21. Trends and Challenges in Mobility and Transportation

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This chapter provides a short overview of the three most important transportation technologies: automotive, aerospace, and rail. It initially examines the economic impact of transportation. A strong economy is usually highly dependent on the transportation of people and goods. The effects of environmental and safety legislation on transportation technologies are also discussed. Processes that will transform transportation over the coming decades are then considered.

After that, relevant legislation for and development trends in automotive, aerospace, and rail technologies are described and analyzed, and the processes used to develop new automotive vehicles, aircraft, and rail vehicles are outlined. More specifically, a section on automotive technology explores the different types of powertrains used in automotive transportation, current trends in the development of automobile bodies, chassis, advanced driver-assistance systems, combustion engines, and electric drives, as well as the automotive vehicle development process. A section on aerospace technology considers the relationship between air transportation and society before discussing the history of and challenges facing aeronautical engineering. A generic development process for aerospace technologies is then signposted. Finally, a section on rail technology describes basic technologies relating to the efficiency of and resistance and traction forces associated with rail transportation. Other important factors in rail transportation are then discussed, such as guidance, the braking system, train protection, management, rail vehicle structure, and coupling, before the development process for rail vehicles is detailed.

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21.1 Overview

Transportation is the process of conveying humans, animals, or goods from one place to another (the word is derived from the Latin *portare*, meaning 'carry,' and *trans*, meaning 'between'). It is one of the most basic human needs, and it has a significant impact on any economy: productivity and economic strength are usually strongly correlated with the amount of people and goods that are transported in an economy. Transportation can be performed on the ground (by road or rail), across the sea, or through the air, leading to four main transportation technologies: automotive, rail, marine, and aerospace. These technologies face severe challenges in the near future due to (i) increased customer requirements and an ever-greater demand for transportation, (ii) energy shortages

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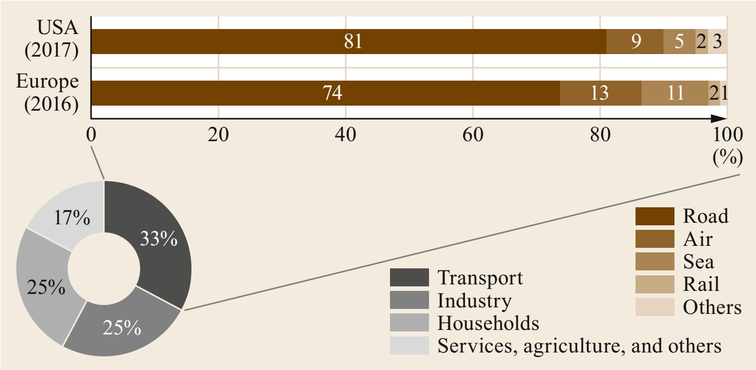

Fig. 21.1 Energy demand of the transportation sector as a proportion of the total energy demand in Europe, and the energy demand of each transportation mode as a proportion of the total energy demand of the transportation sector in Europe and the US (after [21.1, 2])

and rising fuel prices, (iii) more stringent legislative requirements such as those relating to pollutant and noise emissions and safety issues, and (iv) the imminent automatization and digitalization of transportation, which will involve seamlessly linking the transportation sectors together to enhance mobility and the transportation of goods.

In the first part of this chapter, we discuss the economics of transportation. After that, environmental and legislative issues relating to transportation are considered. The final part of the chapter will discuss upcoming changes in the transportation sector.

21.1.1 Transportation as an Economic Factor

The forecast increase in the world's population and the industrialization of large parts of the world are the main drivers for the predicted rise in demand for transportation. The potential environmental effects and risks to energy supplies caused by such an increase in demand for transportation are major concerns. As shown in Fig. 21.1, one-third of the total demand for primary energy in Europe in the year 2016 originated from transportation. In particular, road transportation consumes 74% and 81% of the overall energy demand from transportation in Europe and the United States, respectively.

Figure 21.2 shows the growth in various passenger and freight transportation modes in Europe between the years 1990 and 2020 (including some predicted data). For passenger travel, steady increases in both road and air transportation (in passenger kilometer) can be discerned, while the levels of rail and public transportation have remained more or less constant. An increase in freight transportation is also apparent, with the largest proportion (in ton kilometer) of this increase deriving from freight transportation up to the year 2020. However, it should also be noted that air transportation is forecast to double in the same period.

In Fig. 21.3, the predicted rise in the energy demand of the transportation sector during the period from 2004

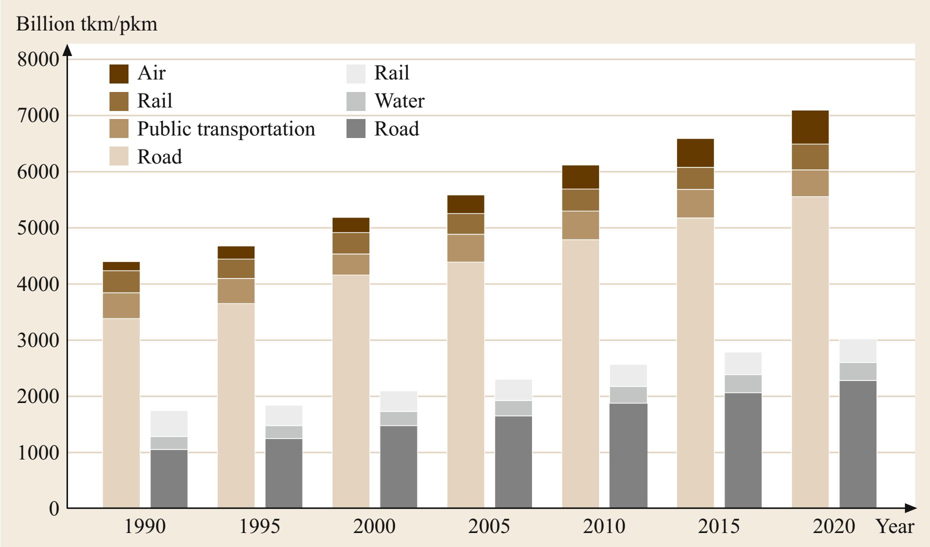

Fig. 21.2 Growth in various passenger (*left-hand bars for each year*) and freight (*right-hand bars for each year*) transportation modes in Europe between the years 1990 and 2020 (tkm: ton kilometer; pkm: passenger kilometer). Source: [21.3]

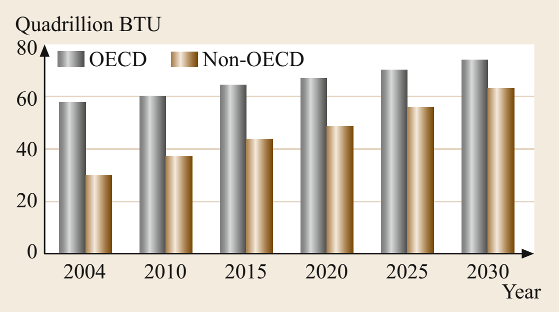

Fig. 21.3 Energy consumed by the transportation sectors of OECD and non-OECD countries during the period 2004–2030 (after [21.4]) ►

to 2030 is shown for Organisation for Economic Co-operation and Development (OECD) countries and for non-OECD countries. For OECD countries, an increase of 48% is envisioned, whereas growth of 66% is predicted for non-OECD countries. Such large increases imply that it is necessary to improve transportation efficiency and to search for new sources of energy.

21.2 Impact of Safety and Environmental Legislation on Transportation Technologies

In Fig. 21.4, greenhouse gas emissions in g/pkm (grams of CO_2 per person kilometer) are shown for various modes of transportation in Germany, based on statistical data from 2017. The plot shows that traveling by plane yields the largest greenhouse gas emissions in g/pkm, and that rail transportation is more efficient in terms of emissions than road transportation. However, it is difficult to accurately compare the emissions of different transport modes (road, rail, and aviation) because calculations of emissions are based on a range of assumptions (e.g., the distance traveled, the transportation speed, and the average occupation of the vehicle, train, or plane), and modifications to these assumed values can have major effects on the calculated emissions. For instance, a small change in the occupation of a small vehicle (e.g., a car) has a huge impact on the calculated emissions (in g/pkm), whereas a small change in the occupation of a train or plane has no noticeable impact on the calculated emissions (in g/pkm).

A combination of economic aspects (e.g., energy efficiency, cost efficiency, investment required, transportation speed, and space required) jointly determine the transportation mode that will become dominant in a particular area. In addition, legislative requirements are placing increasing constraints on all areas of transportation. For instance, limits on the emission levels of pollutants (e.g., nitrogen oxides, unburned hydrocarbons, carbon monoxide, and particulates resulting from the combustion of hydrocarbon-based fuels with air) from vehicles are gradually decreasing around the world.

Figure 21.5 shows that the CO_2 emission levels (in g/km) from new registered cars in Europe dropped considerably (by about 25%) from 2006 to 2015. Future EU legislation aims to decrease CO_2 emissions of new registered vehicles even further. For 2021, new cars must release no more than 95 g/km CO_2 on average or the manufacturers of those cars will face financial penalties. This permitted level of CO_2 emissions is set to decrease by 15% in 2025 and by 37.5% in 2030.

