Chapter 28
Perspectives of Future Evolution

28.1 A Need for a Change?

In the last 60 years the dominant model for mobility, and particularly for urban mobility, has been based on privately owned motor cars, where with this term we mean a four-wheeled vehicle propelled—in their largest majority—by an internal combustion engine operated on oil-derived fuels and fully controlled by a human being (mostly the owner of the vehicle or one of his close relatives) and built following very strict rules regarding safety, air pollution, etc.

This model, which developed in the Western World, diffused to the whole planet as soon as the economy of the various countries grew enough to allow it.

At the same time, a similar model developed for land transportation of goods, with an increse of road transportation and a decrease of the use of freight trains. Most of the goods at present travel on roads using trucks and tractor-trailer rigs.

The advantages of this model are clear: on one side, it granted humankind a freedom of movement—in many cases we should speak of freedom *tout-court* with many people regarding their car like an extension of their home, and enjoying in it a feeling of privacy they can never feel using any other means of transportation—it had never enjoyed, and on the other side it forced to develop a related economy to build the vehicles, to repair them, to build the infrastructures, to extract, refine and distribute the fuel and to provide a host of related services (insurance, finance, selling and maintnance, etc.) which stimulated the world economy for almost one century, creating hundreds million jobs and allowing to improve the lives of billions people.

Clearly this model is not completely free of problems, from the still high number of casualities due to road accidents to the air pollution caused by the combustion of fossil fuels, from the production of greenhouse gases due to the same reason, to the traffic congestions the large number of vehicles—so due to the low occupancy of vehicles for most of the time—causes, from the distress caused in many drivers by the conditions far from optimal which are often encountered on everyday roads to the loss of working hours caused by slow traffic conditions.

G. Genta and L. Morello, *The Automotive Chassis*, Mechanical Engineering Series, https://doi.org/10.1007/978-3-030-35709-2_28

In the last half a century some of these problems were put under close scrutiny and increasingly strict laws have been passed in all countries, in particular regarding safety and pollution.—mostly air pollution. Other laws regarding the reduction of fuel consumption, and consequently the emission of greenhouse gases, have recently been passed and will be made more strict in the future.

But some of these problems are still there, in particular those linked with urban transportation and to the resulting traffic congestion: in spite of the fact that a well known manufacturer advertises its products with the slogan *Sheer driving pleasure*, the number of drivers who can define 'a pleasure' their experience at the wheel is decreasing, at least speaking of driving on public roads—motorsports practiced on suitably built racing tracks is a different thing. Also, one of the fundamental performance index of any transportation means, the average speed at which the transporation takes place, has stopped increasing for motor vehicles since a lot of time, due to strict speed limitations imposed on public roads first for decreasing fuel consumption and then for alleged safety reasons. Here the problem is not so much the decrease of the mentioned pleasure of driving—which would imply driving at the speed the driver responsibly feels is more suitable in the given conditions, but above all the decreased efficiency of the tranportation, which should be measured as the number of passengers transported at the unit distance in the unit time (measured, for instance, in passenger $\times$ km/s).[1]

This set of problems has suggested some people to put in question the very model on which road transportation is based: privately owned four-wheeled vehicles propelled by internal combustion engines and controlled by human drivers. The ideas that our way of providing mobility for most people are basically wrong, are not uncommon; these views are voiced strongly by a motivated and determined minority. These ideas are motivated by a variety of ideologies and political, economical or ethical beliefs, from sheer antitechnological feelings to the fear that the present way of providing mobility damages the environment, from the idea that our mobility system is based on the exploitation of a part of humankind to the belief that it dehumanizes our lives.

These doubts can be synthetized in two questions:

- *is the way we provide mobility wrong?*
- *is the way we design vehicles wrong?*

While the first deals with political choices and has much more to do with the values we believe in than with the technical choices designers have to make in their everyday life, the second point is of a more technical nature and must be dealt with when speaking of the future of automotive vehicles.

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[1] A similar problem is affecting since decades also air transportation, with the decrease of aircraft speeds with the goal of reducing fuel consumption. This is mostly due to the decrease of reasearch in civil aviation, and the new research programs aimed to build efficient and silent supersonic airliners promise to solve this problem—which could be definitely solved only by hypersonic spaceplanes. On the contrary, high speed trains allowed an improvement of the efficiency of rail transportation, which on medium distance tralvels from city center to city center are now competitive with air transportation.

On the issue of how cars are designed almost all people who use cars, at least occasionally, has his or her own opinion. We are all self-appointed experts in car technology, like all sports enthusiasts are self-appointed coaches for their favorite team. The authors remember a bumper sticker popular in the United States in the 1960s, saying ‘made in Detroit by idiots’. Those who went around with this sticker were trying to show their strong dissent from the way motor cars were designed and built. This may seem just a joke, but these feelings are more widespread than what motor vehicles experts think and may influence as well professionals of disciplines that affect the automotive industry, like architects, city planners, etc.

Car design (in its wider meaning, including also the design of the technologies, tools and equipment to build them) is a complex business. Not only is it difficult for the user or in general the layman to understand why a certain design choice has been done, but often, owing to specialization, it is also difficult for experts in the automotive industry to have clear ideas about the decisions taken by other experts in different branches of the same industry. Nobody can be deep in all specializations involved, from mechanical engineering to electronic engineering, from fluid dynamics to thermodynamics, from materials science to stress analysis, and so on. If also economics and business, public relations and management are considered, the spectrum of know-how needed to build a successful car is so wide that only well organized multidisciplinary teams may have the knowledge that can cope with the task.

So, if the way we design cars is wrong, or at least if we can do much better, hopefully the cars of the future can be more intelligent, and thus more or less different from what we now have. In the following sections some of the most common criticisms of the way we build cars are briefly analyzed, accompanied by discussions of the type of vehicles we expect our ways to lead to. Some changes to road vehicles, more radical than have been predicted in the past, are dealt with, to see whether they were just fantasies of the past or may become a reality in a more or less distant future.

Apart from the ownership of the vehicles—at present there is a strong debate between use and ownership of vehicles, in particular about Mobility on Demand (MoD) services—and the number of wheels—no particular configuration study was ever made, and the four wheels configuration is inherited from the animal traction vehicles—the main points are the use of internal combustion engines and the fact that the driving task is entrusted to a human being.

Not only internal combustion engines are being the object of much research work aimed at improving them, but they may be integrated or even substituted by electric motors and the control task may be, more or less completely, performed by the vehicle itself. So two main topics in the future of motor vehicles are *elettrification* and *robotization*.

The future of land mobility, particularly in urban conditions, will be *autonomous E-mobility* (Fig. 28.1)?

