23. Railway Systems–Railway Engineering

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Railway travel is the smallest mode of transport but is becoming increasingly important. Urbanization needs more powerful urban rail systems, while intercity traffic needs fast, reliable, and high-performance long-distance train systems. Also, transport of freight by rail over long distances is increasing. The reason for this is the high transportation capacity with small infrastructure cross section because of their guided nature and high energy efficiency based on low running resistance and regenerative braking, which can transform kinetic energy into electric power with very high efficiency. Also, green electric energy can be used directly.

This chapter argues that railways require good organization not only in operation but also in the construction of vehicles and infrastructure. Special subjects such as wheel–rail interactions are introduced. The basic functions of different elements such as tracks, bogies, bodyshells and their subparts including gearboxes, wheelsets, doors, air conditioning, pneumatic brake systems, etc. for mainline (passenger and freight), metros, and trams are presented using up-to-date examples with modern and widespread applications. Also, safety and environmental issues such as airborne noise reduction and type testing are tackled.

23.1 General Interactions of Modules of a Railway System with Surroundings

Railways have many technical and economical interfaces with their surroundings, as indicated in Fig. 23.1. The aims of a railway are usually defined externally, based on policy and economics with the consideration of markets, finances, and the environment. These aims are then transformed into strategies by the management of a railway company, who will provide instructions to several subareas such as marketing to define the product in terms of timetable and comfort. The timetable provides lots of information; it defines the locations to be connected and the distances to be overcome. By defining the times of departure and arrival, the travel speed is fixed. Also, the frequency of operation of the trains is defined.

The operation of a railway must be able to fulfill these requirements by providing adequate, educated

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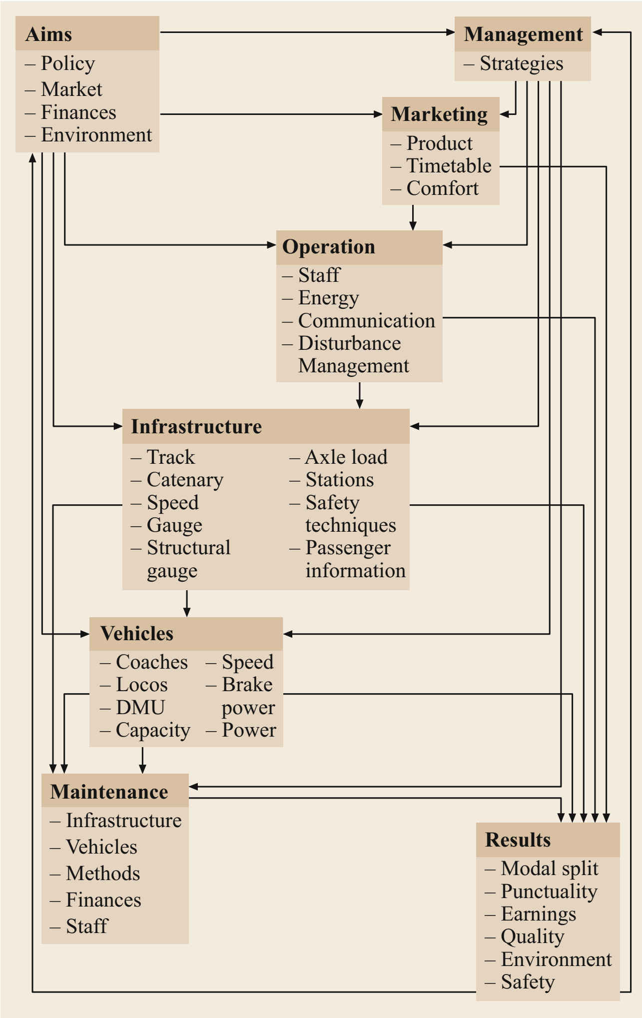


Fig. 23.1 Railway transportation—a system with strong interference

staff on trains and at fixed locations. Also, the energy to move the trains must be provided at the right locations. Communication must be enabled over one or even several lines with many trains. If the schedule fails, disturbance management must be able to restore the system to proper operation as soon as possible, whether the failure is caused for exterior or interior reasons.

Infrastructure such as tracks, perhaps catenary, the design speed of the track and its gauge, the structural gauge, the axle loads, and stations for passengers and/or loading/unloading facilities for goods must all fit the demands of the system. Information technologies for passengers are also gaining in importance.

The type of vehicles chosen must be adequate for the required operation, for instance locomotives, coaches or diesel multiple units (DMUs). The vehicles must fit the infrastructure and its operation in terms of speed, axle load, etc.

Maintenance must provide reliable system elements to avoid failures because of the effects of wear. Maintenance is increasingly being outsourced today.

If all of the elements shown in the boxes on the diagonal in Fig. 23.1 are provided by one company, the system is called an integrated railway; otherwise, it is known as a segmented railway.

The interaction of these elements produces results in terms of earnings and the quality of the process (for example, punctuality).

Because of high cost pressures, the aim for an economically sound railway system is to run as fast (km/(vehicle of the fleet × day)) and reliably as possible.

A high number of kilometers per vehicle in the fleet is important, as the costs for vehicles, stationary equipment, and operational staff are a function of time, whereas the earnings from passenger and freight traffic is more or less a function of distance. Also, fast running in the form of fast point-to-point transportation is itself attractive for passengers and goods.

Good reliability reduces the number of spare vehicles and spare staff required and also reduces the operational risk. Of course, this is also an important quality measure for clients in passenger and freight operations.

Rail vehicles must therefore be designed according to these requirements.

23.1.1 Duration of Passenger Exchange

As the stopping time has a negative effect on the aim mentioned above (covering as long distances as possible per vehicle and day), it should be as short as possible, which results in many technical and operational constraints.

As an example, the different elements or modules that define the stopping time of a train are shown in Fig. 23.1.

The duration of stops (intermediate stops and in the terminus/stations) is affected by the following parameters:

1. The height difference between the platform and train level, which should be as small as possible.
2. The gap between the train entrance and platform, which should be as small as possible (the ideal being gapless, high-level platforms in a straight line and without curves).
3. The ability of passengers to handle the process; large amounts of luggage and disabled persons slow down the loading and unloading process, as do small children and older persons.

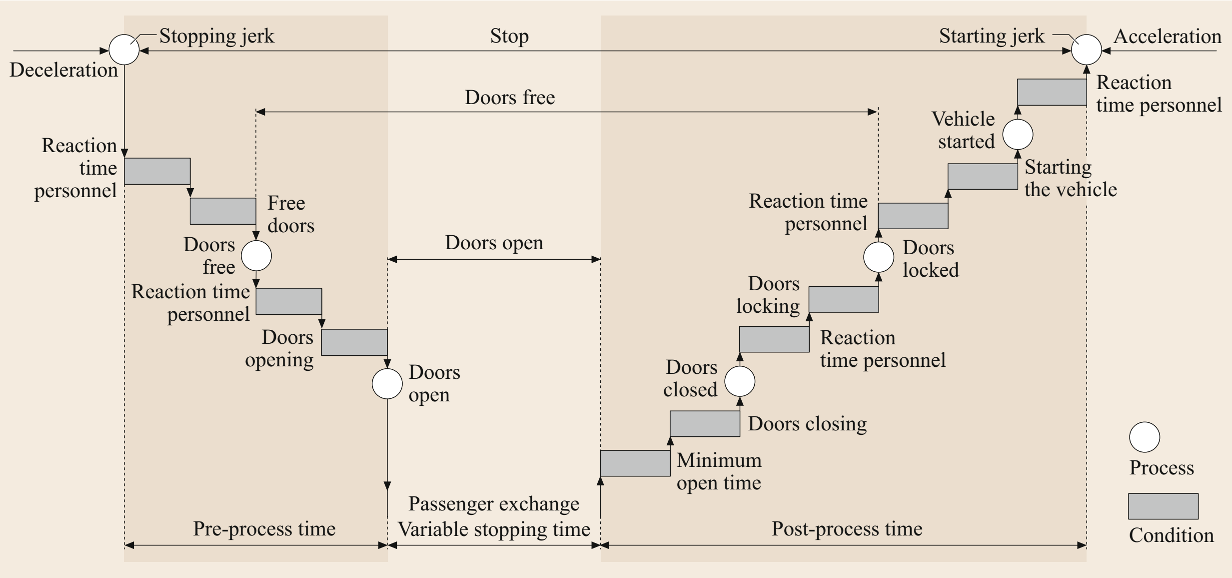


Fig. 23.2 Stopping, door opening/closing, and passenger exchange (after [23.1])

4. The duration of the door opening and closing process. Modern semiconductor-controlled doors often have very lengthy closing procedures, for instance, 20 s for InterCity Express 1 and 2 (ICE 1/2) trains in Germany, and similar values for the *train à grande vitesse* (TGV) in France. The reasons for this are the slow processors used for door control and the connection to the vehicle bus.
5. The number of doors. The number of doors should not be to small because of the possibility of door failures, but for long-distance traffic, doors are costly because of the costs of the doors themselves as well as the space behind the door, which is not usable as passenger seating space.

Especially for trains with frequent stops, it is very efficient to have short stopping times. The preprocess and postprocess time is clearly not productive at all, and the exchange of a given number of passengers is more effective the shorter this time (Fig. 23.2).

23.1.2 Lifecycle Costs

The annual distance traveled by rail vehicles is rather high, from 100 000 km/year for tram cars, over 200 000 km/year for regional trains and freight locomotives, and up to 500 000 km/year for high-speed rolling stock. For freight cars, it may range between 10 000 and 200 000 km/year. Lifetime is typically 30 and sometimes 40 years. Investment costs are rather high and typically account for one-quarter to one-third of the lifecycle costs, the other costs being maintenance and operation. In countries where wear- and noise-related track prices are charged, at least the difference between the cheapest and actual vehicle must be included as a new component of the lifecycle cost.

23.1.3 Reliability, Availability, and Safety

The basis for reliability, availability, maintainability, and safety (RAMS) is the European standard EN 50126 *Railway applications – The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS)* (September 1999) [23.2] (Fig. 23.3).