Besides CO_2 emissions, which are related to the efficiency of the powertrain, legislation is increasingly focusing on reducing the emissions of gases that are harmful to human health. Figure 21.6 shows how the

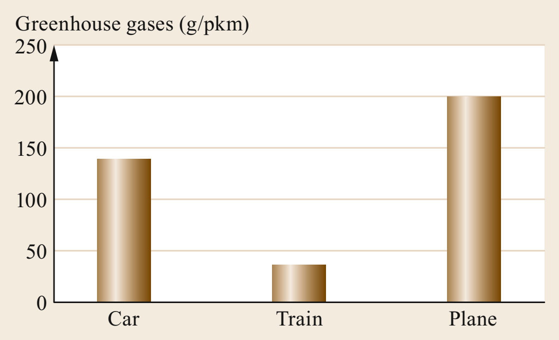

Fig. 21.4 Comparison of the greenhouse gas emissions (in g/pkm) from various modes of passenger transportation (after [21.5])

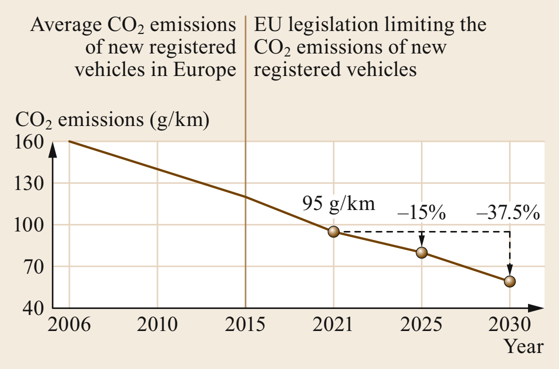

Fig. 21.5 Drop in CO_2 emission levels (in g/km) from new registered vehicles in Europe from 2006 to 2015, and prospective legislative limits on the CO_2 emissions of new registered vehicles in Europe from 2021 on (after [21.6])

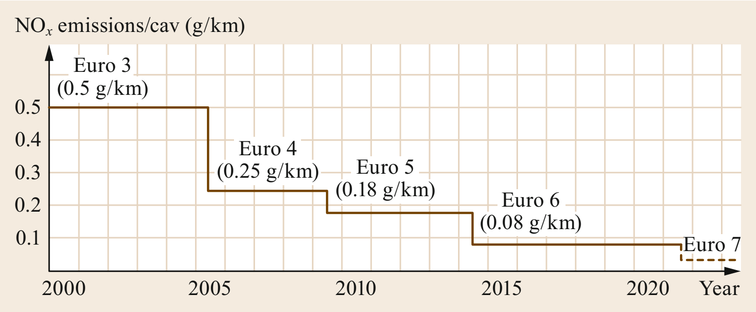

Fig. 21.6 Evolution of the EU limit on NO_x emissions from diesel-powered passenger cars since the year 2000, starting with the introduction of the EU legislation Euro 3; the implementation of Euro 7 is imminent in 2021 (after [21.7])

EU limit on nitrogen oxide (NO_x) emissions from diesel-powered passenger vehicles has evolved since the year 2000. Within 14 years of the first legislation, Euro 3, the limit on NO_x emissions had decreased by 84% from 0.5 to 0.08 g/km (Euro 6). This limit is set to decrease even further in 2021 with the introduction of the Euro 7 legislation.

These graphs illustrate a common trend among the industrialized nations to reduce the limits on pollutants emitted by vehicles. This means that car manufacturers must direct increasing resources into developing technologies that can fulfill all of their legislative requirements.

Besides chemical emissions, noise is also produced by the various modes of transportation. Although noise levels of 130–140 dB(A) are painful to humans, lower noise levels are also considered harmful because they annoy (leading to aggression and high stress levels), cause hearing loss, and have other harmful effects, depending on the noise level and duration of exposure. Major sources of transportation-related noise emissions are road, rail, and aircraft traffic.

Over the years, noise limits have been tightened for all transportation technologies. EU regulation Nr. 540/2014, for example, significantly reduces the permitted level of noise from a car. On the other hand, the regulation also mandates that all electric and hybrid cars (which are generally much quieter than cars that are entirely powered by petrol or diesel) must be equipped with an acoustic vehicle alerting system (AVAS) to warn pedestrians of their presence. In another example, in 1971, the International Civil Aviation Organization (ICAO), an agency of the United Nations that codifies the principles and techniques of international air navigation, established regulations limiting the noise emitted by different classes of civil aircraft.

Finally, safety issues should be mentioned as a major driver of transportation technology development. Improvements in transportation safety are imposed by legislation or prompted by customer requirements. In general, we can differentiate between measures that enable the safe use of the transportation mode of interest and measures that reduce the likelihood of harming a third party who is using the same mode, a different mode, or no mode of transportation. If we take aircraft as an example, measures aimed at improving safety when using this mode of transportation—including stringent servicing routines and heavily scrutinized development processes—are the main focus, rather than measures to reduce the probability of harming a third party. On the one hand, this is because any severe failure in the air would almost certainly cause a large number of casualties; on the other hand, the potential of an airplane to harm third parties cannot be significantly reduced by altering its design. Other measures must be taken to ensure the safety of third parties; for instance, air-traffic control is responsible for ensuring that two aircraft do not collide. In contrast, a road vehicle will often move through dense traffic, and the safety of the vehicle when it is passing through such traffic is largely dependent on the awareness of its driver (although there are various regulations concerning regular vehicle servicing). However, cars are increasingly being fitted with technological support for the driver (such as an automatic emergency braking system and a driver alert system) that lowers the probability of an accident.

21.3 Upcoming Changes in Transportation

When used in combination with fast and comprehensive mobile communications technology, digitalization enables digital networks, automation, artificial intelligence, and predictive analysis of a huge amount of data. Digitalization is therefore leading to a mobility revolution in the transportation of goods and people. The predicted changes in mobility can be summarized by the buzzword ACES, which is an acronym for *automated, connected, electrified, shared/services*. We now consider these four aspects of mobility in turn.

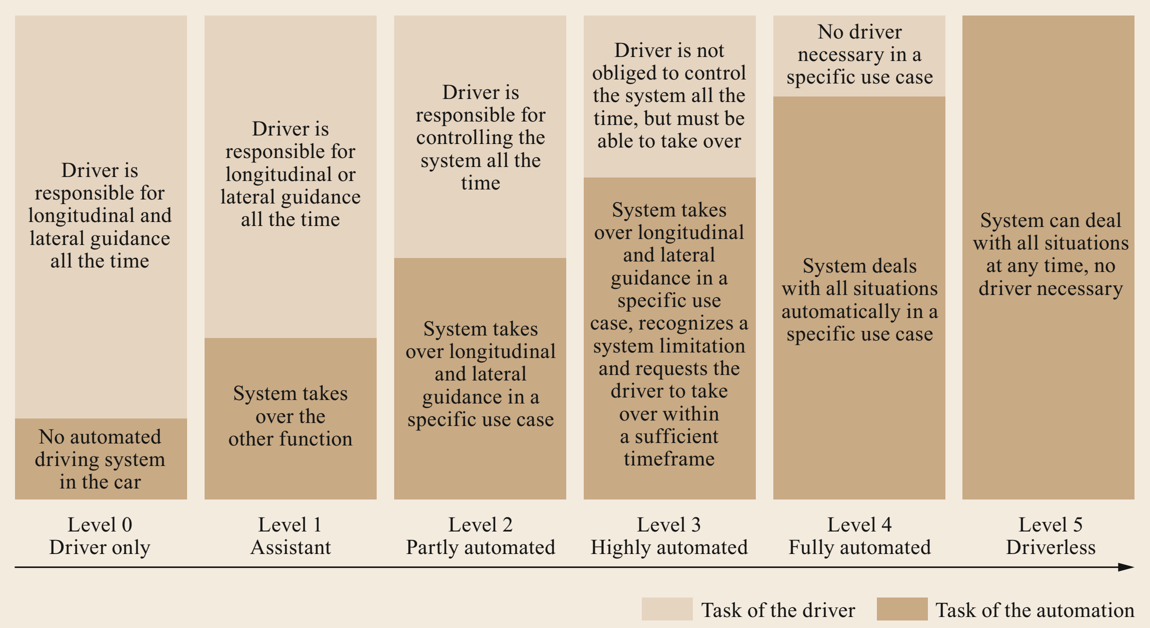

Fig. 21.7 Different levels of automated driving (after [21.8, 9])

21.3.1 Automated

Automation is central to future developments in transportation mobility, and it implies a major change in the use of the traffic infrastructure. In automation, the various tasks involved in driving are gradually transferred from the driver to the vehicle. Five different levels of automation can be distinguished. At level 0 (driver only), the driver is responsible for longitudinal and lateral guidance of the vehicle at all times; there is no active technology in the car that interferes with the driving. At level 1 (assistant), the driver is responsible for longitudinal or lateral guidance, whereas an onboard system is responsible for the other function (e.g., cruise control). Level 2 (partly automated), which is already implemented in modern premium cars, implies that the car can perform longitudinal and lateral guidance under certain circumstances, but the driver always has ultimate control of the system. At level 3 (highly automated), the system performs longitudinal and lateral guidance under certain circumstances, recognizes system limitations, and requests for the driver to take over within a sufficient timeframe. At level 4 (fully automated), the system can deal with all situations encountered while driving automatically in a specific use case (e.g., on a standard motorway). In this specific use case, no driver is necessary but the vehicle must be occupied. At level 5 (driverless), no driver is necessary, and the system can deal with any situation at any time. The different levels are shown in Fig. 21.7.

Level 4 or 5 automation of driving potentially has huge benefits. For instance, trucks can be driven together as a platoon on a motorway to make transportation safer, easier, and cheaper. Former drivers of private cars can use the time that they would have spent driving working or relaxing instead. However, various technical and legal difficulties will need to be solved before safe and reliable level 5 automation is achieved for cars; we may have to wait until at least 2030 for the advent of this level of car automation.

21.3.2 Connected

In the future, vehicle production per se will become less profitable, but, given that automation will relieve the occupants of the vehicle of the need to perform many/any of tasks associated with driving, more revenue will be earned by providing in-car services to the occupants through interconnectivity (e.g., via streaming services). In other words, in the future, business models for the automotive industry will largely focus on providing services on the move.

21.3.3 Electrified

It is very likely that in the medium-to-long term, electromobility will provide the solution to many of the problems with present-day road transportation technologies, including air and noise pollution. One of the major issues with current electric vehicles—their short ranges—

should be solved through future improvements in battery technology. Automation could allow electric vehicles to drive themselves to charging stations between transportation tasks. Especially in the US and Asia, new players are entering the electric vehicle industry, which is driving advances in electromobility technology. However, there is still a range of technical issues with electromobility to address, such as the charging infrastructure and the generation of green electricity.