Autonomous E-mobility is often assessed to be the final solution to most problems of present land transportation: safety, pollution, greenhouse gases emissions, driving

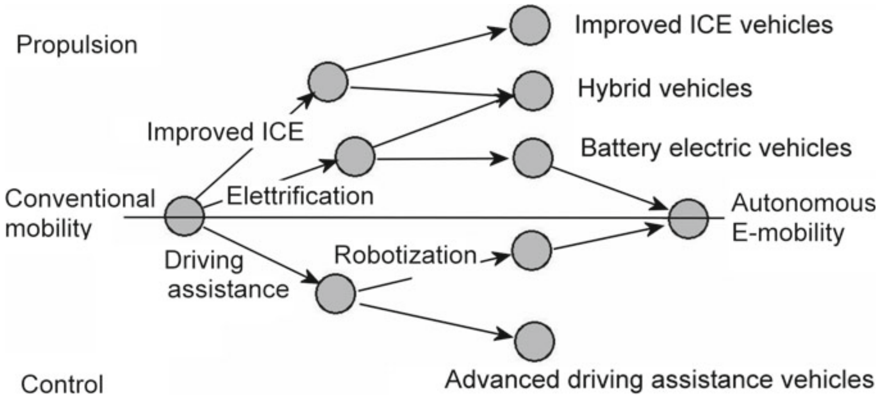

Fig. 28.1 From conventional mobility to autonomous E-mobility

stress and even to traffic congestionstion. However, the problem still to be solved along this way are many: from technical to economical, from legislative to linked to the public acceptance and even to philosophical problems.

28.2 Radically Smaller, Lighter, Cheaper and Greener Vehicles

A common criticism, that has not only technical but also political implications, is that the cars we build are too big and heavy for the needs of people using them. A consequence of this statement is that much smaller, lighter, cheaper and consequently environmentally friendly, cars can be built. These vehicles are mostly thought for urban use, for a number of reasons:

- Cars are presently used mostly within city boundaries, and thus improving the situation in these conditions has the largest impact on the problems we want to solve (fuel consumption, pollution, etc.);
- the same problems are more critical in urban areas, where the size of present cars causes congestion, and the related decrease of the average speed, worse;
- present vehicles seem to be designed with long range travel in mind, and they appear to be unnecessarily fast, powerful, big and even unnecessarily comfortable when used on short distances.

The radical response to this challenge is to introduce innovative vehicles, usually referred to as Urban Personal Mobility vehicles, that are much smaller and lighter, are designed to carry one or two persons and possibly are powered by electric motors. Some examples, with configurations with less than 4 wheels, are shown in Figs. 20.2, 20.3 and 20.4. Other proposals can be classified in the cathegory of quadricycles , or microcars (Fig. 28.2).

Fig. 28.2 Microcars. **a** Nissan Pivo 2; **b** Bajaj Qute

Actually, Urban Personal Mobility vehicles are not as innovative as they seem: we have already something similar, i.e. small motor bikes and mopeds, possibly in their modern electric version, and microcars, that can also be electric. And these new 'alternative' vehicles have the same drawbacks as the old ones: they are much less comfortable, in particular in case of bad weather, they carry only a small quantity of luggage and their cost is comparable to, and in case of electric vehicles, often higher than, that of small city cars, using this term to designate vehicles that fully qualify as cars, although being at the smallest end of the cathegory.

However, the biggest problem of these vehicles is their low safety. In spite of their limited speed, that often is such only theoretically, they offer only a limited protection to the driver and possible passengers. And this is not something that can be corrected by a better design: In a way they are dangerous by design, since they do not comply with the safety regulations of cars. If they did, they would need to incorporate crashworthy structures, safety devices like airbags etc. and their weight would be higher. At this point they would need larger engines (or electric motors and batteries, or perhaps they would need to be hybrid, with the weight and complexity penalty that HV entail), better braking systems and so on, and their mass, power, fuel consumption and environmental impact would be close to those of present—or future, if we project the comparison to a future where both UPM vehicles and cars have benefitted from a few years of continuous progress—city cars. And, if they are Battery Electric Vehicles (BEVs) they will have the same problems of all other electric vehicles. Owing to these factors, they will remain a niche product and will cover the same niche that now is occupied by small motorcycles and mopeds, with which they will compete.

Small city cars, that satisfy all regulations to be considered cars, are obviously another matter, and it is predictable that they will become more common in the future. However, they will be not much lighter and smaller and, if they will use less energy (fuel or electric energy) than present city cars, of which they represent an evolution, it will be for the general advancement of the technology, of which the whole automotive sector will benefit.

28.3 Radically Safer Cars

As we have seen, the main problem which prevents from building much smaller vehicles than those we use today is safety. Often we feel motor cars as an unsafe means of transportation. Some statistics about the safety of motor vehicles are reported in Sect. 17.3.1.

As a consequence, we often claim that we need radically safer vehicles: Here we are speaking about human lives, and even a single dead person on the road is a tragedy that must be avoided. Also the cost of road accidents is huge and, particularly in times of economic restrictions, a cut of these costs would be a welcome achievement. On the other side any human activity involves some risk, and the idea of transportation without accidents is just an utopian goal. The risks linked with any activity may be dealt with only statistically, trying to reduce them but always remembering that safety has a cost and that this cost must always be taken into account. If we forget it, we can easily take counter-productive measures.

Consider for instance that in a country a law is passed imposing very high safety standards (something like the Experimental Safety Vehicles of the 1970s, but this time actually working ones). As a consequence the cost of cars would have a sharp increase, and a number of people, who cannot afford these vehicles or simply want to spend their money in another way, would shift to other means of transportation like bicycles or motorcycles, that are much more dangerous. As a result of that law the number of casualties on the road would have a sharp increase instead of the expected decrease.

Another point is that the way we perceive safety is quite subjective and changes from time to time and from country to country. From Table 17.6 it is clear the the highest incidence of casualities per inhabitant per year occurs in Africa, but most concerns about road safety occurs in the western and east asia countries. We think that the problem of car accidents and casualties due to transportation is linked with our way of moving around, based on cars, however, before cars were used, the casualties due to accidents with horses and carts were much more than those now due to the use of motor cars. And not surprisingly, since there was no safety rule (no rule of any type) for carts, the road were much worse, and so on. But at that time the public concern about safety was much less and nobody bothered about it.

The mortality, in deaths per billion passenger km, due to the use of road vehicles and, for comparison, to air travel is reported in Fig. 28.3 (data referred to the United States, except for those about cycling and walking that are referred to Great Britain). In the case of cars the data are referred to billion vehicles km: Since the average occupancy of cars is 1.6 passengers, to obtain comparable results the curve should be divided by 1.6. Note that the curve related to motorcycles has been divided by a factor of 10, so that it can fit into the plot.

