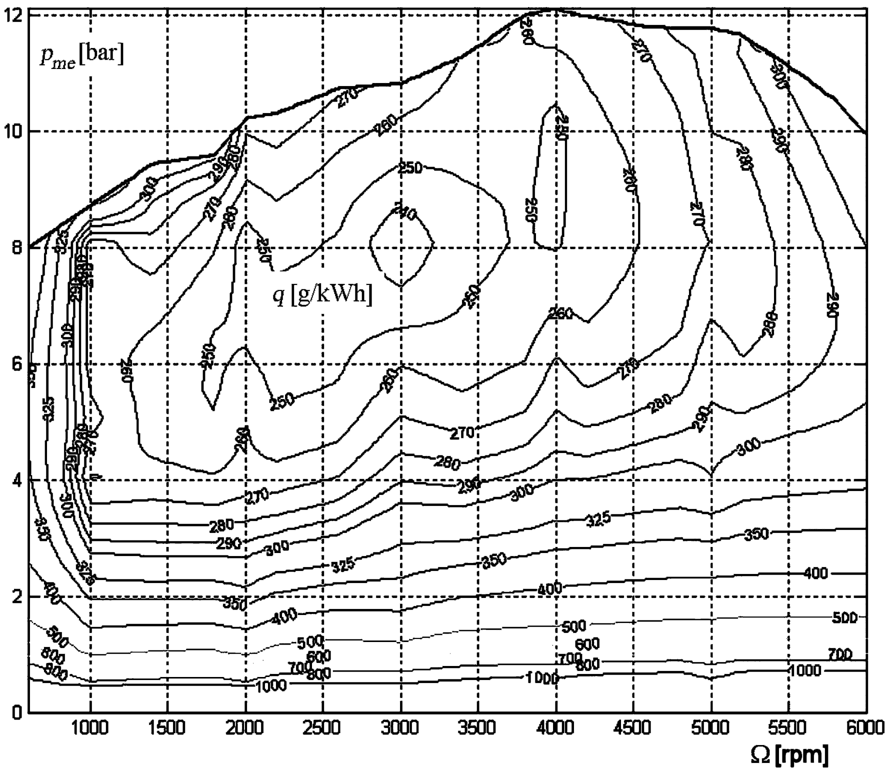

FIGURE 22.5. Map of the specific fuel consumption of a direct injection spark ignition engine of about 2 liters capacity. The consumption of this engine at idle is about 0.90 l/h.

TABLE 22.2. Main characteristics of some battery types for automotive use (M.J. Riezenman, *The great battery barrier*, IEEE Spectrum, Nov. 1992). a): Constant current 3 hours discharge. b): Cycles with 80% discharge depth. c): 100% discharge depth in urban cycle. d): 80% discharge..

Type	E/m [a] [Wh/kg]	P/m [b] [W/kg]	Efficiency	Life[c] [cycles]
Sodium-sulphur	81	152	91 %	592
Sodium-sulphur	79	90	88 %	795
Lithium-sulphides	66	64	81 %	163[d]
Zinc-bromine	79	40	75 %	334
Nickel-zinc	67	105	77 %	114
Nickel-metal hydrides	54	186	80 %	333
Nickel-metal hydrides	57	209	74 %	108
Nickel-metal hydrides	55	152	80 %	380
Nickel-iron	51	99	58 %	918

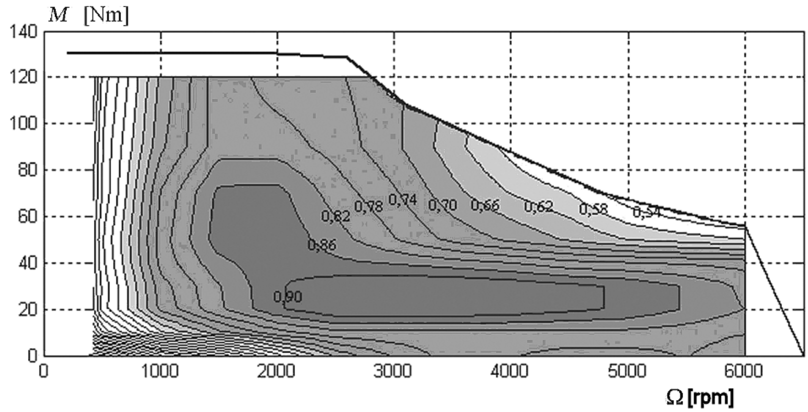

FIGURE 22.6. Map of the efficiency of an induction AC motor with a nominal power of 35 kW.