21.3.4 Shared/Services

The predicted advances mentioned above should enable the operation of huge autonomous car fleets in a manifold and intermodal manner. In urban areas, young people in particular would prefer not to own a car but to be able to hire the transportation they require on a pay-per-use basis. The transportation systems, including cars, envisaged for such a scheme should be ecological, efficient, cheap, and flexible (in terms of mode of usage). Car sharing and ride hailing are becoming increasingly popular in big cities. Many companies already provide transportation as a service, hiring out cars with or without a driver. There is a strong drive to incorporate automated cars into this model to improve the service and optimize costs.

These aspects could lead to an intermodal transportation system that is booked on one platform as a single service; for instance, a trip involving a long-distance flight, an autonomous car ride from the airport to a bike rental facility, and then a bike ride to a hotel in a district in which cars are banned could all be booked in one go as a single service. Huge changes are also foreseen to the transportation of goods. For example, deliveries may be transported by an autonomous truck that passes the goods to a drone stationed within a mile or so of the final delivery address. The drone then delivers the goods directly to that address.

In the next section, we focus on vehicle technology and development.

21.4 Automotive Technology

By far the biggest proportion of all transportation (of passengers and goods) is carried out via the road network, as it is still the most flexible and least expensive way to meet transportation demands (Fig. 21.2). There has been a steady increase in passenger and goods traffic over the years. In this section, we begin by describing the basic technology of, legislation associated with, and development trends in automotive vehicles. After that, trends in automobile body design are discussed, before the automotive vehicle development process is outlined.

21.4.1 Automotive Technology, Legislation, and Development Trends

The automotive industry is a key global industry. In order to compete in the steadily growing automotive market, original equipment manufacturers (OEMs) and suppliers need to generate innovations.

Tougher emission legislation has resulted in a shift from conventional vehicles powered only by an internal combustion engine to more electrified powertrains. As shown in Fig. 21.8, hybrid vehicles contain both an electric drivetrain (with a range of up to 80 km using batteries) with an internal combustion engine (thus increasing the range of the vehicle beyond that achieved using the batteries). The batteries in a hybrid vehicle are charged by recuperation or by the internal combustion engine. If the vehicle can also be charged from a plug socket, it is known as a plug-in hybrid vehicle (PHEV).

A battery electric vehicle (BEV) contains no internal combustion engine; it is driven directly by electrical energy and has a range of up to 500 km. A fuel cell vehicle generates electrical energy by converting hydrogen in a fuel cell to water and energy. This energy is stored in a battery and used to drive an electric engine. The range of a fuel cell vehicle is comparable to that of a vehicle with a conventional drivetrain.

The most important parts of an automobile in terms of technological developments and future challenges are shown in Fig. 21.9; they include the body, chassis, advanced driver assistance system, internal combustion engine, and electric motor. Development trends for these vehicle parts are now described in detail.

Development Trends in Automobile Bodies

The body is not only the load-carrying part of an automobile; it also determines the vehicle's capacity for passenger and/or freight transport, dominates the outer appearance of the vehicle, and has an important influence on safety and driving comfort. The need for passive safety (noise–vibration–harshness, NVH), driving comfort, and dynamics determine the design of the body.

Another aspect of vehicle safety that is growing in importance is pedestrian protection. The introduction of regulations relating to pedestrian protection in Europe and in Japan has already prompted major changes to the design of the front of the body in many car models. As these regulations become increasingly stringent,

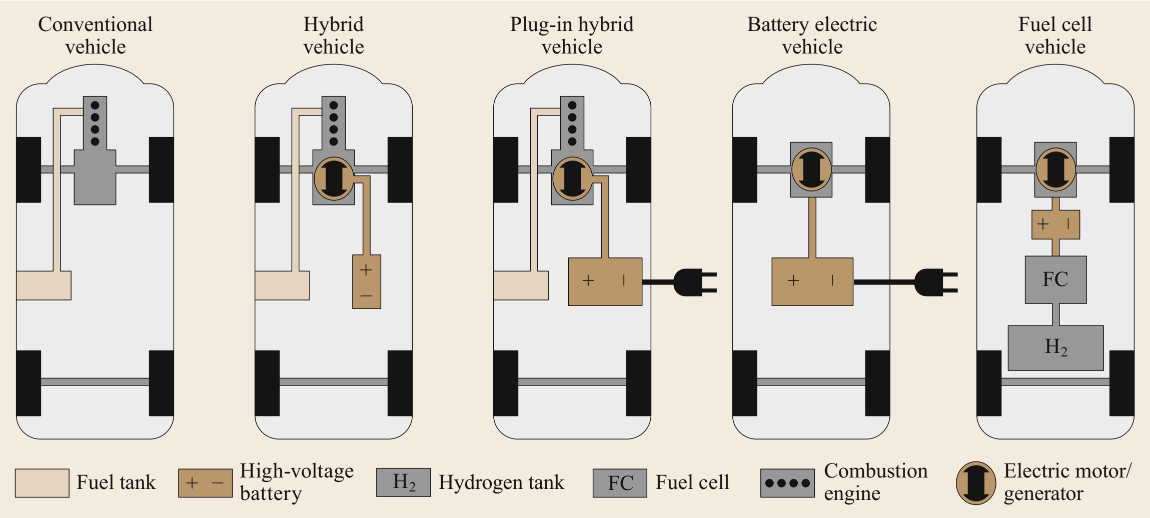

Fig. 21.8 Overview of various powertrain technologies (after [21.9])

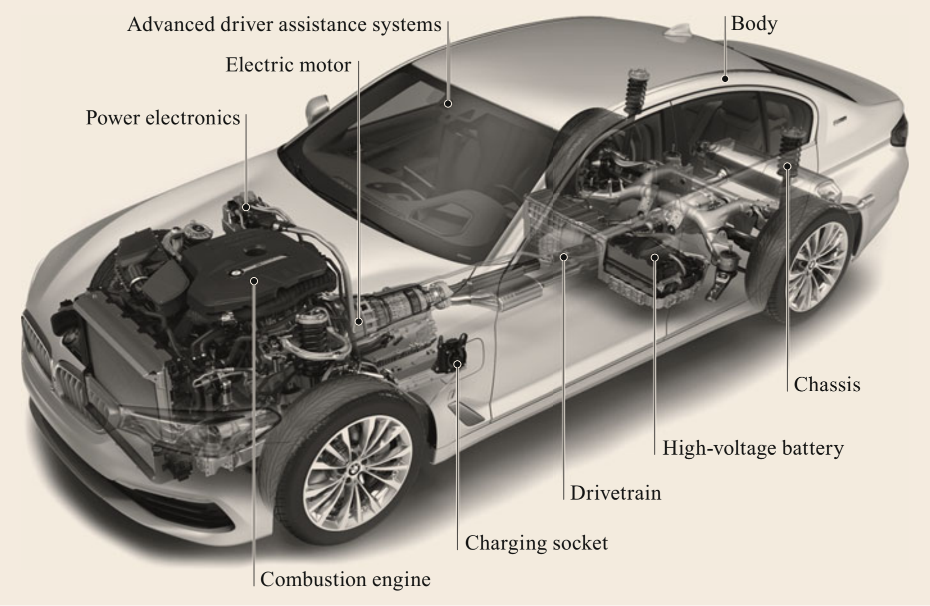

Fig. 21.9 Automobile parts that are currently undergoing prominent technological development; the vehicle shown in the figure is a BMW 5 Series plug-in hybrid (after [21.10])

additional pedestrian safety measures will be launched in the coming years. Moreover, crash compatibility in vehicle-to-vehicle collisions will become an important safety issue in the future, and is likely to influence body design significantly.

While fitting extra safety measures tends to increase the mass of the vehicle, there is a strong drive to reduce vehicle weight in order to improve handling characteristics, driving performance, and—last but not least—fuel consumption and CO_2 emissions. However, over the last three decades, the average unladen weight of a passenger car has steadily increased, despite intensive efforts to produce lightweight body structures. A major challenge in vehicle engineering is to reduce vehicle weight in spite of the push to add extra functionality, the need to fulfill new requirements, and the pressure to keep the cost of a vehicle as low as possible. The standard design concept for high-volume cars is a steel unibody. Substantial improvements in the crash behavior of steel unibodies and weight savings have already been realized through the application of new high- and ultrahigh-strength steels. Rolled profiles and hydroformed tubes are employed due to their superior strength and stiffness in comparison with conventional

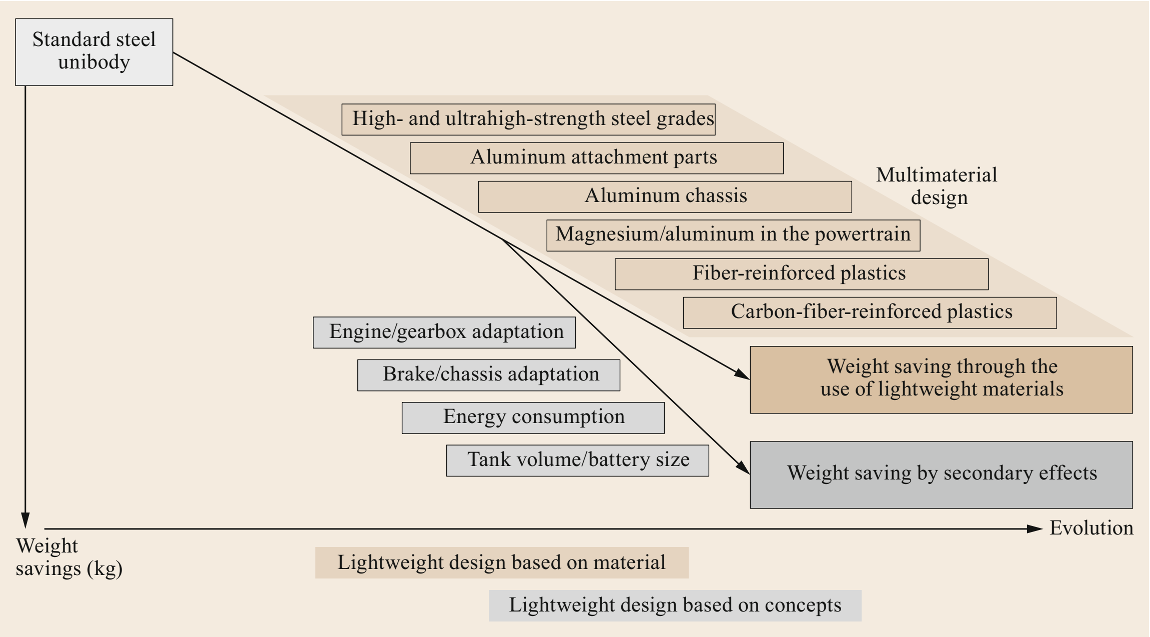

Fig. 21.10 Achieving lightweight vehicles through the application of appropriate materials and concepts (after [21.11])