Traveling by car is thus seven times safer than cycling, eight times safer than walking and 22 times safer than riding a motorcycle. From this plot we can draw the conclusion that cars are the safest way to move, except from aircraft (and trains, not included in the plot). This in a way is obvious: aircraft and trains are operated by

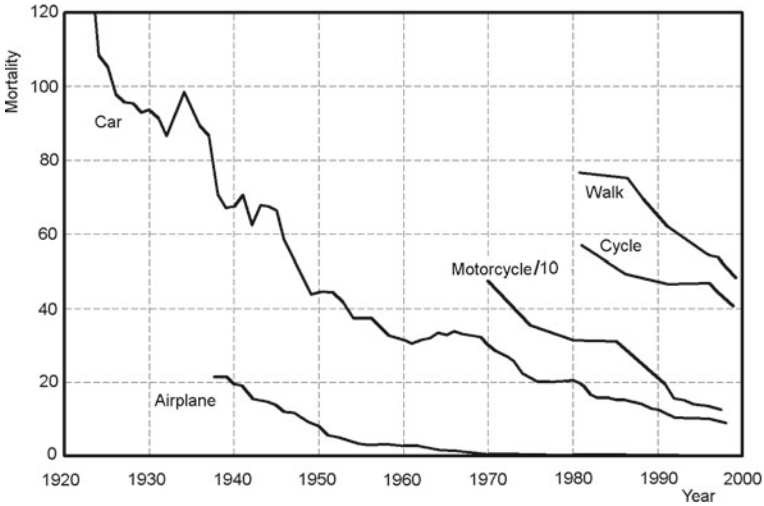

Fig. 28.3 Mortality, in deaths per billion passenger km, due to use of road vehicles and, for comparison, to air travel. In the case of cars the data are referred to billion vehicles km. Note that the curve related to motorcycles has been divided by a factor of 10. The data refer to the United States, except for those related to cycling and walking that are referred to Great Britain (data from Bjørn Lomborg, The Skeptical Environmentalist, Cambridge University Press, Cambidge, 2005)

well trained professionals, whose physical conditions are frequently checked, and are subjected to a maintenance routine managed by *ad hoc* organizations. In case of personal mobility devices the situation can be improved by having vehicles that help the driver in his/her task and can correct some of his/her errors (active safety), that require less maintenance, retaining their safety for a longer time and finally that minimize the effects of a crash on the people on board and on people hit by the vehicle (passive safety).

A further point is that the largest decrease of mortality occurred starting from the 1930s and not from the introductions of the safety regulations (from the 1970s) whose effects do not seem to have been so large; perhaps, however, they were effective in stopping the small increase that took place in the 1960s. The decrease of mortality seems to be more an effect of the evolution of cars, and of the infrastructures (better design, more care to maintenance, better infrastructures, etc.) than of specific regulations.

A final point that can be seen in the plot is that the largest decrease of mortality occurred in a period in which there was a large increase of the average speed of cars: the common opinion that speed is dangerous in itself is not confirmed at all and the introduction of speed limits, that initially were not justified by safety reasons but by the need of saving fuel during the oil crisis of the 1970s, had little effect in increasing the trend toward safer road transportation.

The figure shows that also mortality due to other ways of travelling on roads, walking, cycling, riding motor bikes, decreased. In part this can be ascribed to the safety regulations for cars aimed to reduce the damages that pedestrian and cyclists suffer when colliding with a car.

In any case the trend toward a lower accident rate continued after 1998, the year at which the curves of Fig. 28.3 stop. This decrease must continue also for the future, and the evolutionary trend leading to improvements in vehicle safety must go on. Also here, however, there is no need to resort to revolutionary changes in vehicle design, but only to the application of those provisions that now are available, or will be available in the future, to help drivers in their task and to protect the occupants in case of a crash. Non technical measures, like those designed to prevent people from driving in conditions leading to dangers or to improve infrastructures, will have an important effect.

Future diffusion of vehicular communication systems (V2x: Vehicle to both other vehicles and infrastructure), can improve safety. This concept has been pushed to its ultimate consequences, stating that once each car is connected to the web, and is aware of the position of fixed obstacles and other road users (vehicles, pedestrians, bicyclists, but also animals, etc.) traffic accidents would be totally eliminated. As a consequence, passive safety precautions would no more be needed, and the Urban Personal Mobility vehicles described in the previous section could become fully feasible.[2] While it is clear that communication systems could decrease the number of accidents, it is questionable whether we could rely only on them to protect people travelling by car and other road users, and the possibility of reducing drastically the mass, and consequently the power, fuel consumption and environmental impact of cars in this way is questionable.

The increase of safety due to advanced driving assistance systems and then to autonomous vehicles may lead to the possibility of increasing the average speed on motorways, by raising the speed limitation now enforced in the majority of countries.

28.4 Modular Vehicles

One of the most interesting outcomes of E-mobility is the possibility of locating electric motors in the wheels (see the chapter dedicated to powertrains). It is possible to go further in this direction, by concentrating all the functions regarding each wheel, namely power, suspension, braking and steering, in a single unit, usually defined a *corner* . Each corner can thus be assembled on the car using a mechanical, power and control interface.

An example of this approach is the Active Wheel built by Michelin, shown in Fig. 28.4. In the figure it is easy to see the active suspension, with its spring and electric actuator, the traction motor, the steering system with its actuator, the disc brake and the mechanical interface, consisting in a flange used to bolt the unit to the vehicle frame. The active wheel needs also a power interface, to supply power to the traction and steering motors but also to the active suspension unit, a command

[2] W.J. Mitchell, C.H. Borroni-Bird, L.D. Burns, *Reinventing the Automobile*, the MIT Press, Cambridge, 2010.

Fig. 28.4 The active wheel built by Michelin: a complete corner unit, provided with drive motor, brake, suspension and steering

interface, that carries all the x-by-wire controls for the motor and the steering and brake actuators, and a sensor interface to send back the outputs of all the sensors the wheel is provided with to the electronic control unit of the vehicle. The sensors must include a velocity sensor, accelerometers, pressure sensors for the tire, a steering angle sensor, force sensors and many other sensing units that allow us to keep the operation of the corner under close control.

In this case the drive motor is provided by a fixed ratio speed reducer, and this allows us to keep the unsprung mass to a low value to improve both comfort and handling.

Four active corners of this type (but also three, in case of a 3-wheeled tilting vehicle or six for a larger van) can be directly mounted on a frame, that can be a more or less classical unibody or may be just a chassis like in the *electric skateboard* concept: a unit of this kind, built by GM is shown in Fig. 28.5. In the latter case, the chassis contains the power pack, made of batteries or fuel cells, and in turn carries a body that has little or no structural functions.