RAMS is needed due to the increasing complexity of railway systems and to achieve a high-quality process. In a competitive environment (mainly from other modes of transport such as road, air, and even water), this is essential to survive economically. Very reliable transport (for instance, 99% or even more of trains on time) with high speeds and therefore little standby time must be achieved. Good reliability reduces the need for spare units and personnel; high speeds increase productivity, as payments are received on the

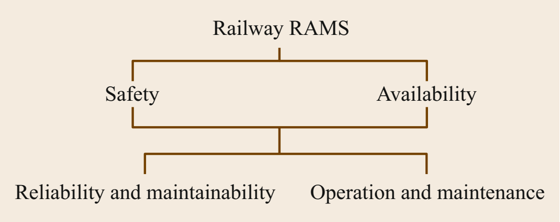


Fig. 23.3 Interrelation of railway RAMS elements

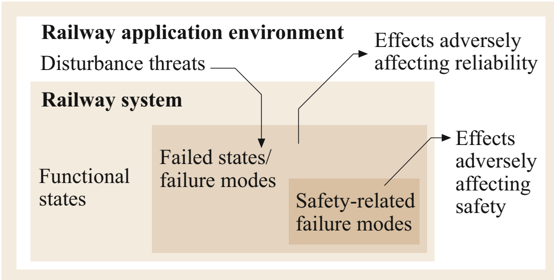


Fig. 23.4 Effects of failures within a system

basis of passenger-km or ton-km measures, whereas the expenses for equipment, including both trains and infrastructure, and also personnel occur on a time basis.

Here, mainly the process is discussed; targets are only mentioned as an example. RAMS covers the whole lifecycle of a system, and must be followed by the railway authorities (track and train operators) and the railway industry (system houses and suppliers).

The following definitions are used (Fig. 23.4):

- *Reliability*: the probability that an item can perform a required function under given conditions for a given time interval (t_1, t_2)
- *Availability*: the ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided
- *Maintainability*: the probability that a given active maintenance action, for an item under given conditions of use, can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources
- *Safety*: freedom from unacceptable risk of harm (note that safety does not mean that no accident occurs at all).

Risk is defined as the product of the size of the resulting destruction and the likelihood of the occurrence of the event. This likelihood of occurrence may be reduced by huge safety margins or by diagnosis that improves the probability of the recognition of a defect at an early and still not dangerous stage.

Around 1980, railways demanded the availability of about 80% of their fleet. Some railways operating under difficult conditions, for instance when suffering from the requisition of spare parts for cannibalization for other units, often did not reach 50%. Today, figures of 95% for electric rolling stock and 92% for diesel rolling stock or even higher are demanded.

The definition of availability does not include accidents (for instance, at points during shunting) or

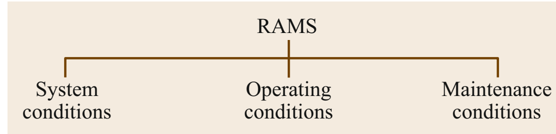


Fig. 23.5 Influences on RAMS

vandalism (for instance, broken windows or broken chairs due to rioting). Operational retardation is also not included. Because of all of these reasons, the number of spare units which are neither available nor down is greater than zero.

The basic equation for availability is

$$\text{availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MDT}}\,, \tag{23.1}$$

where MTBF is the mean time between failures, and MDT is the mean downtime.

Technical concepts of availability are based on a knowledge of:

1. Reliability in terms of:
   - All possible system failure modes in the specified application and environment
   - The probability of occurrence of each failure or, alternatively, the rate of occurrence of each failure
   - The effect of the failure on the functionality of the system
2. Maintainability in terms of:
   - Time for the performance of planned maintenance
   - Time for detection, identification, and location of faults
   - Time for the restoration of the failed system (unplanned maintenance)
3. Operation and maintenance in terms of:
   - All possible operation modes and required maintenance, over the system lifecycle
   - Human factor issues.

RAMS is influenced by the system conditions (vehicle and track, mainly influenced be the vehicle and track producers), operating conditions (the knowledge of the onboard personnel and the available data), and maintenance conditions (knowledge of the maintenance personnel and equipment of the maintenance facilities) (Fig. 23.5).

Methods to reduce downtime include:

1. Improving information to reduce inspection time by diagnosis
2. Parallel maintenance processes, including simultaneous processes of repair, inspection, refilling of water, sand, fuel etc.

For instance, cleaning of the interior (and probably the exterior) and toilets should be done simultaneous with refilling of water, sand, and probably fuel (while ensuring safety), a small overhaul, and module exchange (wheelsets, drive components, air-conditioning modules, etc.).

Simultaneous maintenance of fixed train sets (the locomotive plus wagons) and not locomotives separately from wagons avoids uncoupling and coupling time.

Systems diagnosis is becoming a major issue, and technical systems are becoming increasingly complex. Fault conditions are more difficult to reproduce, but fault analysis times should be reduced. Diagnosis systems for rail vehicles should have three levels:

1. Diagnosis for train personnel, to provide information for greater availability, and advice regarding redundant system operation
2. Diagnosis for maintenance personnel, to provide direct advice for required maintenance operations
3. Diagnosis for technical management, to provide data for reliability statistics as a basis for system improvements or at least spare-parts management (to enable the greatest reduction of spare-parts storage).

Two requirements of the diagnosis system that must be fulfilled are:

1. All data must be collected in one system for the whole vehicle (not separate systems, for instance, for the diesel motor, drive, doors, toilets, etc.).
2. The diagnosis criteria must be adaptable live during vehicle operation. This means that software skills must be available in the maintenance groups.

The reason for this is that the supplier cannot deliver a diagnosis system fulfilling all the needs of the operator because:

1. Not all operation circumstances are clear for the producer or even the operator.
2. Operation conditions may alter during vehicle operation (for instance, due to speed increases, longer trains, or movement from full to inferior service after 10 years or more).

It is recommended to order two or even more releases of diagnosis software after vehicle acceptance (and homologation) has been achieved. Operation experience can then be integrated, and the correct level of information attained.

Useless statements should be avoided, ensuring that information is given for real problems. Also, transfer from industry personnel to railway personnel must be achieved.

Part E | 23.2

23.2 Track

23.2.1 Track Geometry Components

The track geometry defines the position of the track in the landscape [23.3]. The following components are used:

1. Vertical: level track, gradients, and gradient changes
2. Curves: radius R, transition curves with continually adapted curve radius, curvature k as inverse radius $k = 1/R$. Clothoid for the curvature of transition curves $k = L/A^2$, where A is the clothoid parameter that limits the jerk r (change of acceleration) in the lateral direction ($\mathrm{m/s^3}$); limit $\leq 1\,\mathrm{m/s^3}$ (Fig. 23.6)
3. Lateral: cant to reduce lateral accelerations (maximum for standard gauge with mixed traffic 150 mm) in transition curves ramps must be foreseen (Fig. 23.7).

23.2.2 Track Bed Configuration

The sleeper in the track bed (Fig. 23.8) distributes the weight not only in the vertical and lateral directions but also in the longitudinal direction. All forces caused by thermal stresses in the continuously welded rail must be transferred via the sleepers to the ballast. The continuous welding process is carried out at medium temperatures to minimize temperature effects. At high temperatures in summer, buckling of the track is avoided by high lateral resistance.

Rails are denoted by letters, which define the shape of the rail, and a figure, which normally gives the weight per meter in kg or lb (Fig. 23.9).

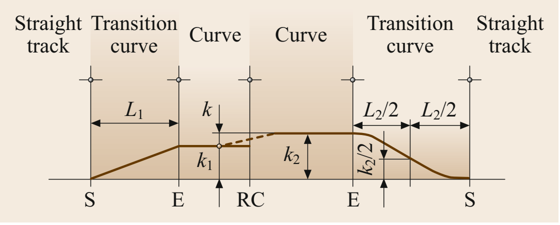


Fig. 23.6 Transition curves and ramps shown as curvature $k = 1/R$. RC – radius change; S – start transition curve; E – end transition curve

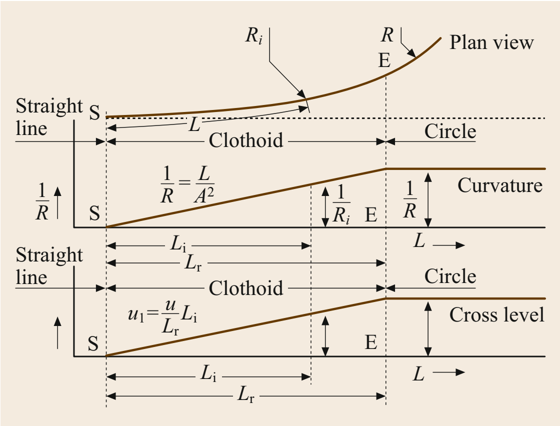


Fig. 23.7 Transition curve with linear ramp, *top* plan view, *middle* curvature, *below* cross level

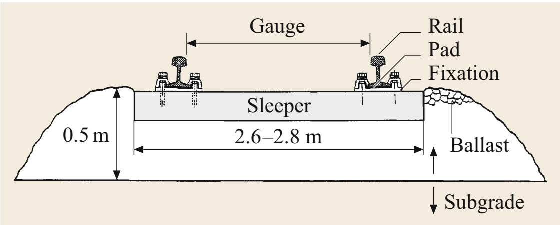


Fig. 23.8 Ballasted track bed (Table 23.1)

Table 23.1 Explanation for Fig. 23.8

Element	Function (construction)
Rail	Guidance of the vehicle, load distribution (rail 1 : 20 or 1 : 40 tilted)
Sleeper	Load distribution
Ballast	Load distribution, elastic element and damping device, distribution of the rail forces in all three directions, noise absorption of rolling noise and gearbox noise

The VST36 is a rail for light axle load, for instance Swiss narrow-gauge railways. The 49E1 is applied on lightly used European standard-gauge lines. The 60E2 is a rail for European main lines, and the AREA141AB is a rail for American mainlines.