spot-welded steel-sheet structures. In addition, a trend towards multimaterial design is apparent. In principle, this means that the most suitable material is selected for any particular body component or module, resulting in an intelligent mix of materials such as aluminum, magnesium, (carbon) fiber-reinforced plastics, and of course steel. Reducing the vehicle weight also has knock-on effects that allow even more weight to be saved; for instance, a lighter vehicle can achieve the required driving and braking performance using a smaller engine and gearbox and smaller brakes. Lowering the weight also reduces energy consumption, allowing the use of smaller fuel tanks or batteries to achieve the same range. Applying all of these weight-saving measures, which are summarized in Fig. 21.10, can reduce the vehicle weight by up to 200 kg.

Development Trends in Automobile Chassis

For decades, the trade-off between safety (roadholding) and comfort (soft suspension and noise insulation) presented the greatest challenge to every chassis engineer. However, this trade-off is gradually becoming irrelevant due to the use of adaptive components and active chassis systems. Over the next decade, the cost of electronic systems built into the chassis is predicted to increase fivefold compared to today (Fig. 21.11). As chassis control systems become more intelligent, there is an increasing need for an integrated control strategy. The next step is to link these systems to passive systems.

The electronic stability program (ESP), for instance, can be linked to active steering or electric power steering to allow combined steering and braking input, or to adaptive air suspension or variable damping systems to facilitate roll-angle adjustment. Also, ESP sensors can detect the risk of an accident and activate passive systems. The MacPherson strut (which is used in 85% of all automobiles) and double-wishbone suspension are the most commonly used front suspension types, while twist beam suspension and multilink suspension are the main choices for the rear suspension. Multilink rear suspension is expected to gradually grow in prominence until it is used in over 55% of all automobiles. Advances in braking, steering, and damping systems are facilitating the development of the so-called *dry* chassis, in which hydraulic actuation is replaced with electric motors. This enables greater chassis control and system integration.

Development Trends in Advanced Driver-Assistance Systems

Due to increasing traffic and the growing complexity of driving tasks, technical systems that support the driver and relieve him or her of some of those tasks have been developed. Such advanced driver-assistance systems (ADASs) include systems that automatically stop or accelerate the vehicle when appropriate as well as active safety measures (e.g., those focusing on pedestrian and cyclist safety). To fully realize such systems, further advances in recognition systems (e.g., front,

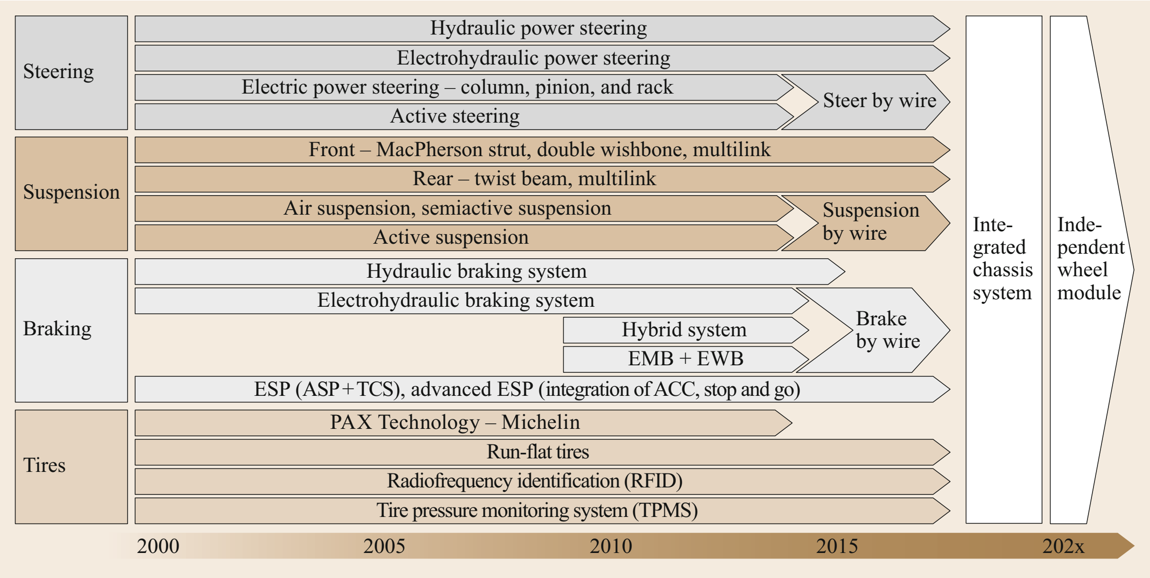

Fig. 21.11 Evolution of chassis components (after [21.12])

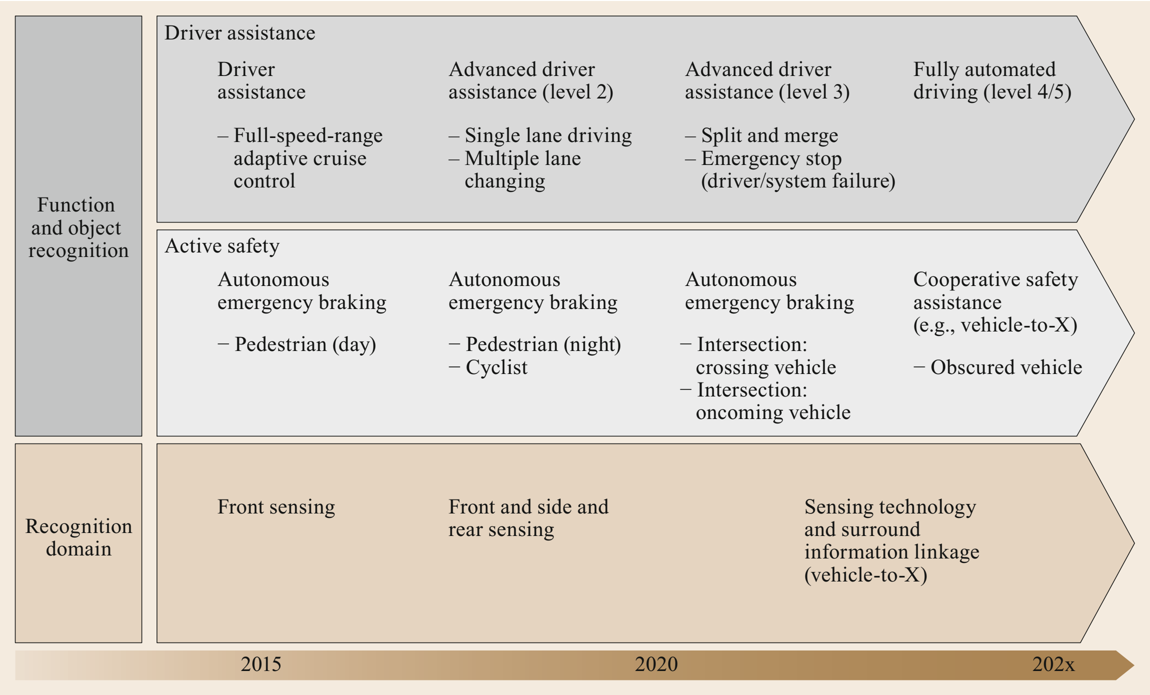

Fig. 21.12 Automation roadmap for advanced driver-assistance systems (according to [21.13])

side, and rear sensing and vehicle-to-X communication) are necessary. The long-term goal is to fully automate driving in order to increase safety and avoid accidents. The automation roadmap for ADASs is shown in Fig. 21.12.

Development Trends in Internal Combustion Engines

Figure 21.13 provides an overview of current development trends for internal combustion engines. The overall aim is to reduce fuel consumption and thus

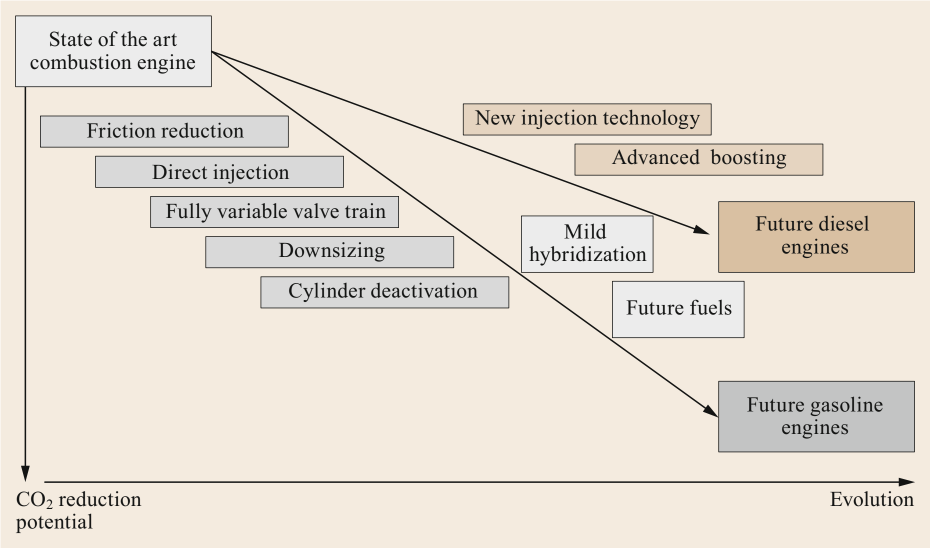

Fig. 21.13 Techniques for reducing CO_2 emissions from combustion engines (according to [21.14, 15])

CO_2 emissions from diesel and gasoline engines. The main targets of gasoline engine development are direct injection combined with advanced boosting strategies, increased variability (e.g., a variable valve train and a variable compression ratio), cylinder deactivation, and an increased level of mild hybridization (increasing the onboard power supply in the car from the current standard, 12 V, to 48 V enables more electrical energy to be recuperated, supporting the internal combustion engine and thus reducing fuel consumption and CO_2 emissions). For diesel engines, research and development is focusing on advanced injection systems (increased injection pressures and higher degrees of variability), boosting technology, and an increasing level of mild hybridization. Additional improvements to both gasoline and diesel engines should be possible through the use of future fuels, such as tailored fuels produced from biomass.