The modularity is thus pushed to its limits, returning to the approach that was common at the beginning of the automotive evolution, when the frame and the body were separate units. New materials, design methods and power plants might make this concept competitive again with the more traditional one. The ultimate goal is that the units can be designed and built separately, being possible to assemble them with a 'plug-and-play philosophy like at present is done with computers. The customer could thus buy a frame, four active corners (all with driving motors or just two motorized and two free wheeling), a body plus all the accessories needed to obtain a fully customized vehicle. This approach will easily be technically feasible, but it is still to be demonstrated that it is also economically feasible, above all if the scale of production and the safety requirements are also taken into account.

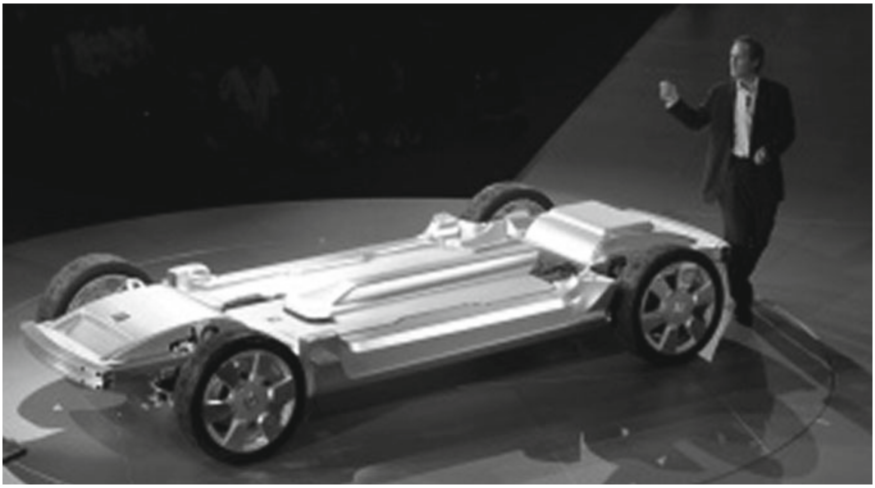

Fig. 28.5 The 'electric skateboard' concept by GM. The frame is here shown complete with its four active corners

28.5 Reduction of the Fuel Consumption

The efforts which are at present made to improve the performance of the power plant have been described in Chapter 22. Another approach for reducing the fuel consumption of a vehicle, thus reducing also its environmental impact, is to reduce the so-called road load, i.e. the total resistance to motion. Any improvement in this area is not only effective in reducing fuel consumption, but also in decreasing emissions, since the amount of pollutant and greenhouse gas emitted is proportional, everything else remaining equal, to the amount of fuel burned, or more in general, to the amount of energy spent.

This applies in general to conventional vehicles, but there are cases where this effect is particularly important: in case of battery electric vehicles, for instance, the reduction of the road load leads to an increase of range, which is the most critical issue for BEV or, if the range is kept constant, in a reduction of the mass of the batteries. The mass of the electric motors and, consequently, the total mass of strategic materials needed for building batteries and electric motors, are reduced too.

In most of the innovative vehicles which will be seen in details in the following sections, the total amount of energy carried on board is quite critical, and so anything that can reduce the total road load increases their feasibility.

28.5.1 Aerodynamic Drag

Much has been done in recent years to reduce aerodynamic drag of vehicles, in particular as a result of the energy crisis of the 1970s. Unfortunately, further improvements are at the same time more difficult and less effective: more difficult because it is difficult to further improve the already streamlined shape of present cars, and less effective because, while aerodynamic drag was a substantial fraction of the total road load when the average C_x of cars was 0.45–0.5, now that it approaches 0.25–0.3 it is much less important.

Moreover, aerodynamic drag is important only at constant high speed, in practice in motorway driving, and the mileage driven by vehicles in these condition is a small fraction of the total, in many cases averaging something like 7% or 8%. In the most frequent driving conditions, namely urban and suburban driving, the importance of aerodynamic drag goes from nil to marginal. This is even more so because of the speed limits imposed by the law in most countries: in North America, for instance, where motorway driving is more important than in Europe, the low speed limits make aerodynamic drag of little consequence. Germany is the only European country in which there are motorways with no speed limitations, and in these driving conditions the reduction of aerodynamic drag can be an interesting energy conservation practice.

This does not mean that a good aerodynamic design will not be important in the future: car aerodynamics does not deal only with drag reduction. Aerodynamic design deals with comfort (mostly noise reduction), safety (improving handling and stability) and other issues, like avoiding the deposition of dirt on head lamps and windows. The point is that in most cases these requirements are conflicting, and what is done to improve handling may for instance cause an increase of drag or an improvement in noise may cause a decrease of handling characteristics. It is well known that aerodynamic negative lift, essential to improve the performance of sports and racing cars by increasing the forces the tires can transfer to the ground, causes a strong increase of drag.

Aerodynamics is also strictly related with style, and with the habitability of a vehicle. As a general conclusion, we can expect that in the future motor vehicles will be carefully studied from the aerodynamic viewpoint but, nevertheless, the reduction of aerodynamic drag will contribute only marginally to the reduction of fuel—or energy—consumption.

28.5.2 Rolling Resistance

The reduction of rolling resistance is on the contrary one of the most important ways to achieve a reduction of fuel consumption. Rolling resistance is the most important form of resistance to motion at low speed, and thus its reduction is important in urban driving, the condition in which cars are mostly used. It has two aspects:

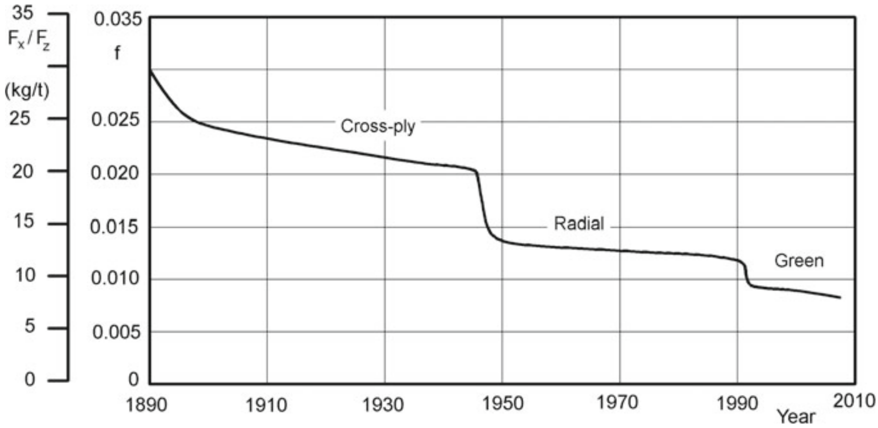

Fig. 28.6 Evolution in time of the rolling coefficient (the ratio between the rolling resistance and the load on the tire). The value of the best research tire has been reported: the values of production tires followed in about 10 years

reduction of the weight of the vehicle (see next section) and improvement of the rolling characteristics of the tires.