The traditional configuration is based on direct current (DC) or alternating current (AC) motors connected to the wheels through a transmission of more or less conventional type. Since the electric motor can start under load, there is no need for a clutch and usually no need for a gearbox with various transmission ratios; only a reduction gear and a differential are necessary. The motor is controlled with power electronic devices (*choppers*) whose efficiency is at present extremely high.

Instead of a DC motor (with brushes) it is possible to use an AC motor, controlled by an inverter.

The map of the efficiency of an induction AC motor with a nominal power of 35 kW is shown in Fig. 22.6.

Recently permanent magnet synchronous brushless motors with related control electronics have also been used in vehicular applications. The efficiency and control are generally better, and the cost is transferred from the motor to the power electronics.

As an alternative to the traditional architecture, with the motor operating the wheels through a mechanical transmission, it is possible to put two or more motors directly in the wheels. This is a configuration suggested and tried several times in the past with limited success except for special vehicles, and it is one that seems to be ready for large scale application today. Traditional CC or AC motors require a mechanical transmission in any case, since they supply an insufficient torque and operate at a speed that is higher than that of the wheels. At present, high torque motors (*torque motors*, both with internal and external rotor) are available; these can be connected directly to the wheels without interposing a reduction gear. Apart from the advantage, which may be important in some applications, of allowing an arbitrarily large steering angle, even up to 360°, putting the motor in the wheels without using a reduction gear leads to high efficiency, low noise and a large degree of freedom in placing the various subsystems of the vehicle.

The motor control system can perform the electronic differential function, distributing the torque to the wheels of an axle, and may do so by simulating all the functions of limited slip (or in general of controlled) differentials. However, to put the motors in the wheels increases the unsprung mass, even if in recent applications such mass increase is not large, and may not be detrimental to comfort. The motors may also be located close to the wheels but fixed to the body, and connected to the wheels using transmission shafts. The reduction of the unsprung mass is compensated by reintroducing transmission shafts and above all joints, which work with a relative displacement of the two parts.

22.4 HYBRID VEHICLES

While the only accumulators able to store all the energy required for motion are electrochemical, the quantity of energy to be accumulated in the secondary accumulators of hybrid systems is lower, and this may allow devices of other types to be used. The drawbacks of electrochemical batteries become also less severe.

Elastic energy can be stored in a solid or in a gas. In the first case, the energy density e/m of the device is

$$\frac{e}{m} = \alpha_1 K \frac{\sigma^2}{\rho E} , \tag{22.7}$$

where α_1 and K are coefficients linked to the ratio of the mass of the energy storage elements and that of the whole device, and to the shape of the storage element and the stress distribution, with σ the maximum stress in the energy storing element and E the Young's modulus of the material.

Material with very high strength (spring steel) or low stiffness (elastomers) must be used. The latter are particularly well suited, since some of them may be stretched up to 500% with a good fatigue life and limited energy losses.

The use of a compressed gas, while considered for fixed installations, has several disadvantages for vehicular uses, due to its lower efficiency, the high mass of the container of pressurized fluid, and burst danger. Hydraulic accumulators, in which the energy is stored in the walls of an elastomeric vessel full of fluid, have been suggested and tested in connection with hydraulic motors and pumps. The pressure of the oil, however, is controlled by the characteristics of the elastomeric material independent of driving or braking (in case of regenerative braking) torque. Reversible variable displacement motors, which are quite complex and costly, are then required.

Energy can be stored in the form of kinetic energy in a flywheel. The energy density of a kinetic energy accumulator can be expressed as

$$\frac{e}{m} = \alpha_1 \alpha_2 K \frac{\sigma}{\rho} , \tag{22.8}$$

where α_1, α_2 and K are coefficients linked with the ratio of the mass of the flywheel and that of the whole system, to the depth of discharge actually performed and to the shape and the stress distribution in the flywheel. σ is the maximum stress in the energy storing element and ρ is the density of the material.