The 60Ri2 is a grooved rail for tramway applications. Though the axle load of trams seldom exceeds 8 t, the stiffness of the tram rail is similar to that of other rails. In this way, much smaller displacements of the rail are achieved in the street plane.

Rails today are rolled as long as possible, typically 120 m long, to reduce the number of weld spots along the line as much as possible. Not only is welding on the line costly, but also the welds are more crack sensitive than the rolled rail.

Concrete sleepers are very durable and environmentally friendly; therefore, they have replaced wooden

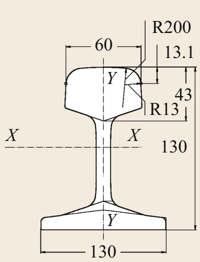
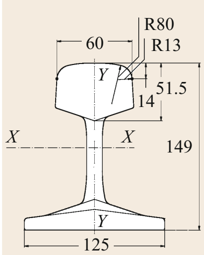
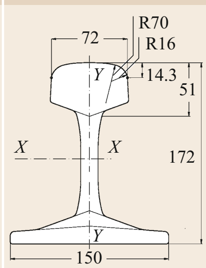
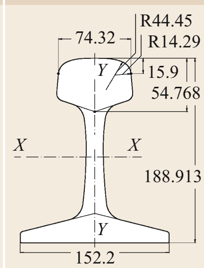
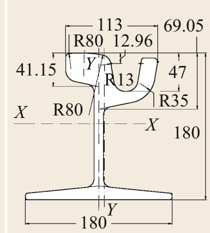
Rail profile	VST36	49E1 (S49)	60E2	AREA141AB	60Ri2 (Ri60-13, Ri60N)
	 Flat bottom rail	 Flat bottom rail	 Flat bottom rail	 Flat bottom rail	 Grooved rail
Mass (kg/m)	35.82	49.39	60.05	69.88	59.75
Area (cm^2)	45.63	62.92	76.5	89.02	76.11
Moment of inertia $X-X$ (cm^4) $Y-Y$ (cm^4)	1009.3 157.7	1816.0 319.1	3022 511.3	4180.0 620.7	3298.1 920.1

Fig. 23.9 Common rails with specific data. Rail profile, *TSTG-Profile-Handbook* (TSTG Schienen Technik, Duisburg)

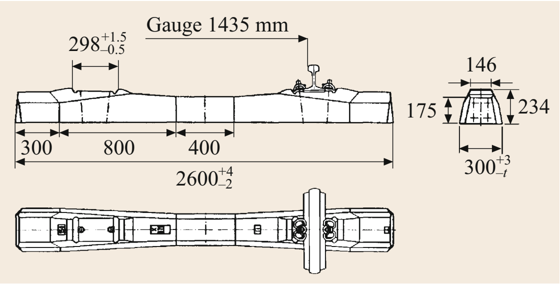


Fig. 23.10 B70 concrete sleeper, weight 445 kg (Pfleiderer Infrastrukturtechnik GmbH & Co KG, Neumarkt)

sleepers in many cases. Their large weight makes assembly difficult but provides good track stability (Fig. 23.10).

Today, the most commonly used sleeper type is concrete, but wood is still used also, and Y-steel sleepers have a growing market share. Y-steel sleepers offer much higher lateral resistance than concrete or wood, thus no ballast is required to avoid sideways buckling at high temperatures. Also, because of the lower height of the sleeper, less ballast is used in the track bed itself (Fig. 23.11). This is an advantage in tunnel construction. On intensively used lines, ballast-less track construction has the advantage of less maintenance effort compared with ballasted tracks (Fig. 23.12).

23.2.3 Switches

To enable networks, switches are essential. Compared with other guided transport modes where switches are large and heavy, on a railway switch only the switch blades must be moved. This is done by bending the blades elastically. Relatively small electric motors with gearboxes apply these forces.

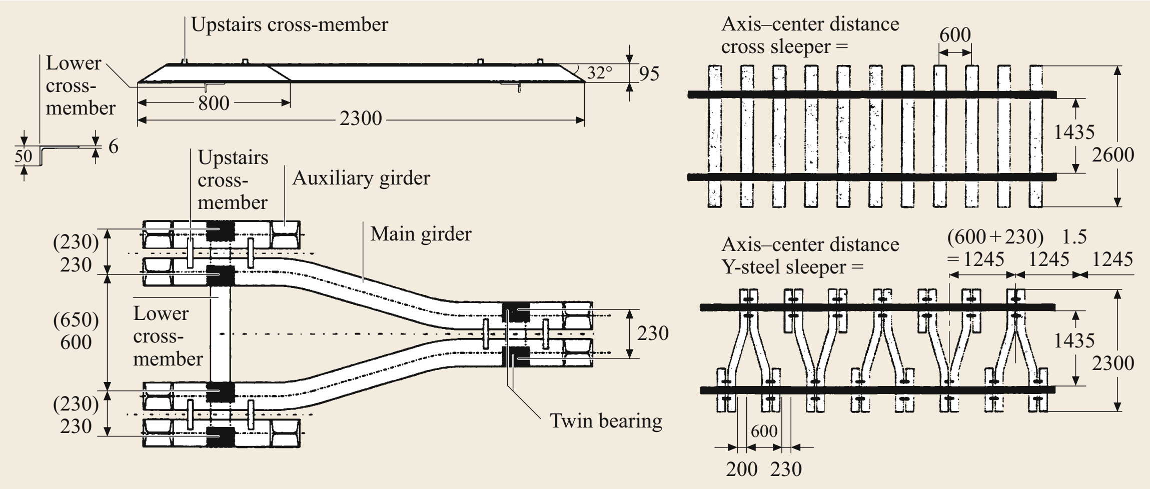


Fig. 23.11 Y-steel sleeper and comparison of steel, wood, and concrete sleeper track beds [23.4]

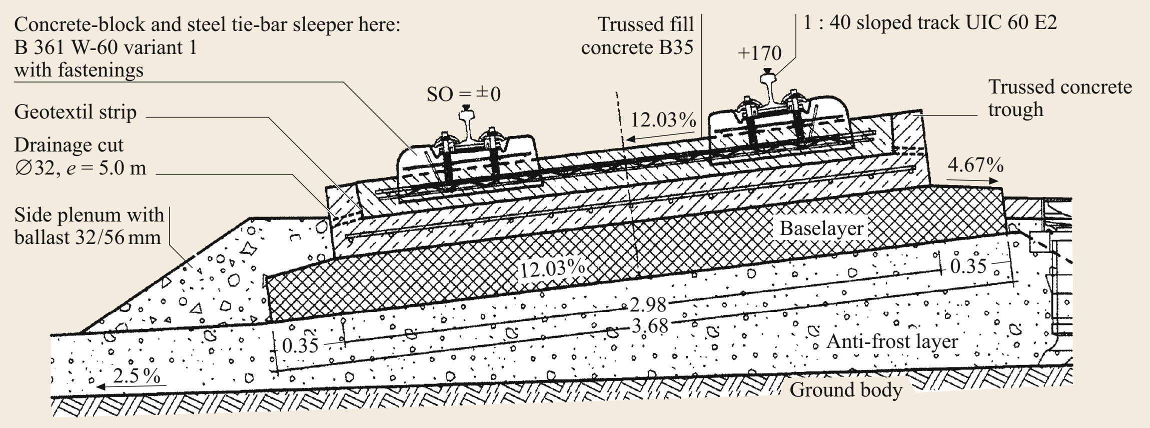


Fig. 23.12 Ballast-less track at the Cologne–Frankfurt high-speed line in a curve with maximum superelevation of 170 mm (Walter-Heilit, Munich) [23.5] (UIC – Union internationale des Chemins de fer)

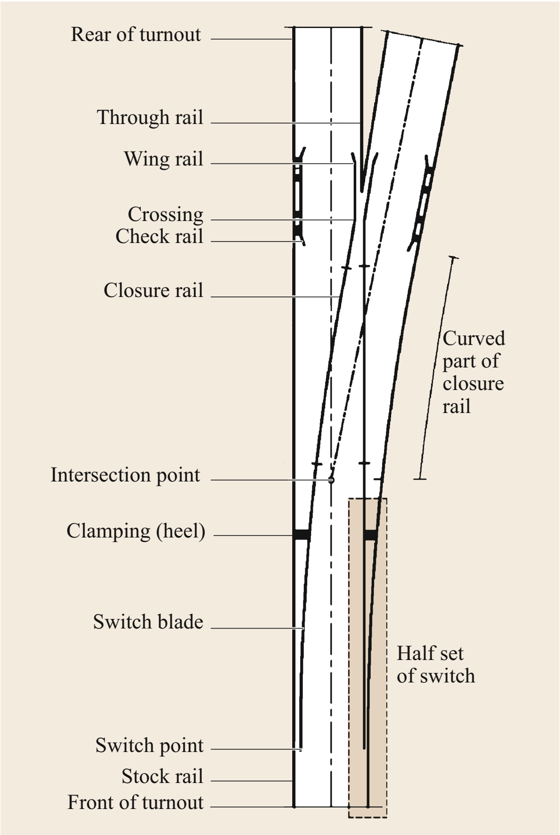


Fig. 23.13 Switches and their elements

In the crossing (also called a frog) itself, there is a gap where no lateral guidance of the wheel flange occurs. Here, check rails and the running rail provide guidance on both sides of the other wheel of the wheelset (Fig. 23.13).

23.2.4 Track Irregularities

The four degrees of freedom of the track are: gauge s, cant m_φ, alignment u, and level h (Fig. 23.14).

The gauge is defined as the smallest distance between the rail heads in a track 0–14 mm under the top of rail (TOR). The cant m_φ is the height difference between the two rails (Table 23.2). The twist is a function of the cant over distance

$$\text{cant} = \frac{m_\varphi(x_1) - m_\varphi(x_2)}{x_2 - x_1} \quad [-]$$

in units of mm/m = ‰.

Track irregularities are defined as a function of wavelength L or spatial frequency $\Omega = 2\pi/L$. With increasing wavelength, the amplitude of track irregularities increases (Figs. 23.15 and 23.16).