Development Trends in Electric Drives

Electric vehicles are still more expensive than conventional vehicles with internal combustion engines. In addition, they have significantly smaller ranges. These two factors are the two biggest challenges to the widespread adoption of electric vehicles. However, battery costs have substantially decreased recently (they have dropped by about 50% over the last 8 years), while battery energy density and thus the average range of an electric drive have markedly improved (on average by about 100% over the last 8 years; an increasing number of electric cars with a minimum range of over 300 km are now on the market or have been announced by manufacturers). Figure 21.14 implies that these two trends are likely to continue in the future. Therefore, even though there is still a huge gap in price between internal combustion engine powertrains and electric vehicles, this gap is gradually decreasing.

Another factor in the widespread adoption of electric vehicles is the charging process and infrastructure. The recharging process needs to be fast and easy to perform, just like refueling a conventional gasoline- or diesel-powered car. This means further technical advances that enable a high charging power are required. In addition, recharging stations must be easy to find and readily available, similar to gas stations today.

21.4.2 The Automotive Vehicle Development Process

The standard development process for a vehicle, as shown in Fig. 21.15, takes about 5 years, although it can be shorter or longer depending on the technical changes required and whether it is a completely new model or it is derived from an existing model. Generic processes such as strategic discussions and decisions, research into new technologies, and innovation management are always underway at an OEM. These inputs are available at milestone 0, the start of the product development process. During the following 6 months, the exact product goals and a rough product definition are established. Inputs at this stage include legislative issues such as emission thresholds and safety standards as well as customer requirements. The activities of competitors are also considered. When this stage is finished, i.e., the goals and the product have been defined, milestone 1 has been achieved. After that, further 6 months are devoted to precisely defining the product concept that fulfills the agreed goals. The rough product defini-

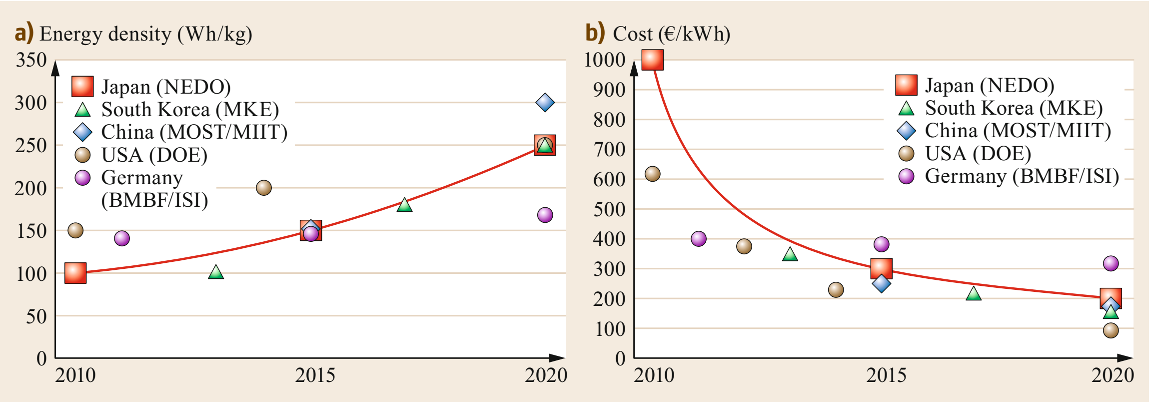

Fig. 21.14a,b Plots showing how **(a)** Li-ion battery energy density (Wh/kg) targets and **(b)** Li-ion battery cost (€/kWh) targets of various countries involved in the development of large-scale third-generation Li-ion batteries for application in BEVs/PHEVs have evolved since 2010. Note that the data were derived based on different definitions of market maturity and different numbers of units (e.g., some data were obtained based on battery prototypes with only a small number of units, while others were obtained based on a larger number of batteries comprising a market-entry/small-scale series) (after [21.16])

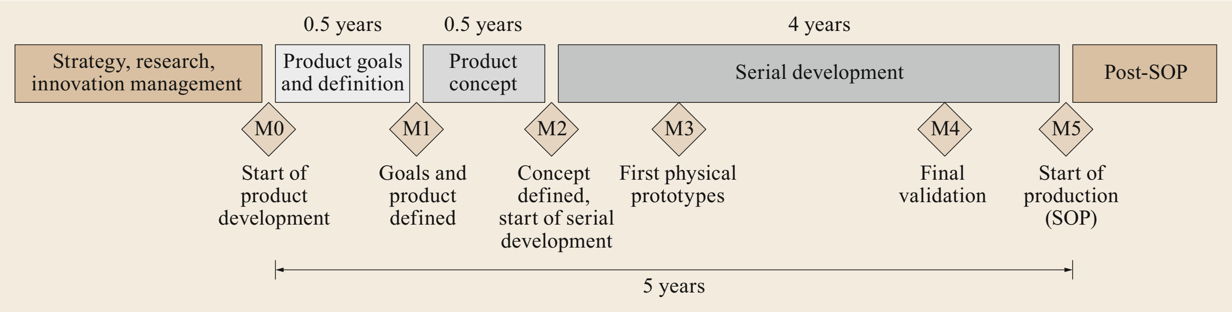

Fig. 21.15 The development process of a car (after [21.15, 17])

tion produced in the previous stage provides additional guidelines. At the end of this phase (milestone 2), the concept has been defined in detail and serial development can begin. Concrete constructions are realized, including a production concept, and negotiations with suppliers are initiated. The first physical prototypes are created (milestone 3) to test the product. At the end of the serial development process, a final validation is carried out (milestone 4) to check the quality of the final concept; then, assuming that the product is validated, the process moves to milestone 5, the start of production (SOP). The serial development process takes about 4 years. After that, post-SOP activities are carried out, such as facelifts of the product.

We now move on to describe aerospace technology and development.

21.5 Aerospace Technology

The wealth of modern society is based on the fast and reliable transport of information, passengers, and freight in an environmentally acceptable way. Products of the aerospace industry are a crucial element of the global transportation system: satellites provide weather information and navigation signals and transmit messages worldwide; aircraft permit the fast and safe transportation of passengers and/or freight across borders; and military aerospace technology is an important part of any military strategy. In commercial terms, the future of aviation is bright: passenger traffic has been increasing at a stable rate of around 5% per year for three decades, and this trend is forecast to continue for the next few decades; cargo transportation is growing at a faster rate, around 6% per year. From Fig. 21.2, it is apparent that the number of passengers that are transported annually by aircraft surpassed the number transported annually by rail and public transport in 2015. In this section, aerospace technology, legislation, and development trends are explored. The aerospace development process is also described.

21.5.1 Aerospace Technology, Legislation, and Development Trends

In the following, the relationship between aerospace technology and society is considered, especially from the perspective of pollution and noise. After that, different aerospace disciplines are described, and then challenges in aeronautical engineering are discussed and analyzed by dividing the historical development of this field into four different phases.

Aerospace Technology and Society

Space vehicle launches are undeniably spectacular, but they are limited to only a few locations in the world. Therefore, the public takes considerable interest in these launches, because it is linked to that dream of mankind mentioned before. On the other hand, even though aircraft are also part of that dream and are mandatory for modern life, they tend to receive greater criticism than many other modes of transport. Whereas, for example, railway noise is generally accepted (even in city centers at midnight), aircraft noise is often said to be annoying, even when it is barely noticeable. The public has largely accepted the drawbacks of all other forms of traffic, but noise and emissions from aircraft seem to generate a disproportionate amount of irritation considering the contribution of air travel to the overall transport system. This may be due to the fact that the human desire to fly is rooted in observations of birds soaring in the sky, which they appear to do with an elegant ease and weightlessness. Thus, people react more sensitively to aircraft noise and pollution than to pollution from any other means of transport. In reality, much progress has been made in this area in recent decades. Noise from aircraft has been drastically reduced, with the aim being to keep most of the noise contour within the airport area (Fig. 21.16). For instance, the Airbus A350-900 has a 40–50% smaller noise contour than its predecessor models (the A-340-600 and A340-300). Exhaust emissions have also been decoupled from the number of aircraft, as illustrated for aircraft of the Lufthansa Group in Fig. 21.17. However, the overall fuel consumption of aircraft is still rising.

As in other fields, the tasks involved in aerospace engineering can be discussed from various perspectives. We can consider the work of specialists in many fields, or we can adopt a system approach in which various disciplines contribute to the creation of increasingly complex components up to the level of the final vehicle. Finally, we can also employ a *system-of-systems* approach when contemplating the air transport system (ATS). In astronautics, this system-of-systems approach includes the vehicle, payload, transfer, and ground support. In any case, the overall lifetime of the aircraft must be addressed, from its first flight or launch to the period in which it is operating as envisaged and finally to the disposal of the aircraft. The disposal process is becoming increasingly important in both aeronautics and astronautics due to the need for global resource management and the issue of space debris, respectively.