The first substantial improvement in this sense took place in the 1960s with the introduction of radial tires, whose rolling resistance is about 20% lower than that of cross ply tires. In Europe radial tires became eventually compulsory, mostly for this reason (Fig. 28.6).

Rolling resistance is mainly due to energy dissipation in the tire, and thus can be lowered by decreasing the damping of the tire material; in the usual formulation of elastomers used in tires, natural rubber has a lower damping than synthetic rubber and damping increases with increasing amount of carbon black in the compound. But while lowering damping lowers the rolling resistance at low speed, it makes the tire more prone to vibrate, and vibration causes a sharp increase of energy dissipation at high speed. At a certain speed (the critical speed) this increase causes overheating of the tire and this must be avoided: it is thus impossible to decrease too much the damping of the rubber material, at least in tires meant to be used on fast vehicles.

In the 1970s low speed, low resistance tires were built for electric vehicles, with the goal of increasing their range. At the end of the 1990s a new approach was introduced: by substituting silica for carbon black it was possible to introduce a dependence of damping on the frequency, yielding tires with superior performances, accompanied by a lower rolling resistance. These tires were first introduced by Michelin and dubbed as *green tires* , with a play on words: they were *green* in the sense they used less energy, so lowering their environmental impact, but owing to the lack of carbon black they could be built in any color and, in the initial intention of their manufacturer, they would have also been green in color. Market studies showed that customers would not like tires of colors making them look like toys, and so they were colored in black, and the term 'green' applied only in a figurative sense. Notice that the term 'green tire' is also used in a wider sense, for any tire allegedly more environmentally friendly than traditional ones, and these claims are sometimes little substantiated.

The tendency toward a reduction of rolling resistance will continue in the future, with the obvious caveat that a tire is a complex object and that any change in its structure, material, production technology, etc. will affect its performance as a whole, from the ability to produce forces to safety considerations, from rolling resistance to cost and duration. A tire must be a compromise among all these features, and it makes no sense to try to optimize a single feature neglecting the other ones. It seems that at least a partial substitution of silica for carbon black is effective and that future cars will have a lower rolling resistance than present ones.

28.5.3 Vehicle Mass

Reduction of the mass of a vehicle has a twofold positive effect on the reduction of fuel consumption: on one side it reduces rolling resistance, and on the other it reduces the energy needed to accelerate, together with the energy to be dissipated in the brakes. The energy needed to accelerate can be reduced also by reducing the moment of inertia of the rotating parts, at equal mass. These effects are all particularly important in urban driving, and so reducing the vehicle mass plays an important role in the conditions that are statistically the most frequent.

In spite of these considerations the mass of cars has increased in the recent past and it is difficult to predict a decrease in the near future. This is a result of several mechanisms, partly linked with customer's requirements (customers are increasingly interested in comfort and less in performace, preferring large saloon cars or SUVs to smaller sportcars) and partly with the regulations, mostly regarding safety, imposed on the car industry.

From experience in the aeronautic industry, it is well known that weight reduction is not a matter of cutting much weight in a few selected spots of the vehicle, a thing that is usually impossible, but to shave a few grams in a large number of places. In a similar way, an increase of weight is not usually the result of adding a few large masses, a thing that is easily controlled, but of adding in many places masses that, each one considered in itself, seem to be negligible.

Modern cars must pass a number of safety tests that require not only an accurate structural design, but also the introduction of safety related elements. Safety has costs, and the increase of the vehicle mass is one of them. Structurally, the requirements of absorbing crash energy and at the same time of providing a rigid survival cell, providing rigid attachment points for safety belts, introducing elements like air bags, with all the related electronics and deployment systems, anti-intrusion beams and plates, fireproof elements, etc. cause an increase of the vehicle mass.

Three wheeled vehicles, that in most countries are not required to comply with the safety regulations that apply to cars but to the more relaxed rules that apply to motorcycles, can be much lighter. The same is true for those microcars or quadricycles that, owing to their mass and power lower than given limits stated by the law, are not required to comply with the automotive safety rules. No doubt they are much lighter, but they are also much less safe, by design.

Active safety has a lower impact on the vehicle mass, but all the devices like ABS, antispin, VDC, EPS and so on have their electronic control unit, actuators and other devices that add to the mass of the vehicle. Large windows to improve visibility are another weight increase factor.

The ever-increasing search for comfort implies the introduction of phono-absorbent materials, vibration insulators, vibration absorbers and improved internal finishing materials. Even electronic devices, sometimes with an utilitarian scope, others just entertainment gadgets, have their mass.

Many customers like large cars, and in many countries, particularly in Europe, the average size of cars has not decreased in the past years. In North America, after a decrease in the 1970s, as a consequence of the energy crisis, the size of cars started to increase again mostly due to the success of SUVs and the continuing popularity of pick-ups. This trend is not likely to be reversed, except for unexpected events like a generalized increase of the cost of energy or the introduction of regulations penalizing large cars.

From what has been said, it is predictable that the trend toward larger vehicle masses is going to continue. The only factors that may fight against it are the improved stress analysis techniques, that can contain the structural mass through a more optimized design, and the introduction of new materials. These two factors, and in particular the first one, are not new, and in the past allowed a reduction of the increase of the mass of vehicles below what could have been if the traditional approach was used.

28.6 Possibilities of Breakthrough

From the previous sections a conclusion can be drawn: it is unlikely that the car of the future will be radically different from that of today, due to revolutionary changes, while it is likely that it will accumulate a large number of small improvements that can be seen as a continuation of the evolution that has occurred in the past. The accumulation of these improvements will eventually lead to vehicles that will be much better than the present ones in a scenario of continuity.

However, we cannot exclude that sooner or later this evolution will lead to a radically new vehicle that could be considered as a motor car only because it will fulfil the task that now cars are performing in our society. The point is the usual one: In the past several times prototypes of vehicles intended to perform the same tasks of cars in different ways were built, some of them performed in a more or less successful way, but they were never produced in significant quantities and they never substituted for conventional motor vehicles.

28.6.1 Flying Cars

The enthusiasm for light aviation that was so widespread in the 1950s and 1960s, in particular in the United States, lead to the idea that it was possible to build vehicles that could travel on normal roads and, when required, fly like aircraft. They were usually called *flying cars*, but the term *roadable aircraft* was also used. As usual with hybrid concepts it is possible to conceive a variety of solutions from a true car that could (sometimes) fly to a true aircraft that could taxi and take off from roads open to the public.