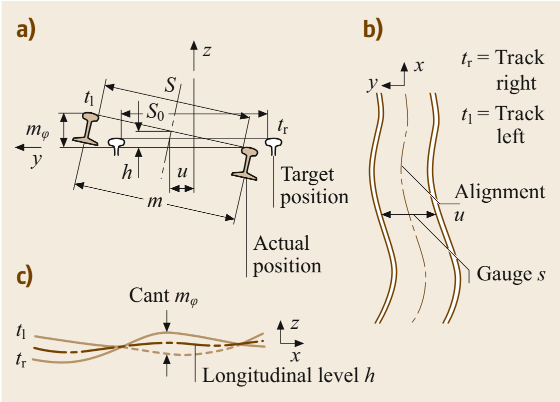


Fig. 23.14a–c Geometric track components: **(a)** coordinates in the measurement plane, **(b)** horizontal track coordinates: gauge s and alignment u, **(c)** vertical track coordinates: level h and cant m_φ

Table 23.2 Nominal international gauge distribution (caution: large tolerances between −3 and +35 mm are possible)

Name	Metric (mm)	British (inch)	Worldwide (%)
Meter gauge	1000	$3\text{–}3\frac{3}{8}$	7.5
CAP (gauge)	1067	3–6	7.7
Standard gauge	1435	$4\text{–}8\frac{1}{2}$	64
Russian broad gauge	1524[a]	5	11.8

[a] New 1520, since about 1980

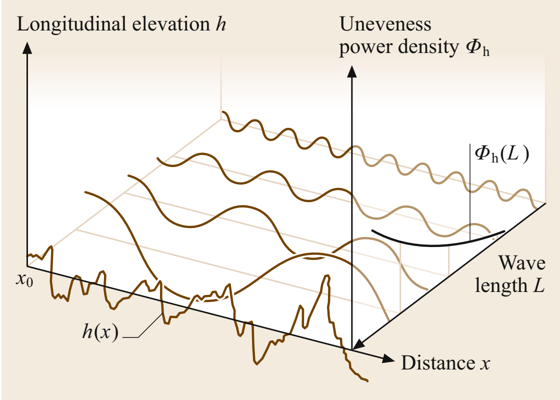


Fig. 23.15 Principle of calculation of power spectral densities (PSD) $\phi_h(L)$ from the displacement curve $h(x)$

The following track irregularities are common [23.6]:

- Level

$$\Phi_z(\bar{\Omega}) = \frac{A_V \Omega_c^2}{(\bar{\Omega}^2 + \Omega_r^2)(\bar{\Omega}^2 + \Omega_c^2)} A,$$

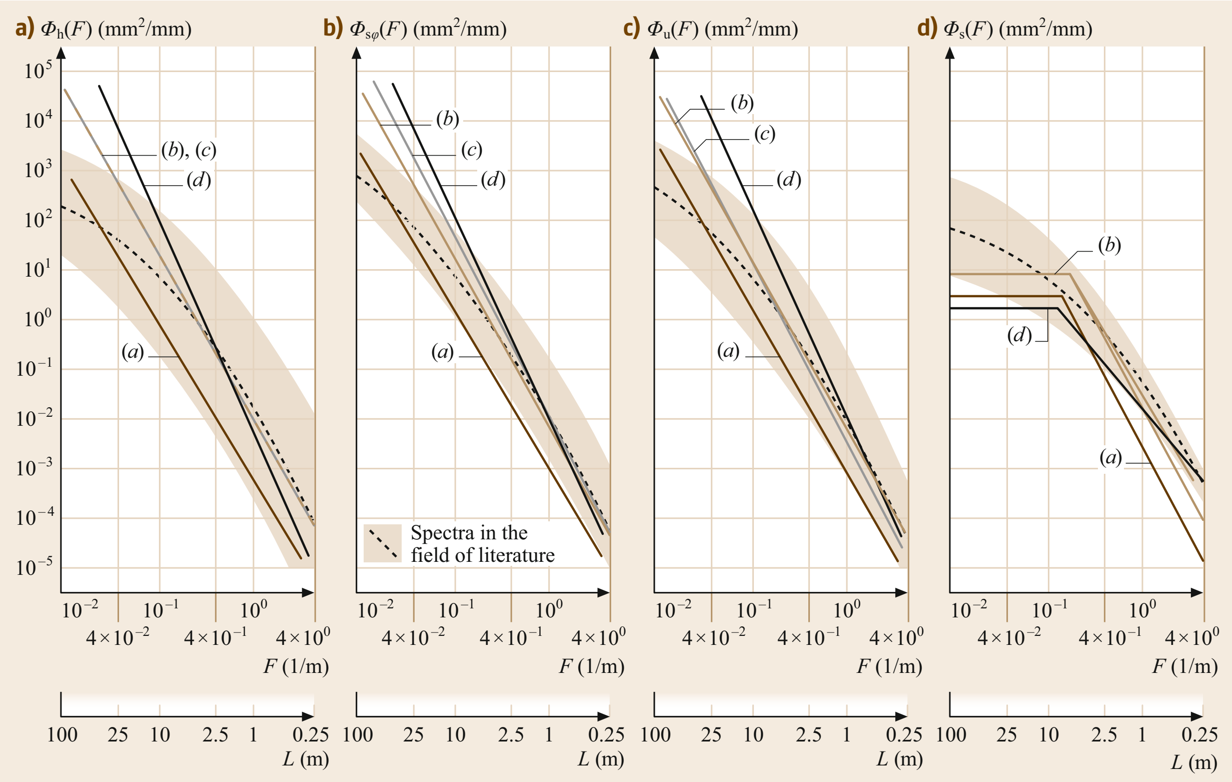


Fig. 23.16a–d Examples of track power spectral densities: **(a)** longitudinal level Φ_h, **(b)** cant $\Phi_{s\varphi}$, **(c)** alignment Φ_u, **(d)** gauge Φ_s. *Curve a* – standard gauge; *curve b* – city railway flat bottom rails (route track); *curve c* – city railway flat bottom rails (driving school track); *curve d* – city railway grooved tramway rails track

- Alignment

$$\Phi_y(\bar{\Omega}) = \frac{A_A \Omega_c^2}{(\bar{\Omega}^2 + \Omega_r^2)(\bar{\Omega}^2 + \Omega_c^2)}$$

- Cant in radians

$$\Phi_\rho(\Omega) = \frac{(A_C/a^2)\Omega_c^2 \bar{\Omega}}{(\bar{\Omega}^2 + \Omega_r^2)(\bar{\Omega}^2 + \Omega_c^2)(\bar{\Omega}^2 + \Omega_s^2)} ,$$

with the following data for a conventional track in good conditions:

$$\Omega_s = 0.4380\,\text{rad/m} , \quad \Omega_c = 0.8246\,\text{rad/m} ,$$
$$\Omega_r = 0.0206\,\text{rad/m} ,$$
$$A_V = A_A = A_C = 5.9233 \times 10^{-7}\,\text{m rad} ,$$
$$a = 0.75\,\text{m} .$$

Impact of the increase in speed (Fig. 23.17):

(a) Without track quality improvement
(b) With track quality improvement

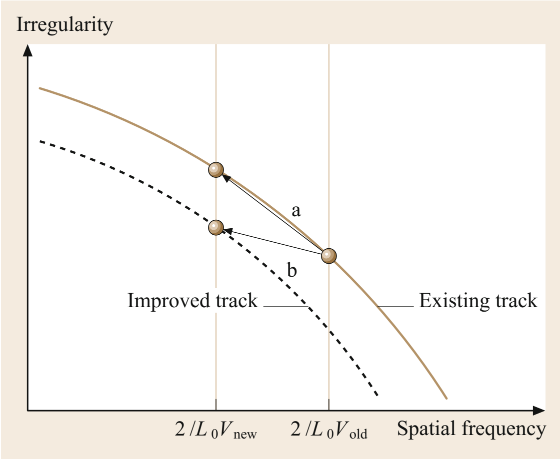


Fig. 23.17 Effect of speed increase on track amplitudes for a specific eigenfrequency of the vehicle

The relevant wavelength L_0 increases as the eigenfrequencies f_0 of the vehicles are time invariant

$$f_0 = \frac{V}{L_0} .$$

23.3 Running Gears

23.3.1 Wheel–Rail Interaction

The standard element of railway running gears is a wheelset, consisting of a rotating shaft on which two wheels are fixed by a press or shrink fit.

Additionally, the wheel profile together with the rail profile generates a steering effect (Fig. 23.18).

To introduce this effect, a conical thread geometry is first assumed.

The difference in radius Δr between the two rolling wheels leads to a self-steering effect, as both wheels have the same rotational speed but the outer wheel is running on a larger radius than the inner wheel.

This desirable behavior is superimposed by an effect called sinus running for conical profiles or wave running for practical profiles.

Equivalent Conicity

The wavelength of the real profile is equal to the wavelength of a wheel profile with constant conicity, as shown in Fig. 23.19.

To characterize the interaction between the wheel and rail for different wheel and rail profile shapes, Figs. 23.20 and 23.21 show examples for two different rail inclinations. The desired behavior is that the surfaces of the wheel and rail make contact on a rather broad level and that the difference in radius Δr reaches high values before flange contact occurs. If the angle of attack between the wheel and rail is large, then a two-point contact occurs (Fig. 23.22).

The running gears of a two-axle wagon are of link suspension type (Fig. 23.23). The links admit not only lateral but also longitudinal movements. In this way, self-steering of the individual wheelsets is enabled. The system is damped by friction, which is load sensitive; the higher the load, the greater the friction force. The diameter of the link is increased in the contact zones to increase the friction force.

The spring constant is very much a function of the amplitude. For small amplitudes, caused for instance by small track irregularities, the system is very stiff. For large amplitudes, caused for instance by severe rail twist, the system becomes rather soft [23.8] (Fig. 23.24).