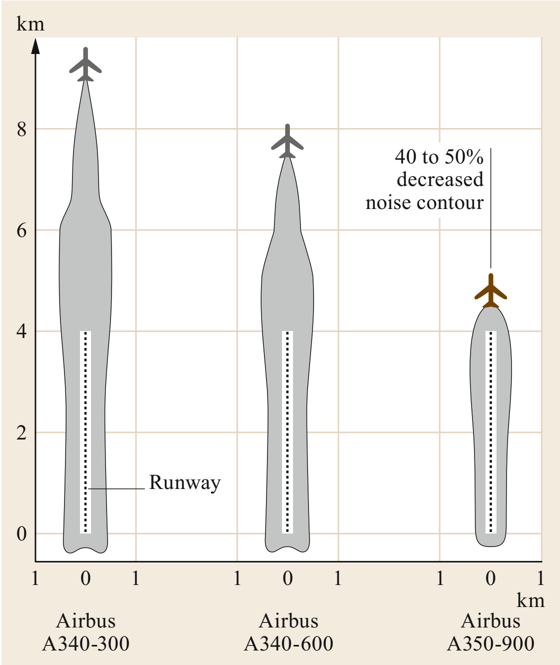

Fig. 21.16 Noise contour of a state-of-the-art Airbus A350-900 as compared to those of its predecessor models, the A340-300 and A340-600 (after [21.18])

Aerospace Disciplines

Aerospace in general is an integrated or so-called integration subject that includes aeronautics and astronautics as particular activities. Aircraft design is carried out based on inputs from the fundamental engineering disciplines of aerodynamics, structures, and systems, which in turn include flight mechanics, statics, kinematics, and other subdisciplines. In addition, combinations of those fundamental disciplines have emerged, such as aeroelastics and aeroacoustics. Advances have been made in all of these disciplines, such as new flow control methods, new materials, and new electronic systems. Components are designed and created based on

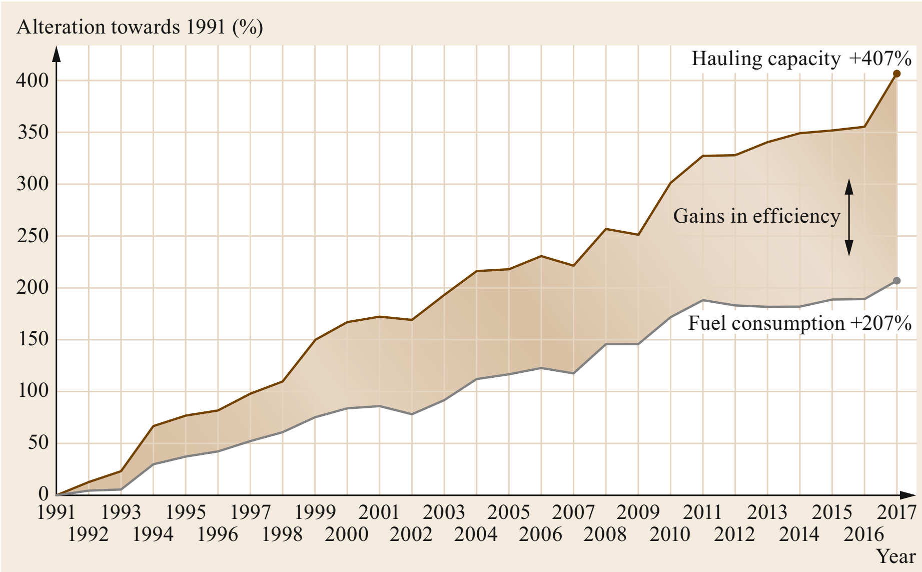

Fig. 21.17 Decoupling of fuel consumption from hauling capacity for the fleet of the Lufthansa Group since 1991 (after [21.18])

work done in the individual disciplines. This process is an interdisciplinary task; for example, a knowledge of aerodynamic performance and structure, including the kinematics and actuators on the systems side, is required when developing an aircraft flap. In aeronautics, the largest components are the complete aircraft structure and the engine, which are developed and manufactured separately.

The development of components and the process of combining those components to construct an aeroplane are multidisciplinary and interdisciplinary tasks. New aircraft are constructed from materials and components generated by monodisciplinary research (such as new materials, new actuators, or a specific aerodynamic vortex generator) and from integrated technologies. For example, fly-by-wire technology was required for the European supersonic airliner Concorde in the 1960s. Without this technology, it would not have been possible for pilots to fly Concorde in various flight regimes (e.g., taking off, cruising, and descending), given that the control behavior of the aircraft changes with the flight regime. Afterwards, this immature technology was introduced into the Airbus A310; then, when the technology had matured, it was fitted to the Airbus A320, which made its maiden flight in 1987.

Flow control technology and artificial instability are other examples of technological development in this field, and manufacturing technologies such as friction steel welding, laser beam welding, advanced bonding, and surface coating have been developed and are now part of the production process.

Following complete vehicle assembly, the aircraft is then operated in a diverse system.

Aircraft navigate with the aid of air-traffic control, and they are linked to other traffic in the air and on the ground, especially in the vicinity of airports. They need to be loaded and unloaded. They are also included in the concept of intermodality, in which personal and public ground transportation is linked to air or sea transportation.

Challenges in Aeronautical Engineering

The history of aeronautics can be divided into three phases. During the first phase, which lasted from the inception of aeronautics until the end of World War II, the main aim was to gain a physical understanding of powered flight. This began with daring pilots in *fantastic flying machines* who were constantly trying to break range, speed, and altitude records. The next phase coincided with the introduction of jet engines and the emergence of commercial aeronautics. Many different aircraft configurations were studied, including vertical take-off and landing (VTOL) aircraft such as the Dornier Do 31, supersonic transport such as Concorde, and flying wings such as the Northrop YB-49. This led to the third phase, corresponding to a mature commercial aviation industry based on aircraft that all look rather similar regardless of the manufacturer. This optimal aircraft configuration is the pay-off from all of the expensive civil aircraft design and manufacturing studies performed in the previous phase.

Due to the success of commercial air transportation, three other issues have emerged. First, airports are more often operating at their capacity limits, so it is questionable whether it is possible for air traffic to increase, even if there is a demand for it. The second issue is linked to this: even though the contribution of aviation to global emissions is relatively small (about 2%), it is still the focus of intense debate. The third issue is that of safety, which is becoming an increasingly important topic in aviation, and is one that is again linked to the growth of air transportation. The current reliability rate for critical aerospace components (10^{-9} failures per flight hour) will not be sufficient if the number of aircraft doubles within a decade. In order to reduce the number of accidents as the number of aircraft increases, functional hazard analysis must become more reliable. This must be achieved for single components such as an actuator, subsystems such as an aileron, and the complete aircraft system and structure.

These issues are addressed by the European Commission in its *Vision 2020* on aeronautics and by the National Aeronautics and Space Administration (NASA) in its *Aeronautics Blueprint*. Both draw similar conclusions: given the importance of air transportation to the wealth of society on the one hand and the environmental issues that are linked to the aviation industry on the other, additional top-level aircraft requirements (TLAR) will be required to balance transport needs with societal needs (i.e., safety and security) and environmental protection. These additional TLAR may lead to different aircraft configurations as well as new ways of operating them. In addition, a system approach is needed to address these issues; for example, in contrast to road and rail transport, security will play an increasingly important role in commercial aviation. There are an increasing number of studies of seamless air transport, which will require new ground procedures and probably new aircraft designs. Defining the new TLAR and ensuring that the overall vehicle and system composition complies with those TLAR will be a demanding task for all aerospace disciplines, including both aeronautics and astronautics. With the implementation of the new TLAR, we can expect a fourth phase to begin: *sustainable growth*.

21.5.2 The Aerospace Development Process

Just like other product development processes, the general process of designing an aircraft or spacecraft has been established over the past few decades. Initially, there is a market analysis that searches for desirable products that are currently missing from or understocked in the market. In aeronautics, this may be defined by the so-called *transport task*, i.e., the requirement to move a given payload across a given distance within a given time. In astronautics, aside from the vehicle, the payload itself (such as a satellite) may be the product that needs to be developed. The TLAR can then be derived from these general requirements set by market demands, and these TLAR provide the basis for future project office (FPO) work. The general arrangement (GA) of the vehicle to be designed is then derived using tools based mainly on statistics and/or simple calculation methods. This GA will then be passed to various departments, such as flight physics or structures. Together with aircraft program management, they will start developing components using test rigs or simulators and by performing wind tunnel tests. At this stage, new technologies that have been made available by various disciplines can be included in the design process. Digital mock-ups (DMU) are increasingly used in the first part of the development phase instead of hardware.

When the GA and first performance estimates are available, launching customers must be found. The needs of those customers will influence the final design. When a certain number (which depends on the product size and cost) of products have been sold, the actual development of the product begins with the program *go-ahead*, which occurs almost in parallel with the production of the first parts. Specific tests will be carried out on prototypes, which may require some final (hopefully minor) changes in the design. The last step is the certification process, which ends with product entry into service (EIS). The overall development process as outlined above is almost the same for any aircraft manufacturer, and can be seen as a series of milestones, as shown in Fig. 21.18.

At present, the market analysis stage can last for 2 years, the predevelopment stage for 3 years, the development and manufacturing stage for about 5 years, and the certification stage for another year. Just before a program is initiated, technology development may be carried out, with technological feasibility considered in a first step and technology application studies performed in the final step. Overall, the time between the first suggestion that a new aircraft should be developed and the EIS is approximately 10–15 years. For example, the first document proposing what would become the Airbus A380 was published in 1989; at that point the proposal was for an ultra-high-capacity aircraft (UHCA) called the Megaliner. Later it became the Very Large Commercial Transport (VLCT), a joint feasibility study by Airbus and Boeing. The committed program started in 2000, and the A380 was finally introduced into airline service in 2007, corresponding to a total of 18 years of development. Of course, all manufacturers try to speed up this process. Further optimization of the development process for aircraft based on the already highly optimized standard configuration (i.e., fuselage, wing, engines, and tailplane) is possible mainly through improvements to the design chain, including supplier management.