Since the beginning it was clear that the two concepts of car and aircraft are in a way alternative and that it was difficult to strike a compromise. A car must cover a small area to share the road with other vehicles, and in particular cannot be wider than a given size, imposed by the width of a road lane, that is in turn established by laws. An aircraft needs a lifting surface to collect aerodynamic forces, a surface that cannot be too small owing to the low differential pressure air can exert on it and the width of this surface, the wingspan, is critical. Moreover, the smaller is this area, the higher is the take-off speed and the higher the power needed to fly, not to mention the difficulties to control the aircraft. Owing to these contradictory requirements, in some attempts, mostly the earliest (the first prototype that actually flew was built by Waldo Waterman in 1937), the vehicle had two configurations and had to be manually reconfigured to pass from one to the other. More modern prototypes are able to reconfigure themselves using a number of actuators that unfold the wings or the rotor blades. A recent prototype of the last type is the flying car presented by Terrefugia at the 2012 New York Auto Show, named The Transition® (Fig. 28.7). More than a flying car, it is a roadable aircraft.

One of the points with flying cars is not technical: owing to the very nature of this type of vehicle, at present there is no specific standard for flying cars. They are motor vehicles but also aircraft so there is no specific certification they must obtain to be used on roads open to the public and to fly in an open airspace. By their own nature, they will fly, at least in the take-off and landing phases, at altitudes at which

Fig. 28.7 The Transition®, a roadable aircraft presented by Terrefugia at the 2012 New York Auto Show

flying is forbidden, particularly in urban areas, and must land where regular aircraft cannot land.

Moreover, many projects at present underway deal with multicopters, a configuration which by now is used only for drones (UAV). A specific regulation for human carrying multicopters is still missing. And in general it is likely that flying cars, particularly if powered by electric batteries, are too heavy to enter the ultralight cathegory.

Before flying cars can be used in spaces (on the ground and above it) open to other vehicles, a new specific cathegory of vehicles must be introduced, and specific standards must be issued.

Both fixed wings and rotary wings prototypes were built, the latter both in the form of helicopters and autogyros. After a period of stagnation, a new golden age of these attempts started about year 2000, and the new prototypes could take advantage of the advancements in automatic control systems to make flight control easier and safer. Both NASA and DARPA took interest in developing the concept. In 2007 NASA funded a two-million dollars contest to build flying cars, dubbed for the occasion Personal Air Vehicles (PAVs) and DARPA started a 65-million dollars program to develop a four-places roadable aircraft by 2015, able to take off vertically and having a 450 km range. Also the Society of Automotive Engineers (SAE) promoted conventions on the subject of flying cars in various cities.

The fixed wing solution is more typical of roadable aircraft than of flying cars. The take-off and landing speed is fairly high, particularly if the wing load is high, as it could easily happen in the case of flying car in which it is difficult to have a large enough wing.

The aerodynamic lift on a wing has already been studied when dealing with the devices to produce downward forces to increase the forces at the road-wheel contact. The expression of the lift force is here repeated:

$$F_z = \frac{1}{2}\rho V^2 S C_L \,. \tag{28.1}$$

where C_L is the lift coefficient which depends, like the already seen drag coefficient, on the Reynolds and the Mach numbers.

The lift and drag coefficients of a wing are plotted as functions of the angle of attack α in Fig. 28.8a. On the same plot also the efficiency of the wing

$$E = \frac{L}{D} = \frac{C_L}{C_D} \tag{28.2}$$

is reported. The curves are for a given wing, but are typical.

The curves $C_L(\alpha)$ and $C_D(\alpha)$ are influenced by many characteristics of the wing, like the airfoil and the planform. In particular, the drop of the lift after its maximum value has been reached (a phenomenon called *stall* of the wing), can be more or less abrupt.

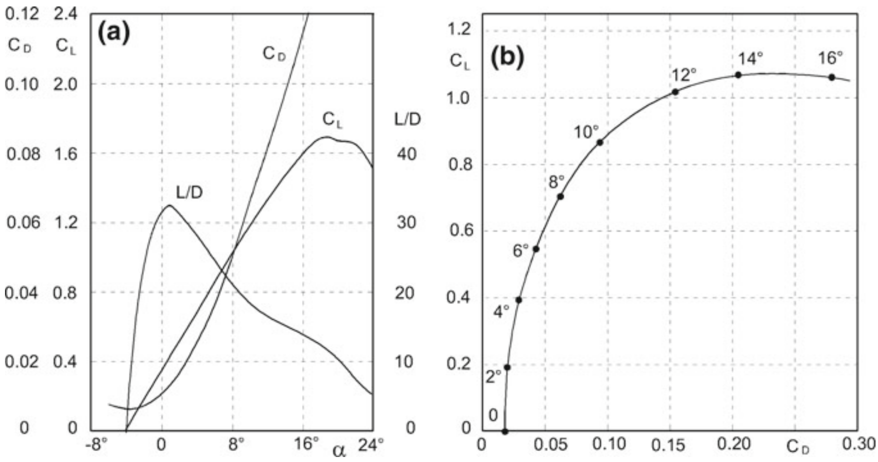

Fig. 28.8 **a** Lift and drag coefficients and efficiency of a wing as functions of the angle of attack. **b** polar diagram of an airplane

It is possible to increase the lift coefficient, although at the expense of an increase of the drag coefficient, by using suitable moving surfaces located at the trailing edge (flaps) or at the leading edge (slats), which change the airfoil characteristics. These high lift devices, used in all modern aircraft for take-off and landing, may be even more important in case of flying cars because of the need of reducing the take-off and landing speed.

The dependence of the aerodynamic characteristics of a body from the angle of attack can be summarized in the polar diagram: a plot of the lift coefficient as a function of the drag coefficient. The polar diagram for an airplane is reported in Fig. 28.8b.

The speed at which a fixed wing aircraft must fly to sustain itself can be easily computed by equating the weight with the aerodynamic lift

$$mg = \frac{1}{2}\rho V^2 S C_L \, . \tag{28.3}$$

This yields the flying speed

$$V = \sqrt{\frac{2mg}{\rho S C_L}} \, . \tag{28.4}$$

The minimum take-off speed can thus be computed by introducing the maximum value of the lift coefficient into Eq. (28.4). At higher speeds the airplane flies with a lower lift coefficient.

The drag at the flight speed is

$$D = \frac{1}{2}\rho V^2 S C_D = mg\frac{C_D}{C_L} = \frac{mg}{E}\ , \qquad (28.5)$$

i.e. is equal to weight divided by the aerodynamic efficiency.

The reciprocal of the efficiency is thus a sort of a friction coefficient, i.e. a number that multiplied by the weight gives the force that opposes to motion.

The attitude of the aircraft that minimizes the drag is that characterized by the maximum aerodynamic efficiency.