23.3.2 Bogie Principle

The wheelsets are spaced with an axial distance $2a$ and situated in a frame (Fig. 23.25). This frame together with the wheelsets forms the bogie. The vehicle body in general is supported in the middle of the bogie

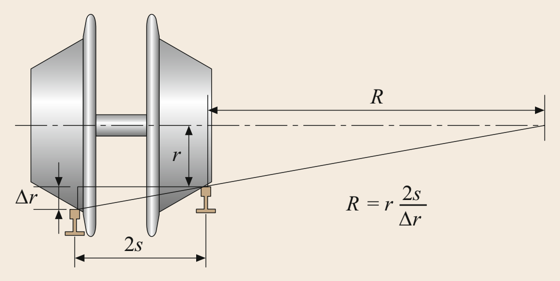


Fig. 23.18 Steering effect of a slip-free wheelset on a tight curve (radius R) related to the inner rail; $2s$ is the distance of contact points (typically 1500 mm at standard gauge); r is the rolling radius at the inner wheel; Δr is the radius difference between the outer and inner wheel

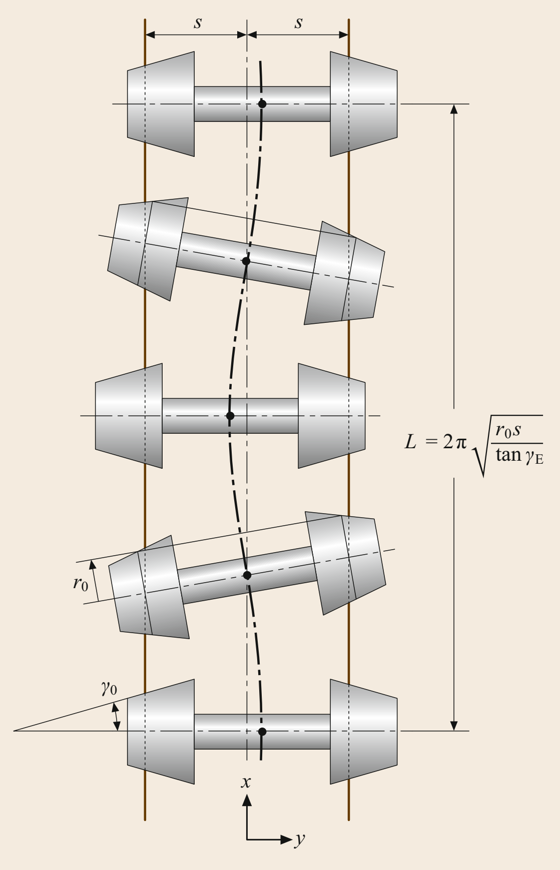


Fig. 23.19 Idealized wheelset moving: the wavelength L which occurs in slip-free movement [23.7]

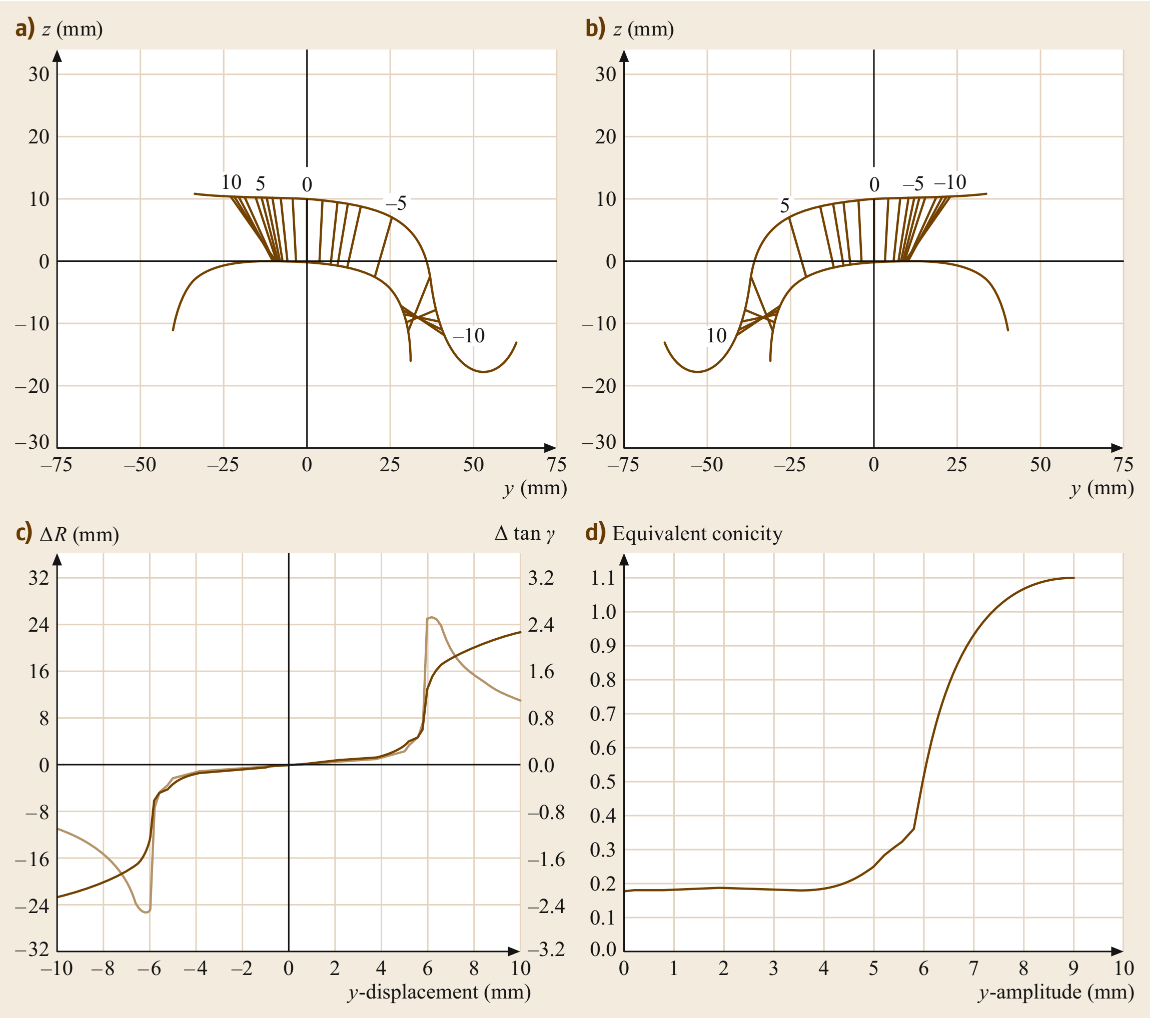


Fig. 23.20a–d Wheel–rail contact for S1002/UIC 60 1 : 40 inclined. Contact points and contact functions of wheel and rail, wheel profile S1002 (wheel diameter 700 mm, flange gauge 1426 mm, wheel load 175 kN), rail UIC 60, 1 : 40 inclined, track gauge 1435 mm. **(a)** Left contact point, **(b)** right contact point, **(c)** difference of contact radii ΔR (dark brown curve) and contact angle difference $\Delta \tan\gamma$ (light brown curve), **(d)** equivalent conicity

frame at z_P. This geometrical configuration leads to the reduction of track regularities. As a function of their wavelength, track irregularities are reduced between two extremes: no reduction at all (for wavelengths equal to the wheelset distance $2a$) and complete reduction (for wavelengths equal to half of the wheelset distance), as illustrated by the equations below:

Geometrical transfer function of a bogie

$$z_\mathrm{P}(x_0) = \left[z(x_0-a) + z(x_0+a)\right]\frac{1}{2}\,.$$

Track irregularity $z(x)$

$$z_\mathrm{P}(x_0) = \frac{1}{2}\left(z\mathrm{e}^{\mathrm{i}\Omega(x_0-a)} + z\mathrm{e}^{\mathrm{i}\Omega(x_0+a)}\right),$$

$$z(x) = z\mathrm{e}^{\mathrm{i}\Omega x}\,, \quad \Omega = \frac{2\pi}{L}\,,$$

$$z\mathrm{e}^{\mathrm{i}\Omega(x_0-a)} = z\mathrm{e}^{\mathrm{i}\Omega x_0}\,\mathrm{e}^{-\mathrm{i}\Omega a}\,,$$

$$z_\mathrm{P}(x_0) = \frac{1}{2}z\mathrm{e}^{\mathrm{i}\Omega x_0}\left(\mathrm{e}^{-\mathrm{i}\Omega a} + \mathrm{e}^{\mathrm{i}\Omega a}\right),$$