Apart from some applications, like the city busses built by Oerlikon in the 1950s and actually used in public service, flywheels are now considered for use only in hybrid systems. Their potentially high power density makes them very suitable for supplying short bursts of power for acceleration or for storing braking energy.

Nor is the problem of designing an adequate transmission trivial: the velocity of the vehicle must be variable at the will of the driver down to a full stop, while the angular velocity of the flywheel is proportional to the square root of the energy it contains. The flywheel reaches its maximum speed after recovering all the energy of the vehicle, when the latter stops. This demands complex continuous transmissions that may offset the advantages of this solution

Some possible schemes for hybrid vehicles are the following (Fig. 22.7):
a) internal combustion engine – electric accumulator,
b) internal combustion engine – elastic accumulator,
c) internal combustion engine – flywheel,
d) electric accumulator – flywheel,
e) internal combustion engine – electric accumulator – flywheel.

The first three systems are similar, at least in principle. The thermal engine supplies the average power, working in conditions that may be optimized in terms of efficiency or pollution. A trade-off between these requirements can be made.

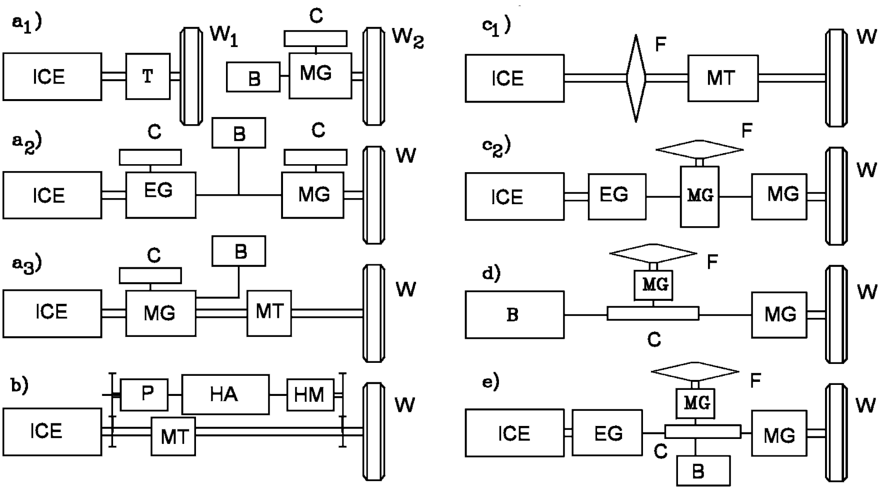

FIGURE 22.7. Some possible schemes of hybrid vehicles B, batteries; C, control unit; EG, electric generator; F, flywheel; HA, hydraulic accumulator; HM, hydraulic motor; ICE, internal combustion engine; MG electric motor/generator; MT, mechanical transmission; P, pump; W wheels.

When the duty cycle includes frequent accelerations and braking, the advantages of disconnecting the instantaneous power requirements from the working conditions of the thermal engine, and of making regenerative braking possible, are large. The possibility of using a far smaller engine allows one to keep mass and cost within the limits of conventional systems or even to obtain mass and cost savings.

The solutions (a) above in Fig. 22.7 are based on an internal combustion engine and electric batteries. The Prius built by Toyota is an example of a hybrid vehicle of this type (see below).

Remark 22.5 *Hybrid vehicles with internal combustion engine and batteries appear the worst alternative in theory, since electric accumulators work exactly in the way which should be avoided, being called to supply high power for short periods; nevertheless this is the only system used in practice today.*

Solution (a_1) is the most interesting, since the presence of an axle controlled by a thermal engine and one controlled by electric motors allows side advantages, like fully controlled 4WD and an active differential on the electric axle, as effective as a VDC system, to be obtained.

Solution (b) may be used in hydrostatic transmissions; owing to the cost of the latter, it is mainly considered for large city buses.

Solution (c) allows the use of a mechanical transmission, although the requirement of an efficient CVT with a wide range of transmission ratios is not easy to meet. The very high efficiency and power density of flywheels can be exploited.

Solution (d) is very interesting, since the flywheel manages the power peaks occurring during acceleration and regenerative braking, allowing the use of batteries with low power density, thus increasing the efficiency, and hence the range, of the vehicle, and the life cycle of the batteries.