The power required for flight is the product of the drag by the speed

$$P = DV = mg\frac{C_D}{C_L}\sqrt{\frac{2mg}{\rho S C_L}} = \sqrt{\frac{2m^3 g^3 C_D^2}{\rho S C_L^3}}\ . \qquad (28.6)$$

To reduce the take-off speed and the power required, it is possible to increase the wing area.

The attitude (i.e. the angle of attack) of the aircraft that minimizes the power required for motion is that at which the product

$$\sqrt{\frac{C_L^3}{C_D^2}} = \sqrt{C_L}E\ .$$

is maximum. Such attitude is also that allowing the maximum flight duration for a given quantity of energy stored on board.

The attitude maximizing the flight time is the same as the one that minimizes the power required for flight.

It is easy to understand that a fixed wing flying car is unpractical and requies great skill, particularly for taking off and landing, which are practically impossible from urban roads. A flying car may have two types of application: long range journeys, to exploit the higher speed of air travel, and for urban use, to avoid traffic. In the first case fixed wings flying cars may be used, while in the second the possibility of taking off and lnding vertically (Vertical Take-Off and Landing, VTOL) of helicopters is essential. A helicopter flying car has the added advantage of landing on the roof of buildings.

A helicopter flying car can thus be used as a urban taxi or, speaking of autonomous vehicles, as Autonomous Mobility on Demand (AMoD) vehicle.

However helicopters have the disadvantage of having a large rotor, with no outer shroud at the blade tips, and being quite difficult to control. The control is performed through cyclic pitch, to incline the rotor plane about the x-axis and the y-axis, collective pitch to control the vertical motion and the tail rotor to control rotations about the z-axis.

These reasons made multirotors, provided with a number of fixed pitch propellers, a much better solution, particularly for city flying cars.

One of the most interesting concepts is the quadcopter/convertiplane Skycar M400 built by Moller International (Fig. 28.9).

Fig. 28.9 The Skycar built by Moller International

The interesting point of this concept is that it does not need to be re-configured for flying and that, owing to its strongly automated control and GPS-based navigation systems, can be flown safely by anyone, or at least this is the claim of its builder. On the other side it seems that the designers were more concerned with the behavior of the vehicle as a flying machine than as a car: the wheels are apparently more the undercarriage of a helicopter than the running gear of a road vehicle, but this can be improved later.

A configuration for unmanned rotorcraft that is now quite popular is the so-called *quadrotor* or *quadrocopter*, generally consisting in a cruciform structure with a rotor at the end of each one of the four arms. Quadcopter UAVs (Unmanned Aerial Vehicles) or drones have usually fixed pitch rotors, that in the smallest models usually reduce to four propellers rotating about vertical axes. Their control is much simpler than that of single or twin rotors helicopters, which must have a variable pitch with both collective and cyclic pitch control. A picture of a miniature quadcopter is shown in Fig. 28.10a (the size of the machine is just a few centimeters across), while a larger machine (the Parrot AR. Drone) is shown in Fig. 28.10b.

The control of a quadcopter is achieved by varying the speed, and then the thrust, of each rotor, a thing which is easy if electric motors are used. With reference to Fig. 28.10a, rotors 1 and 4 rotate in one direction while rotors 2 and 3 rotate in the opposite direction, so that the reaction torques are balanced and no tail rotor is needed, as in single rotor helicopters. By

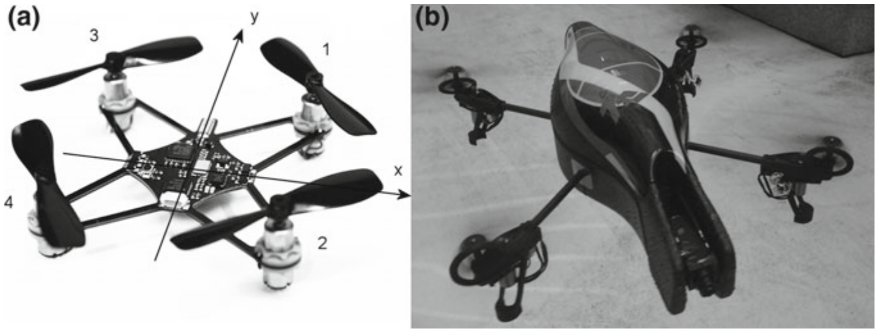

Fig. 28.10 **a** A miniature quadcopter UAV; **b** the Parrot AR.Drone, a commercial quadcopter UAV

- Reducing the speed of rotors 1 and 3, and increasing that of rotors 2 and 4, a roll rotation (rotation about x axis) to the left is obtained, while the torques are still balanced.
- Reducing the speed of rotors 1 and 2, and increasing that of rotors 3 and 4, a pitch rotation (rotation about y axis) to dive is obtained, while the torques are still balanced.
- Reducing the speed of rotors 1 and 4, and increasing that of rotors 2 and 3, a yaw rotation (rotation about z axis) is obtained. The direction of the yaw rotation depends on the direction of the rotation of the rotors.

By using a simple control electronics and sensors (generally rate gyros) a quadcopter can be easily controlled, achieving a good maneuverability, being able to fly in any direction and turn on the spot. They are scalable from miniature to large machines.

From the experience gained with millions of quadcopter drones already sold and scaling them up, it is possible to build electric flying cars based on this configuration, although some problems with batteries still remain. A hybrid configuration with the ICE—or perhaps a gas turbine—used as a range extender is however possible. Recently Italdesign and Airbus presented the *pop-up* project based on the quadcopter configuration (Fig. 28.11): a modular vehicle based on a capsule carrying 2 people, which can be attached either to a four-wheels skateboard or to a quadcopter. The vehicle has been designed to be an autonomous vehicle in both configurations.

A propeller rotating at an angular velocity Ω produces a thrust which can be approximated by the formula:

$$F = 2k\rho S\Omega^2 , \tag{28.7}$$

where k is a constant which in hovering depends only on the geometry of the propeller and S is the area of the propeller disc. If a multicopter (Fig. 28.10) with n rotors has a mass m, the equilibrium equation at take-off is

$$mg = 2nk\rho S\Omega^2 . \tag{28.8}$$

Fig. 28.11 The Italdesign and Airbus *pop-up*

The total power (all rotors) needed to produce the thrust is

$$P = n\frac{F^{3/2}}{\sqrt{2\rho S}} = n\frac{(mg)^{3/2}}{(n)^{3/2}\sqrt{2\rho S}}\,, \tag{28.9}$$

i.e.

$$P = \frac{(mg)^{3/2}}{\sqrt{2n\rho S}}\,. \tag{28.10}$$

Consider for instance a quadcopter with a mass of 800 kg provided with propellers having a diameter of 1.5 m and operating at sea level ($\rho = 1.225$ kg/m^3) in standard conditions. The power required for taking off and hovering is 167 kW, i.e., 41.8 kW on each motor even if larger power is needed to insure the required flight performace.