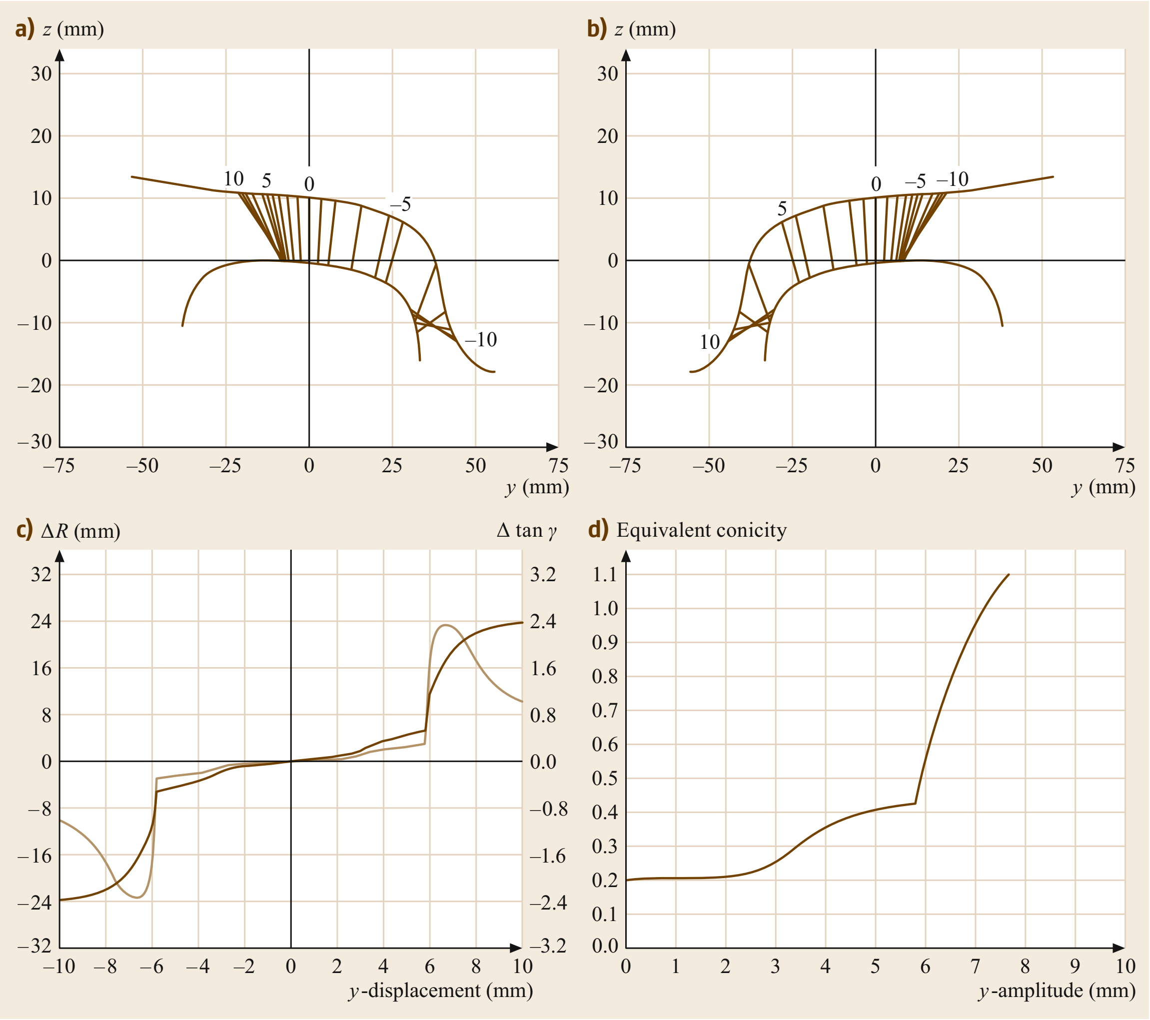


Fig. 23.21a–d Profile combination KKVMZ–UIC 60 1 : 20 (track gauge 1435 mm). Contact points and contact functions of wheel and rail, wheel profile KKVMZ (wheel diameter 700 mm, flange gauge 1426 mm, wheel load 175 kN), rail UIC 60, 1 : 20 inclined, track gauge 1435 mm. **(a)** Left contact point, **(b)** right contact point, **(c)** difference of contact radii ΔR (dark brown curve) and contact angle difference $\Delta \tan \gamma$ (light brown curve), **(d)** equivalent conicity

$$H = \frac{\text{Output}}{\text{Input}} ,$$

$$H = \frac{1}{2}\left(e^{-i\Omega a} + e^{i\Omega a}\right) ,$$

$$e^{i\Omega a} = \cos \Omega a + i \sin \Omega a ,$$

$$H = \frac{1}{2}\left(\cos \Omega a \, i \sin \Omega a + \cos \Omega a + i \sin \Omega a\right)$$

$$= \cos \Omega a$$

$$= \cos \frac{2\pi a}{L} .$$

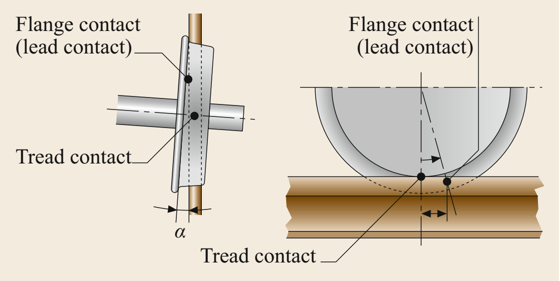


Fig. 23.22 Two points of contact in different planes, if the angle of attack between the wheel and rail α exceeds a certain value. Lead contact in the flange

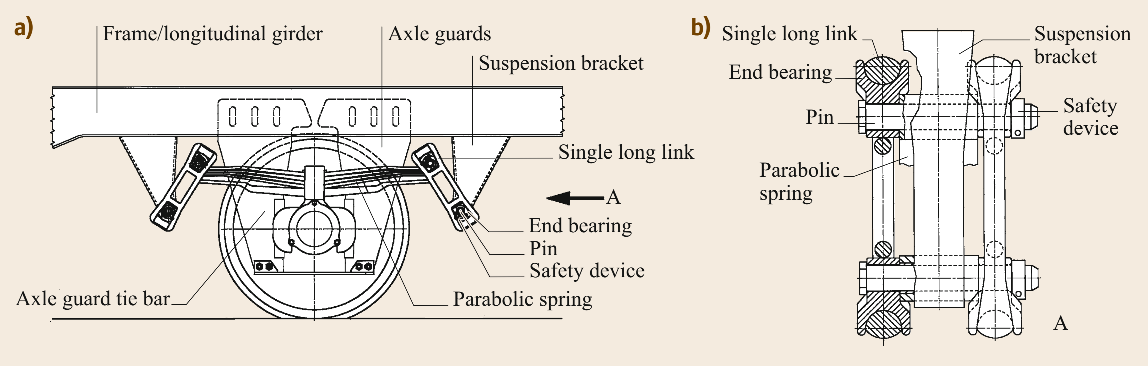


Fig. 23.23a,b Running gear for two-axle wagons with single long-link suspension *Niesky2* (Waggonbau Niesky GmbH, Niesky): **(a)** side view, **(b)** top view

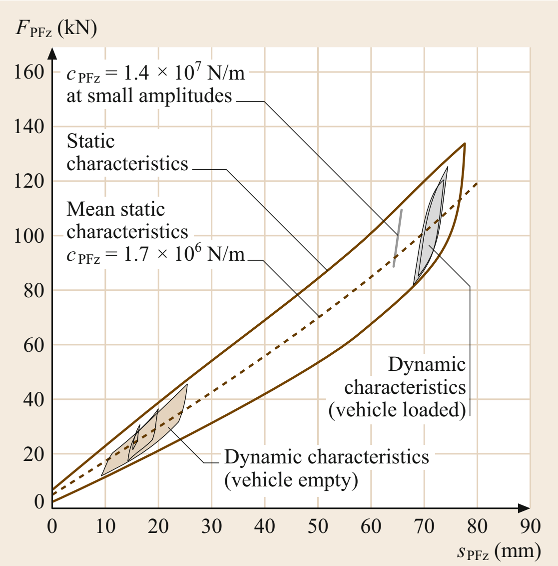


Fig. 23.24 Measured force–displacement diagram in the vertical direction of a leaf spring–link suspension system: spring constant and friction damping

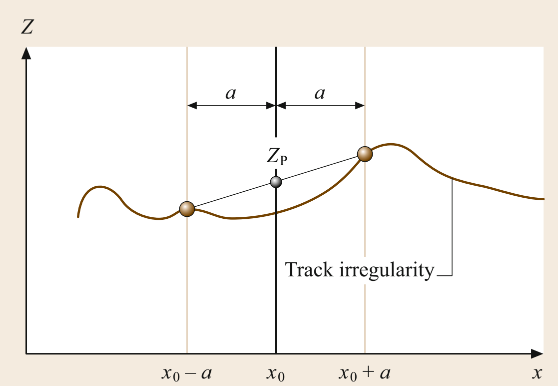


Fig. 23.25 A bogie with two wheelsets spaced from the bogie center

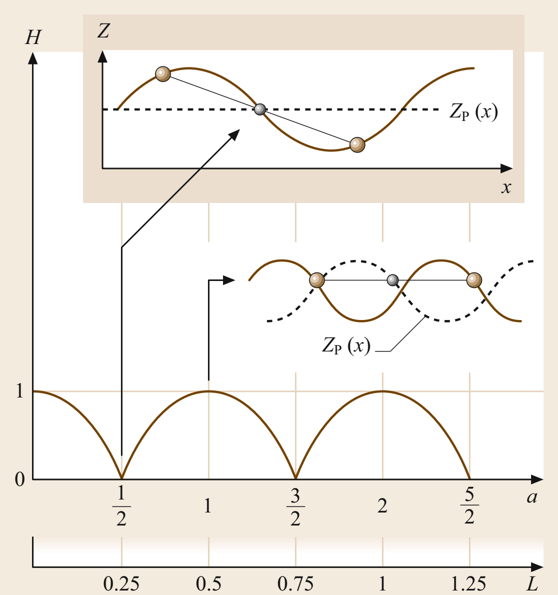


Fig. 23.26 Geometrical transfer function with values between 0 (no transfer of track irregularities) to 1 (all track irregularities are fully transferred, but not amplified)

For railways, very often the lateral dynamics is even more important than the vertical dynamics, and this good behavior of a bogie also applies for the lateral direction (Fig. 23.26).

23.3.3 Constructive Elements

Wheelsets

For tramways, where the track is always very stiff and therefore rather soft, rubber-cushioned wheels must be used. They also reduce noise (Fig. 23.27).

Low-floor trams cannot use wheelsets but instead use cranked axles, so that the height of the floor can be reduced (Fig. 23.28).