Solution (e) combines the advantages of (a) and (d): The batteries work in optimal conditions, and hence a smaller mass of batteries than in (a) is required. The presence of the batteries allows a far larger engine-off range than in (c), to cope with conditions in which the use of an internal combustion engine is not allowed (here it behaves like a *zero-emission vehicle*), while the latter allows a practically unlimited range outside these conditions.

In actual use, as already stated, the configurations considered for applications are those based on an internal combustion engine plus electrical batteries only, labelled as (a) in the figure.

The other solutions are more suitable for particular types of vehicles, like city busses, heavy industrial vehicles, working machines and military vehicles.

Vehicles with electric transmission (electric generator connected to the engine and electric motor driving the wheels) without any energy storage system are sometimes defined as hybrid. This configuration has been used for decades in diesel electric systems, and much used in rail transportation. The lack of a storage device makes it impossible to perform regenerative braking. Often a solution of this type is called a Fake Hybrid (FH).

True hybrid vehicles are subdivided into *parallel hybrids* (PH, Fig. 22.7a1) and *series hybrids* (SH, Fig. 22.7a2).

In series hybrids, at least a part of the energy generated by the thermal engine is transformed into electric energy and used to recharge the batteries, or stored in the designated way.

In parallel hybrids, the electric energy (or the accumulated energy) does not interact with the internal combustion engine, but comes only from recovered energy.

Remark 22.6 *The difference between the two types of hybrids does not depend so much on the configuration shown in Fig. 22.7, but mostly on the strategy of the controller.*

The advantage of parallel architecture is its simple layout and the possibility of being offered as an *option* on a conventional vehicle. A traditional rear wheel drive vehicle may be transformed into a parallel hybrid just by adding an electric motor operating the front wheels and a battery, along with the necessary control system.

Another possible advantage of parallel hybrid systems is the higher efficiency with which the power flowing through mechanical transmission is transferred to the wheels.

Another distinction is between *weak hybrids* (WH) and *strong hybrids* (SH).

In weak hybrids the vehicle usually works with the thermal engine, while the electric motor is used to increase performance, when needed, and above all to restart the engine, also working as a generator for regenerative braking. The internal combustion engine is thus switched off when the vehicle stops even for a short time, or supplies only a very small amount of power (*restart systems*).

The layout of Fig. 22.7a3 is that of a conventional vehicle with starter motor and generator integrated in a single unit and an oversized battery.

In the case of strong hybrids, the capacity of the battery is such as to allow both a non-negligible power increase and a certain engine off range. The instant needs of the vehicle can therefore be completely uncoupled from the power supplied by the engine, to the point that it is even possible to avoid a gearbox.

Finally, there are *Plug-capable Hybrid Electric Vehicles* (PHEV) that use a battery that can be recharged from an external source, so that the vehicle can operate like a true Battery Electric Vehicle (BEV) as well. It is possible to speak of a weak version, where the engine-off operation is limited to low speed and short range, and a strong version that may operate in engine-off mode at higher speed with a larger range.

The possibilities offered by the various hybrid layouts are summarized in Table 22.3

TABLE 22.3. From conventional to hybrid and electric vehicles.

Type	Regenerative braking	Battery operation	Rechargeable	Primary el. traction	Indep. of fossil fuels
Normal - FH	–	–	–	–	–
PH(W)	X	–	–	–	–
PH(S)	X	X	–	–	–
PHEV(W)	X	X	X	–	–
PHEV(S)	X	X	X	X	–
BEV	X	X	X	X	X