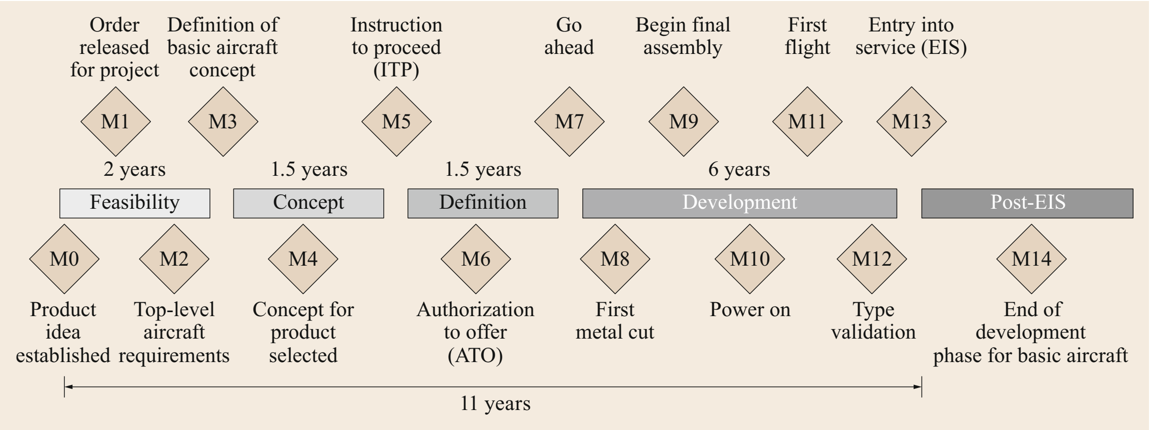

Fig. 21.18 Development process for an airplane

21.6 Rail Technology

As shown in Fig. 21.2, the amount of goods and people transported by rail in Europe has remained stable for a considerable amount of time. In this section, we discuss the basic technology and legislation associated with rail transportation and we consider the development of vehicles used in rail transportation.

21.6.1 Rail Technology, Legislation, and Development Trends

The main difference between rail and other means of transportation is the automatic guidance of rail vehicles along the track, which leaves only one degree of freedom for any rail vehicle—its velocity. This automatic guidance from the track keeps the vehicle on a particular course defined by the rail infrastructure, but it also means that it is not possible for the vehicle to sidestep other rail vehicles spontaneously; rail vehicles can only pass each other at specially equipped locations along the track. To prevent system deadlock, it is necessary to implement a schedule of rail vehicle movements—a timetable. Together with the timetable, there is a need for a protection system that prevents head-on collisions of trains on the same track.

Efficiency, Resistance, and Traction Forces

One advantage of using a railway schedule is that trains can run almost nonstop from one station to another (as long as the schedule works properly!). Thus, long and heavy trains can be operated in an energy-saving manner as they do not have to perform multiple accelerations and decelerations between stops. This is also important because the traction needed to accelerate a train must be generated from the friction between the wheels and the track, meaning that the acceleration of a train is limited. The frictional coefficient between rolling steel bodies is always correlated with the relative velocity (slippage) between the bodies (Fig. 21.19). The maximum coefficient of friction for steel wheels on dry rails is about $f_x \approx 0.45$; if the rails are wet or polluted, this can decrease to $f_x \approx 0.1$. This also means that a maximum deceleration b (where all wheel axles are braked) of $\approx 1\,\mathrm{m/s^2}$ can be achieved, as shown below.

$$\begin{aligned} F_\mathrm{B} &= mb = f_x mg \\ \Rightarrow\ b &= f_x g = 0.1 \times 9.81\,\mathrm{m/s^2} = 0.981\,\mathrm{m/s^2} \end{aligned} \tag{21.1}$$

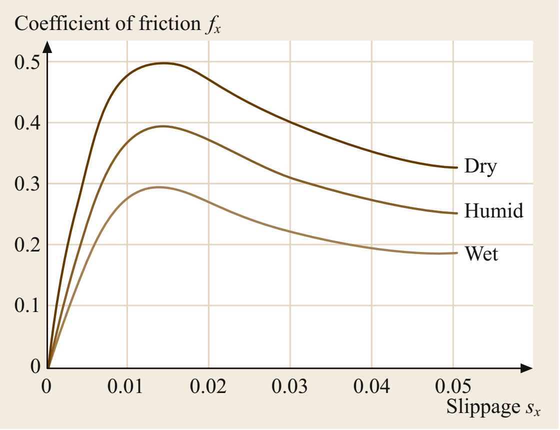

Fig. 21.19 Coefficient of friction of steel wheels on a dry, humid, or wet steel railway track

Table 21.1 Rolling resistances of different vehicles ($F_R = f_R mg$)

Wheel type	f_R	Example of contact pair
Heavy rail	0.002	Intercity train on track
Light rail	0.008	Tram on tram track
Tire	0.01	Tire on tarmac
Tire	0.2	Tire on unfortified road
Tire	0.007	Racing bicycle on tarmac

Besides the traction, the maximum acceleration depends on the number of powered axles and the friction conditions. For passenger trains, this problem is increasingly being solved through the use of multiple train units in which the traction is distributed across the whole length of the train. Freight trains are still equipped with conventional locomotives, meaning that only four or six powered axles pull the entire train. Once a train is in motion, the low frictional force of the wheel–rail contact is highly advantageous due to the low rolling resistance of steel on steel. Compared with road transportation (in which rubber tires are rolling on tarmac), resistance is marginal, which is especially useful for transporting heavy loads. Therefore, only a small amount of traction is needed to keep the train moving when it reaches its cruising speed (Table 21.1).

Guidance

Automatic guidance is another effect of the wheel–rail interaction. A conventional wheelset (i.e., a pair of torsion-resistant wheels fixed on a shaft) is guided by an effect called *sinusoidal movement*, which is caused by the wheel profile. In a simplified approach, wheel profiles can be regarded as conic, so that deflection of the wheelset causes the wheels to have different circumferential speeds. Together with the slippage–adhesion correlation, this leads to different traction forces on both wheels and thus a turning torque acts on the wheelset. As shown in Fig. 21.20, this torque on the wheelset always acts to push the deflected wheelset back towards the centerline of the track. After passing the centerline, the direction of the torque will change such that it will push the wheelset back into an offset position that is aligned with the centerline of the track. The whole deflection process will then start again, albeit in the opposite direction. The resulting motion of the wheelset with respect to the track's centerline is wavelike (i.e., sinusoidal).

Besides this desired effect (guidance), the sinusoidal movement causes lateral forces that disturb the comfort of passengers riding on the rail vehicle and can lead to the derailment of the wheelset when a certain velocity is exceeded. To achieve higher speeds and to increase riding comfort, it is therefore necessary to damp this sinusoidal movement. As sinusoidal movement always coincides with slippage and tangential forces, energy dissipation from noise and wear will occur. The vast majority of rail vehicles are equipped with wheelsets; however, a few rail vehicles have single wheels that are independently joined to the axle (Fig. 21.21). Here, guidance is achieved by geometrically induced forces. The inclination of the wheel profile increases towards the wheel flange. When the wheel flange approaches the rail, the lateral normal force between the wheel and rail will be greater than the lateral normal force for the opposite wheel, as the flange of the latter is further away from the rail and thus the inclination of the wheel profile is smaller. Therefore, the pair of wheels are pushed back towards the centerline of the track.

As a single wheel does not need an axle connecting it to another wheel, single wheels are primarily used in trams to facilitate a low-floor design without any steps between the wheels. Only the Spanish manufacturer Talgo provides vehicles with single wheels that are in-

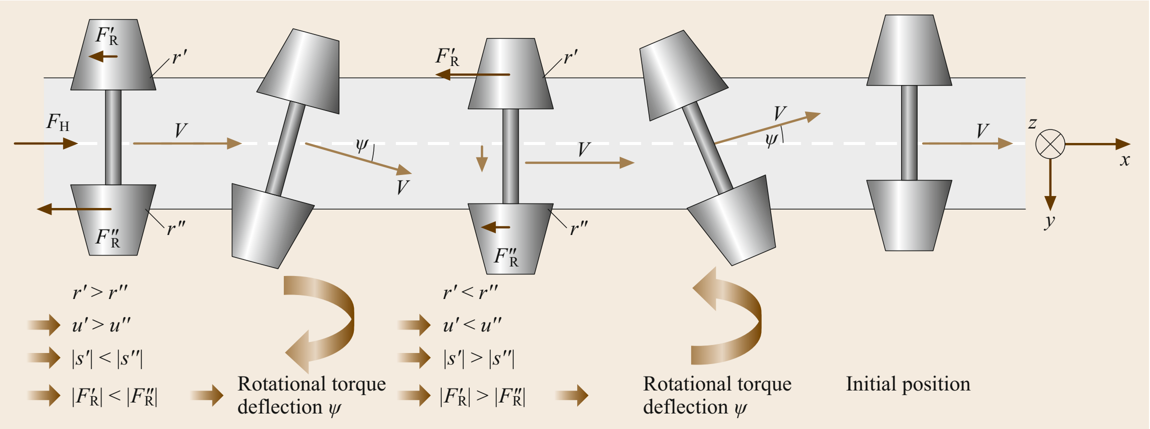

Fig. 21.20 Sinusoidal movement of a (powered) wheelset (circumferential velocity u > translational velocity v)

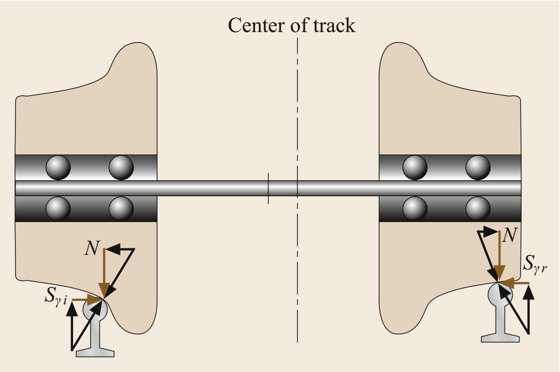

Fig. 21.21 Guidance of single wheels along a railway track

tended for heavy rail applications; here, the advantage is that the single wheels result in smoother guidance along straight tracks due to the lack of sinusoidal movement.