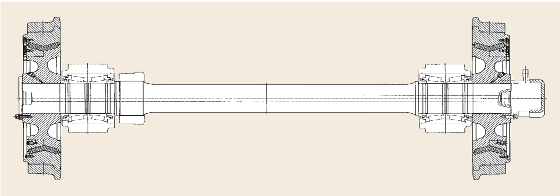


Fig. 23.27 Driven wheelset with inside bearings and rubber elastic wheels for the low-floor tram Schwerin (Germany), wheel type B02000, running circle new 600 mm, gauge 1435 mm, weight 552 kg, without bearings, wheel stiffness 20.0 kN/mm radial and 20 kN/mm axial (Bochumer Verein, BVV, Bochum)

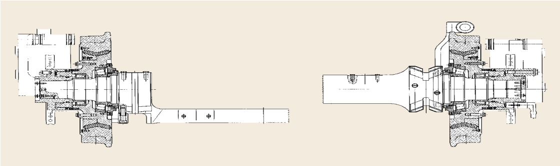


Fig. 23.28 Idle wheels with cranked axle for low-floor tram Schwerin with rubber-cushioned individual turning wheels of type BO2000, wheel diameter new 600 mm, gauge 1435 mm, weight 897 kg, with bearings and brake system, wheel stiffness 200 kN/mm radial and 20 kN/mm axial (Bochumer Verein, BVV, Bochum)

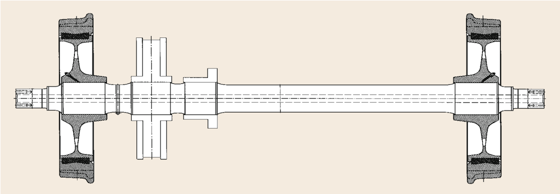


Fig. 23.29 Driven wheelset with brake disk from the Vienna Metro, rubber sprung wheels of type BO54, wheel diameter 840 mm new, gauge 1435 mm, weight 852 kg, wheel stiffness 75 kN/mm radial and 8 kN/mm axial (Bochumer Verein, BVV, Bochum)

Many wheelsets are hollow-bored. This reduces weight and also enables ultrasonic testing (Figs. 23.29–23.32).

23.3.4 Bogies

Figure 23.34 shows the so-called three-piece bogie. This is the most common freight bogie type in the world. Several million bogies of this type are running outside Europe. There is only a secondary spring according to Fig. 23.33a. The three pieces that give the name to the bogie are the two side frames and the bolster assembly. The wedge (Fig. 23.34) applies load-sensitive damping.

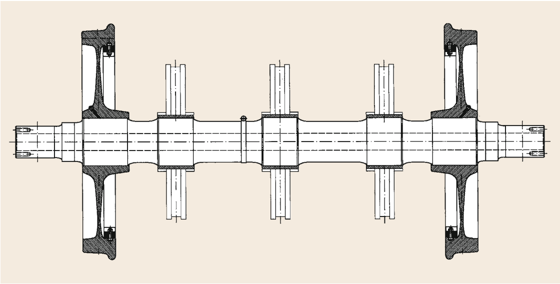


Fig. 23.30 High-speed wheelset with seats for three brake disks and wheels with sound absorbers. The shaft is hollow-bored for weight reduction and to enable ultrasonic crack detection, wheel diameter 920 mm new, gauge 1435 mm, weight 948 kg without brake discs (Bochumer Verein, BVV, Bochum)

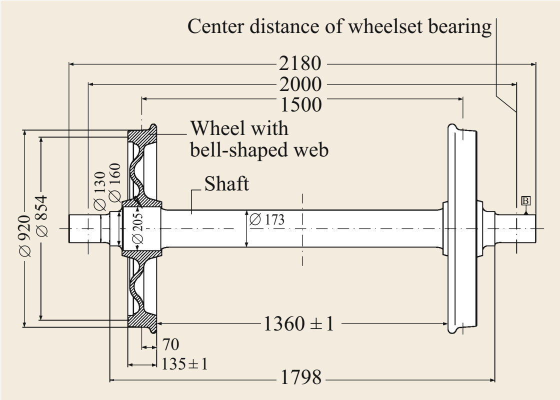


Fig. 23.31 Standard freight car wheelset type BA 304 for 25-t axle load (wheel with bell-shaped web to reduce stresses from block braking), wheel diameter 920 mm new, 854 mm worn, weight 1003 kg (Radsatzfabrik Ilsenburg Rafil)

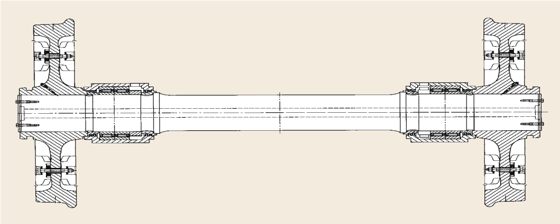


Fig. 23.32 Leila freight car wheelset for 22.5-t axle load with inside bearings and wheel brake disks 920-mm wheel diameter new, gauge 1435 mm, weight 1392 kg with bearings and aluminum brake discs (not to scale)

The three-piece bogie has unsuspended side frames, whereas the Y 25 bogie (Fig. 23.35) has individual suspended axle boxes, so-called primary suspension, according to Fig. 23.33b.

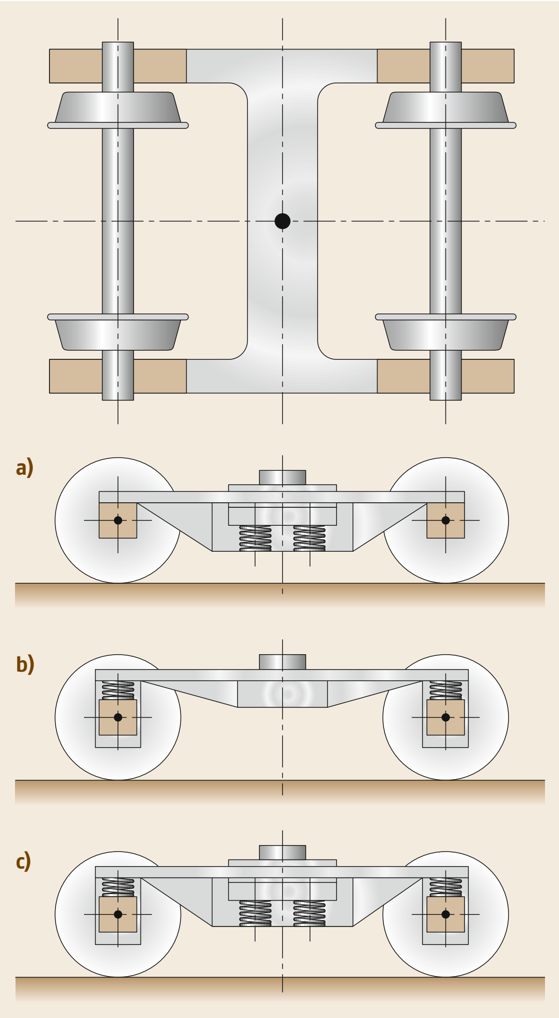


Fig. 23.33a–c Basic concepts of bogie suspension: **(a)** only secondary sprung (three-piece bogie), **(b)** only primary suspension (Union international des Chemin de fer (UIC) freight bogie), **(c)** with primary and secondary suspension; all in longitudinal stiff design

The bogie type mainly used in Europe is the so-called Y 25 (Fig. 23.35). The helical springs are responsible for vertical and lateral suspension. Over the inclined links in Fig. 23.33a, longitudinal friction force is caused in the axle guides, which damps the vertical and lateral movements. This force is load related.

The Leila freight bogie (Fig. 23.36) enables better load distribution by internal bearings and radial steering by the cross arm. The wheelsets are those from Fig. 23.32.

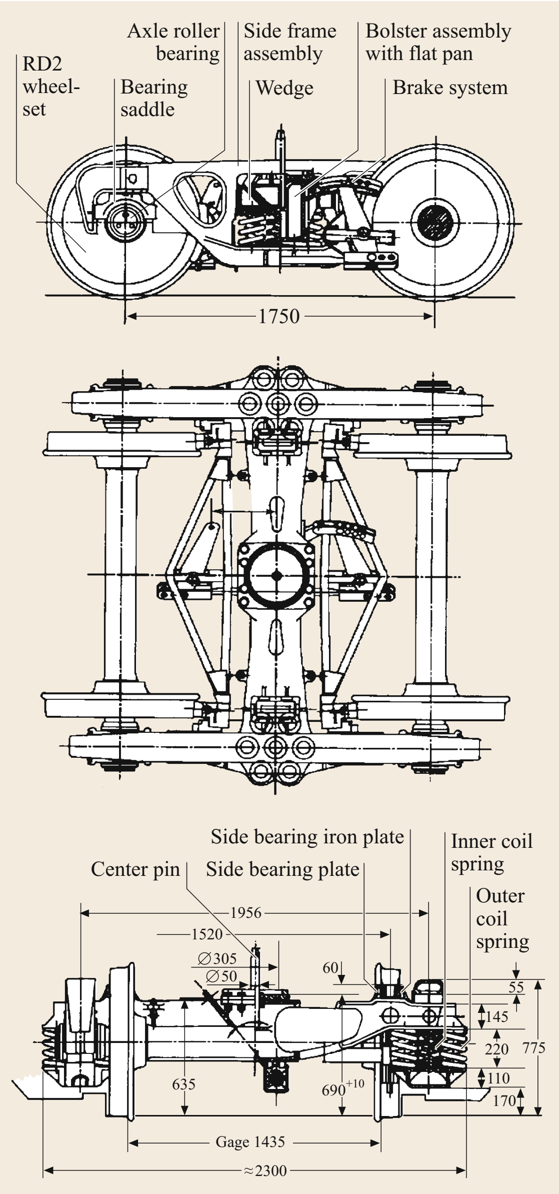


Fig. 23.34 Z8A freight car bogie (China) weight 4100 kg, max. axle load 210 kN (Qiqihar railway rolling stock Co., China) (RD2 is a wheelset type name)

In passenger transport as well, interior bearings offer huge benefits with about 30% lower bogie weight (Fig. 23.37).

The driving motor is located in the body shell, and the momentum is transferred to the axle-hung gearbox via a Cardan shaft (Fig. 23.37).