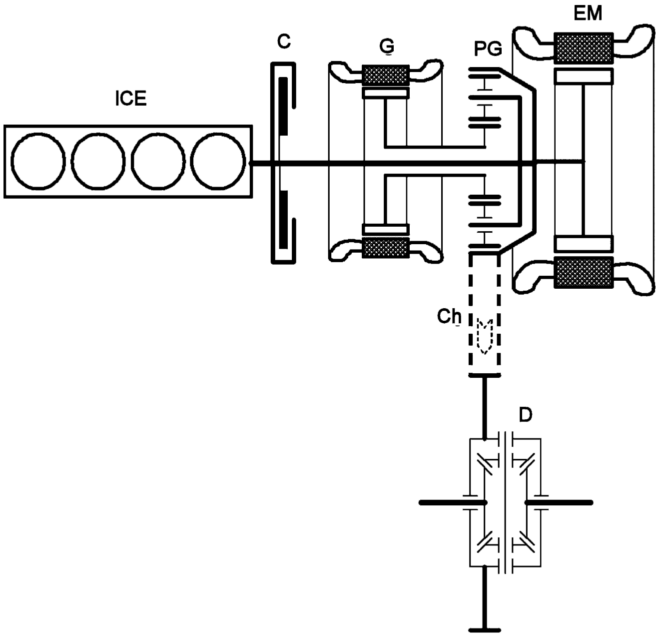

FIGURE 22.8. Layout of the hybrid power system of the Toyota Prius; ICE: thermal engine, C: automatic clutch, G: generator, EM: driving electric motor, PG: planetary gear, Ch: chain driving the final gear at the differential D.

One of the few hybrid vehicles that went beyond the research phase and entered the market at a reasonable price is the Toyota Prius. Its hybrid system is sketched in Fig. 22.8.

In the figure, ICE is the thermal engine, C is an automatic clutch, G a generator, EM a traction electric motor, PG a planetary gear, Ch a chain controlling the gear ratio of the final drive of the differential D. Note that there is no gearbox between the thermal engine and the transmission to the wheels[2].

[2]M. Duoba *et al., In-situ mapping and Analysis of the Toyota Prius HEV Engine,* SAE Paper 2000-01-3096

If τ_o is the gear ratio on the planetary gear when the carrier is fixed (here the carrier is connected to the thermal engine), it follows that

$$\tau_o = -\frac{n_a}{n_s} , \tag{22.9}$$

where n_a and n_s are the number of teeth of the crown and the sun ; the sign is minus since, when the carrier is fixed, the crown and the sun rotate in opposite directions.

The simple equation

$$-\frac{1}{\tau_o}\Omega_G + \Omega_{EM} = (1 - \frac{1}{\tau_o})\Omega_{ICE} , \tag{22.10}$$

where the angular velocities of the various elements are Ω_G, Ω_{EM} and Ω_{ICE}, can be written.

In the same way, by indicating with M_G, M_{EM} and M_{ICE} the torques acting on the same elements, it is possible to write

$$\begin{array}{l} M_T - M_{EM} = M_{ICE} - M_G , \\ (M_T - M_{EM})\Omega_{EM} = M_{ICE}\Omega_{ICE} - M_G\Omega_G . \end{array} \tag{22.11}$$

These equations have been obtained by stating the equilibrium for rotation of the gears and the conservation of the power that goes through it. M_T is the available torque on the gear wheel driving the chain Ch. By eliminating one of the three equations, it follows that

$$M_G = M_{ICE}\frac{1}{\tau_o - 1} , \tag{22.12}$$

$$M_T = M_{EM} - \tau_o M_G . \tag{22.13}$$

This system works both as a parallel and a series hybrid.

The angular velocity of the thermal engine adapts to that of the vehicle by changing the speed of the generator, following Eq. (22.10), something that can occur only by subtracting a torque, through the generator, following Eq. (22.12). By doing this, some power from the thermal engine charges the battery, as in the series layout.

At low speed, a part of the power needed for motion is supplied by the electric motor, which takes it from the battery. Finally, at a very low speed only the electric motor operates, as in parallel layouts. This also occurs when the speed of the thermal engine can adapt itself to that of the vehicle, without the generator subtracting any power.

When the vehicle slows down, the available kinetic energy is recovered.

This method allows the working range of the thermal engine to be restricted to that where minimum fuel consumption is obtained, for a given power requirement. It is also possible to stop the engine when the vehicle stops and to restart it easily at a speed greater than those at which conventional starter motors operate, owing to the generator that is now used as a motor.

The batteries are never recharged from outside the vehicle.

The fuel consumption, obtained using a gasoline engine (Atkinson cycle), is similar to that of a diesel vehicle with similar performance; CO_2 emissions are lower, due to the lower quantity of carbon contained in the same volume of gasoline; other emissions are much lower, due to the reduced working of the engine in variable conditions owing to the more constant use of the thermal engine made possible by the hybrid layout.