Braking Systems

Because rail vehicles are automatically guided, the system's safest state is at standstill. Therefore, railways are designed to default to a standstill in the case of a severe failure. Braking systems play a major role in achieving this failsafe behavior, so the braking systems themselves must also exhibit failsafe behavior. In the past, braking systems have been improved after almost every serious rail accident to prevent the specific failure that led to the accident from occurring in the future. This has, in turn, led to the current situation in which railway brake regulations are very strict, rendering almost any technical solution other than pneumatic brake systems inapplicable.

One of the main characteristics of a pneumatic railway brake is the main air pipe (MAP), which is a pressure line that runs along the full length of the train (Fig. 21.22). The pressure within the main air pipe controls the driver's brake valve such that, for detached brakes, the maximum pressure is 5 bar. To apply the brakes, the pressure in the pipe is decreased and the distributor valve transmits the pressure of the reservoir to the brake cylinder. This engineering methodology makes the train failsafe: a loss of energy within the MAP causes the brakes to be applied.

Two different devices are used to convert the pressure in the cylinder into a braking torque. For ordinary rail vehicles, a tread brake is used, where a brake pad is pressed directly onto the running surface (the tread) of the wheel. However, this causes wear and ripples on the running surface of the wheel, which lead to a noisier rail vehicle during use, and the thermal energy that must be absorbed by the brake when it is applied can damage the wheel. For passenger cars, the braking torque is usually generated by a disc brake, where two brake pads are applied to a disc mounted on the wheelset. This eliminates the chance of causing mechanical damage to the wheel upon applying the brake, but damage can still be induced if the brake locks up and forces the wheel to slide on the rail, as this can cause the wheel to be planed. Wheel-slide protection (WSP) is therefore needed to avoid wheel flats.

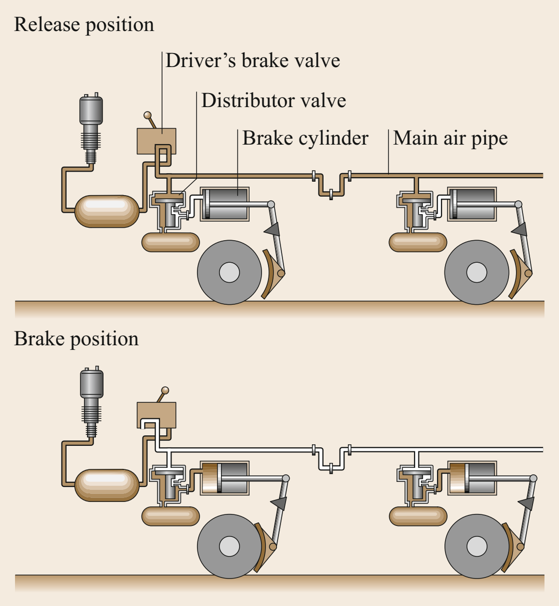

Fig. 21.22 Pneumatic braking system used in rail vehicles

Its failsafe behavior aside, the pneumatic brake has various disadvantages, including its relatively long response time. Not only does it have poor controllability for purposes such as WSP, but braking performance also suffers due to the length of time it takes for the pneumatic signal to reach the last car (for freight trains, a delay of approximately 30 s until the last car has reached full braking performance can be expected). To improve the performance of a conventional pneumatic brake, passenger trains are usually equipped with additional braking devices such as electropneumatic brakes, in which the brake signal is transmitted electronically to achieve better response times. Furthermore, powered cars are equipped with regenerative brakes and retarder brakes to increase the efficiency of and decrease the wear and thermal stress on the brakes.

Train Protection and Management

As mentioned above, a train schedule must be imposed to protect the system from deadlocks and to make sure that there is only one train per section of track. Also, to ensure safe operation when trains are not running on time, a train protection system is applied. Interlocks ensure that a train cannot enter a section that is al-

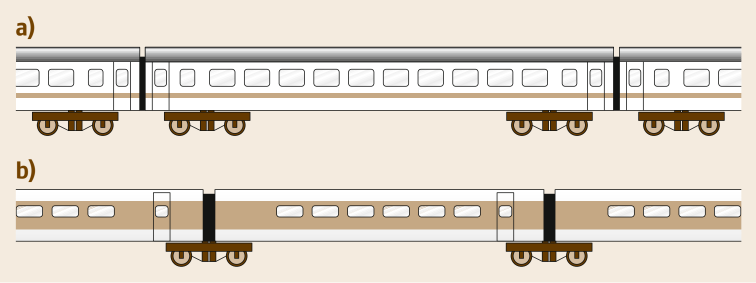

Fig. 21.23 **(a)** Conventional passenger car. **(b)** Passenger car with Jacobs bogies

ready occupied by another train. Entry to each section is guarded by a signal that allows or denies access to the block. As a crash is hard to avoid once two trains are on the same track, railway signals are even more important to rail safety than traffic lights are to road safety. To avoid human mistakes, railway signals are equipped with automatic train protection devices that can stop a train automatically if the driver does not react properly to a signal. These systems can differ from country to country and thus restrain international rail traffic. Because of their long stopping distances, trains cannot stop within their range of visibility. Thus, approach signals are installed several hundred meters before an event to give the engine driver ample time to adjust to the upcoming event. As the train has to come to a standstill within the approach distance to the main signal, this distance has to be the stopping distance of the train, which is one parameter that defines the maximum allowable speed of the train, along with the minimum curve radius of the track. To ensure passenger comfort and to prevent cargo from slipping, the maximum lateral acceleration of a train is limited to $1.0\,\mathrm{m/s^2}$.

Rail Vehicle Structure

The appearance of a rail vehicle is primarily dominated by the car body. The size of the car body is determined to a large extent by the rail infrastructure: the maximum height and width of the car must be within the clearance outline and the distance from the track that is guaranteed to be free from obstacles (e.g., platforms, bridges, and signal posts). As the vehicle must also travel along curves with specified clearance lines, the length of the vehicle is defined by these parameters. A rail vehicle must be designed such that it does not touch the clearance line, even on narrow curves. This has led to the establishment of typical dimensions for a passenger car running on European standard-gage tracks: a length of 26.4 m, a width of 3 m, and a height of 4 m. Such cars are usually carried by two bogies with two axles each.

Furthermore, the mass of a rail vehicle is limited by the permitted axle load. In Europe, the load is usually limited to 22.5 t per axle, meaning that a conventional four-axle car has a maximum weight of 90 t. Passenger cars and freight cars with small payloads may, however, use different axle arrangements to reduce the tare weight by minimizing the number of axles. Aside from the four-axle car, the most common type is the articulated train with Jacobs bogies, where two car bodies share one bogie (Fig. 21.23). The disadvantage of this arrangement is that the bodies can only be separated in the workshop, as the link to the bogie replaces the coupling between the cars.

Coupling

The most obvious use of a coupling is to create a detachable connection between cars. Couplings are also used to transmit longitudinal forces within the train and to prevent the train from being exposed to forces that exceed its specifications. If tensile forces become too high (e.g., if the pulled train is too heavy), the coupler will break; if compressive forces are exceeded (for example during a crash), the coupling can absorb some of the energy. Another important function of a coupling is data transmission. Conventional couplings only transmit the pneumatic signal and energy of the brake's main air pipe. For passenger cars, there is also an electric coupling that links the car to an energy supply and various types of signal cables. A manually operated screw coupling that offers the ability to combine all cars without limitation is used as standard in Europe. This standardization compensates for the disadvantage that this type of coupling cannot be automated. In Europe, automatic couplings are only fitted to multiple-unit passenger trains that must only be coupled to other units of a similar type. In the US and in countries that were formerly in the USSR, automatic couplings are also used for conventional passenger and freight trains.

21.6.2 The Rail Vehicle Development Process

Figure 21.24 shows a idealized development process for a rail vehicle. At the start of the process, the requirements aligned with those of the potential customer (usually a big railway undertaking). Milestone 1 is reached if the offer and the requirements are clear. Then the process enters the concept phase, which finishes at milestone 2,

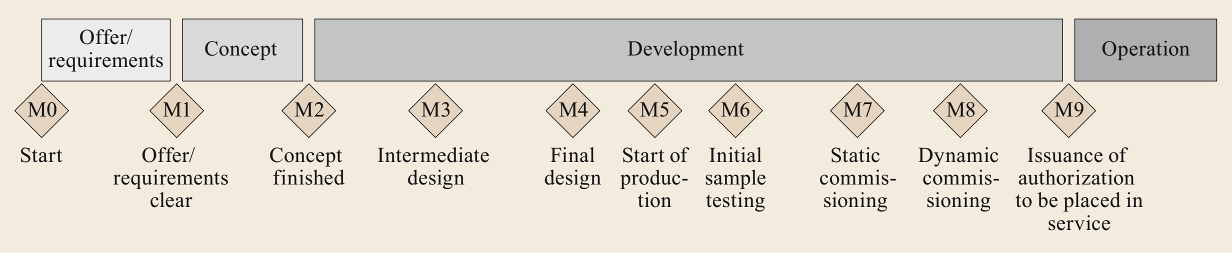

Fig. 21.24 Development process for a rail vehicle (after [21.19])

when the concept has been fixed. After that, the development phase can start. At milestone 3, an intermediate design has been developed. The final design is then fixed (milestone 4), and production of the rail vehicle is initiated (milestone 5). The beginning of the production process includes the initial sample testing (milestone 6). The development process then continues until static vehicle commissioning is performed to check that all of the functions of the vehicle work (milestone 7). If this vehicle function check is successful, dynamic commissioning is implemented (milestone 8). If all further tests carried out during the development process are successful, milestone 9 is reached, at which point the vehicle is authorized to be placed in service. After that, the vehicle can be operated with regularly scheduled maintenance by the railway undertaking. As the length of the development process is largely dependent on customer requirements and technical details, it is difficult to pinpoint the typical length of the rail vehicle development process.

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