Instead of quadcopters, hexacopters (with 6 propellers) may be used with the advantage of redundancy. In case of the failure of one of the motors, the others can still ensure flying with reduced performance and above all a safe landing. On the other side, simpler configurations with just 3 rotors can be built, although the control simplicity of multicopters with 4 or more rotors is lost. Vehicles with just two rotors, often called hovering bykes, have also been tested: they require either cyclic pitch, like twin rotors helicopters, or a control similar to that of motor bykes, in which the driver moves his/her body to maintain equilibrium even if an automatic control system may perform the same task.

Multicopters are usually provided with electric propulsion, because the drivers of the electric motors can perform the control functions varying the speed of the various propellers in a straightforward way. While machines similar to multicopters have been built using gas turbines to power the propellers, (in the case of Fig. 28.9 the nacelles with the turbines and the propellers are orientable, like in the case of convertiplanes, so that the control is different from that of a typical quadcopter) the idea of fully electric multicopter flying cars is the most common. In this case the weight of the batteries may easily be the limiting factor, and these devices may have

Fig. 28.12 The Aero-X hoverbike: a twinrotor vehicle, which is half way between a multirotor and a hovrcraft

to wait until batteries with a high enough specific energy and specific power have been developed.

A possibility is a flying car powered by a gas turbine (or two for redundancy) driving an alternator powering the electric motors through a number of inverters which perform the control tasks. Instead of two turbines, just one can be used, with safety being assured by a small number of batteries, which guarantee a safe landing in case of power generator wailure. The vehicle can thus evolve toward an hybrid configuration, with the possibility of being a BEV when on city roads, and flying as a turbine powered multicopter when in the sky. While a quadcopter needs that all rotors are working to maintain controllability, an exacopter can continue working even with one rotor out of service: a sort of redundancy which improves safety. A much simpler solution is a twinrotor vehicle like the hoverbike shown in Fig. 28.12. A twin rotor is not controllable around the roll axis using its rotors, but requires either a displacement of the rider position (like bikes) or a cyclic pitch control like in helicopters. The hovebike is however more an hovercraft than a multirotor and likely it cannot travel at large distances from the ground.

The problems with flying cars are however not only technical, even if just to have them flying successfully and safely is a great achievement: the bigger concerns are how to control the flight of many of these flying vehicles in a small, possibly urban, area. In fact this was the point raised by the FAA (Federal Aviation Administration) when Henry Ford proposed to mass produce flying cars before World War 2, and this is still the point today, in spite of the improvements of the air traffic control systems.

Perhaps the only way is to have automatic route planning and collision avoidance devices based on networking of the computers installed in each car and working through V2x (Vehicle to both other vehicles and infrastructure) communications, but this is a difficult task, much harder than the similar systems proposed for dealing with traffic control on motorways and not yet implemented.

Issues about energy consumption and environmental sustainability of air cars will also be raised. As a conclusion, it is likely that flying cars will be built in the future and a niche market will develop—for instance, an air taxis market, like that predicted by Uber—, but it seems unlikely they will become a popular transportation means, with a diffusion comparable with that of present motor cars.

28.6.2 Other Advanced Vehicles

Starting from the late 1950s, particularly in the United Kingdom, a new kind of vehicle was developed and raised great hopes: the hovercraft. This device was based on an air cushion created by vertical axis fans, and could travel on land and water, not needing a prepared surface, although the power required for hovering grows fast with increasing ground irregularities. On very smooth ground the power required for motion is comparable with that of wheeled vehicles. In spite of the predictions about hovering cars, the development of hovercraft was toward large commercial or military crafts, and even those started declining. Small personal hovercraft are now limited to amateur usage and there are several clubs of people who build their own vehicles often from drawings or kits. Hovercraft are much more suited to moving over water than over solid ground and, in the latter application, there is no reason for which they should be considered better than conventional wheeled vehicles: they use more power, are more noisy, more complicated and much more difficult to drive since driving, braking and cornering forces are not supplied by the contact between the vehicle and the ground, but by aerodynamic forces. It is easily predictable that there are no hovering cars in the future of ground transportation.

Magnetic levitation vehicles have been extensively experimented and there are commercial short lines served by magnetic levitation (Maglev) trains. All these vehicles are however guided vehicles and are comparable with trains and not with cars. After many contrasting decisions, at present it seems that Maglev trains will not be a widespread option for the near future.

Even dimmer is the perspective of building magnetic levitation cars. In the enthusiasm raised by the discovery of high temperature superconductors in 1986 many predictions about the possibility of levitating objects as big as vehicles were forwarded. These ideas were based on the prediction that higher and higher temperature (possibly up to room temperature) superconductors could become possible and that their performance could be improved. These predictions didn't materialize, and non-guided magnetic levitation vehicles remained just dreams, but patents have been filed and designs have been forwarded. Moreover, like in the case of hovercraft, the problem of generating driving and cornering forces without a contact with the ground remain.

Another more realistic idea has also been forwarded: a wheeled vehicle whose wheels are supported by magnetic bearings instead of rolling element bearings, or in a more fantastic way, vehicles whose tires are suspended to the wheels through magnetic bearings. To suspend the wheels on magnetic bearings is fully possible (less to suspend the tires, a thing that anyway has no advantage) but the advantage in doing so is not clear. With respect to a conventional wheeled vehicle the only energy saving is due to the reduced bearing drag, that is at any rate much less than the rolling resistance of the tires. In trains the advantage of magnetic levitation is linked with the possibilities of reaching speeds well above the maximum speed allowed by the wheels, and even in this case the progress of conventional railways that allowed reaching higher and higher speeds makes questionable the actual large scale use of maglev trains. In cars the possibility of actually travelling that fast is ruled out, so that there is little space for dreams of maglev cars.

As a conclusion, short of radical advances leading to ‘science fiction’ technologies allowing levitation of a vehicle over a road surface, it seems that we can safely exclude this possibility in a foreseeable future.

The only possibility for radically new types of vehicles that remains is linked to discovering new physical principles, like antigravity vehicles. Although the possibility of controlling gravity is accepted as a theoretical possibility by a number of scientists and a number of experiments have been conducted by respectable scientific institutions, sometimes even with the sponsorship of space agencies like NASA, there is no proof that it is actually possible, and no serious hint about how to do it. But is it worth while anyway? In particular, the advantage would be only to avoid rolling resistance, that is responsible for a not too large part of the energy required for motion while all other problems would remain there, and some, like producing tractive, braking and cornering forces, would become much worse.