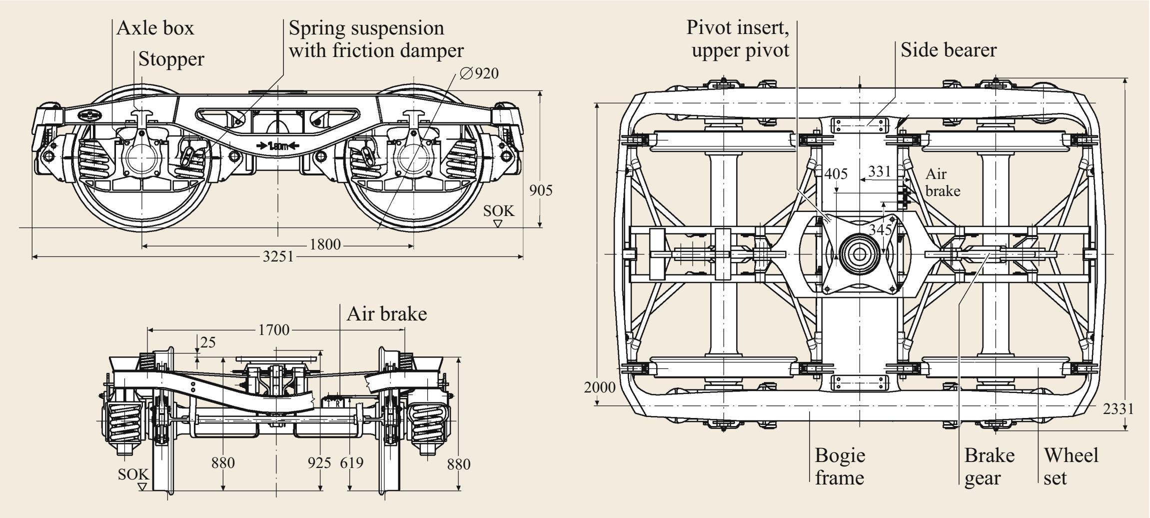


Fig. 23.35 Freight bogie Y25Lsd1-K with K-brake block insert in single brake block arrangement for axle load 22.5 t, mass 4390 kg (with wheelsets type BA 004 and pivot) (Eisenbahn Laufwerke Halle, ELH)

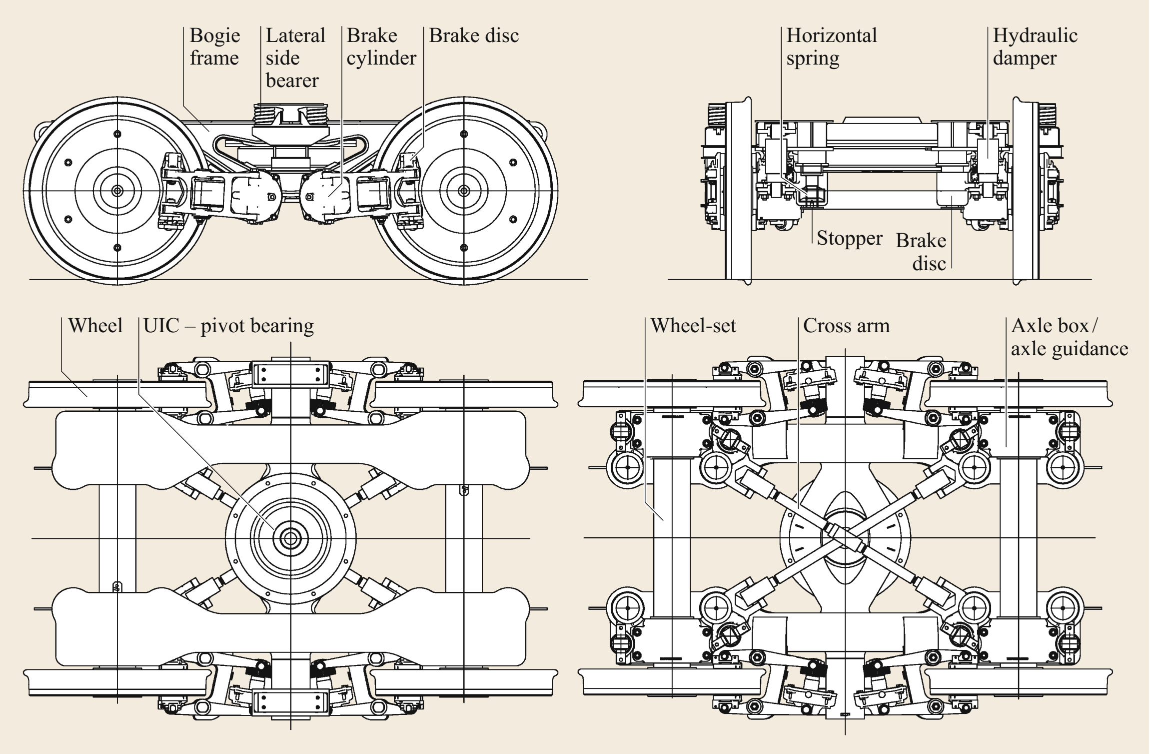


Fig. 23.36 Leila freight bogie (Josef Meyer Waggon AG, Rheinfelden)

Figure 23.37 shows a bogie for high-speed tilting trains with internal bearing wheelsets. This assembly offers huge benefits in terms of weight reduction and good access to the wheels.

The bogie shown in Fig. 23.38 is a very-high-speed bogie for the fastest scheduled passenger service today.

Low-floor trams need bogies with free space in the center (Fig. 23.39).

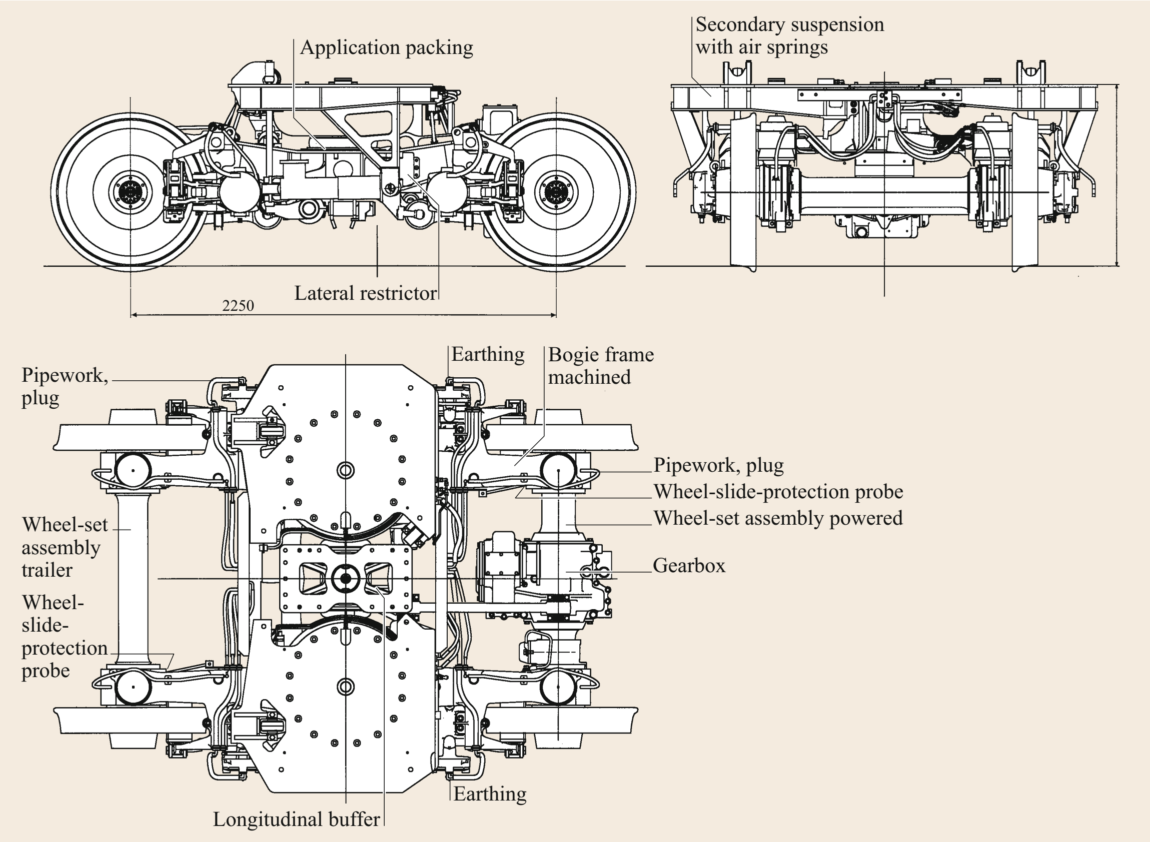


Fig. 23.37 Bogie assembly type A type B5000 for axle load 16 t, weight 4700 kg powered, wheel diameter new 780 mm, worn 716 mm, wheelbase 2250 mm, V_{max} 200 km/h (Bombardier Transportation, Berlin)

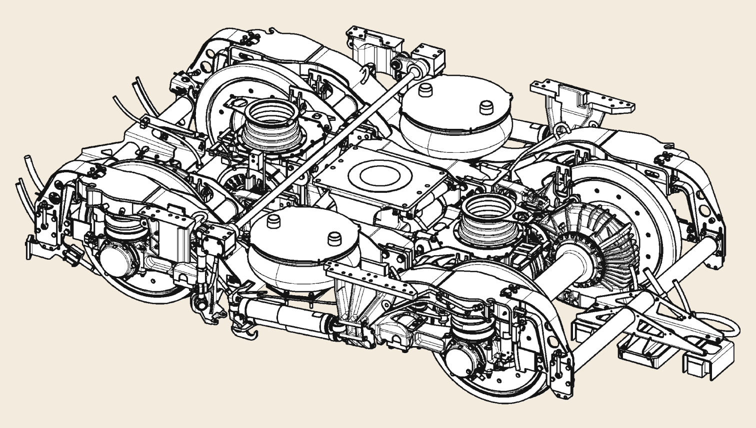


Fig. 23.38 Running gear SF 500-type motor bogie for operating speed up to 350 km/h, wheelset load maximum 17 t, continuous power per wheelset up to 500 kW, maximal starting tractive effort per wheelset 19 kN, wheelset distance 2500 mm, gauge 1435 mm, wheel diameter new/worn 920/830 mm minimal curve radius service/workshop 150/120 m, weight with pivot and traverse 9.2 t (Siemens Transportation Systems, Erlangen)

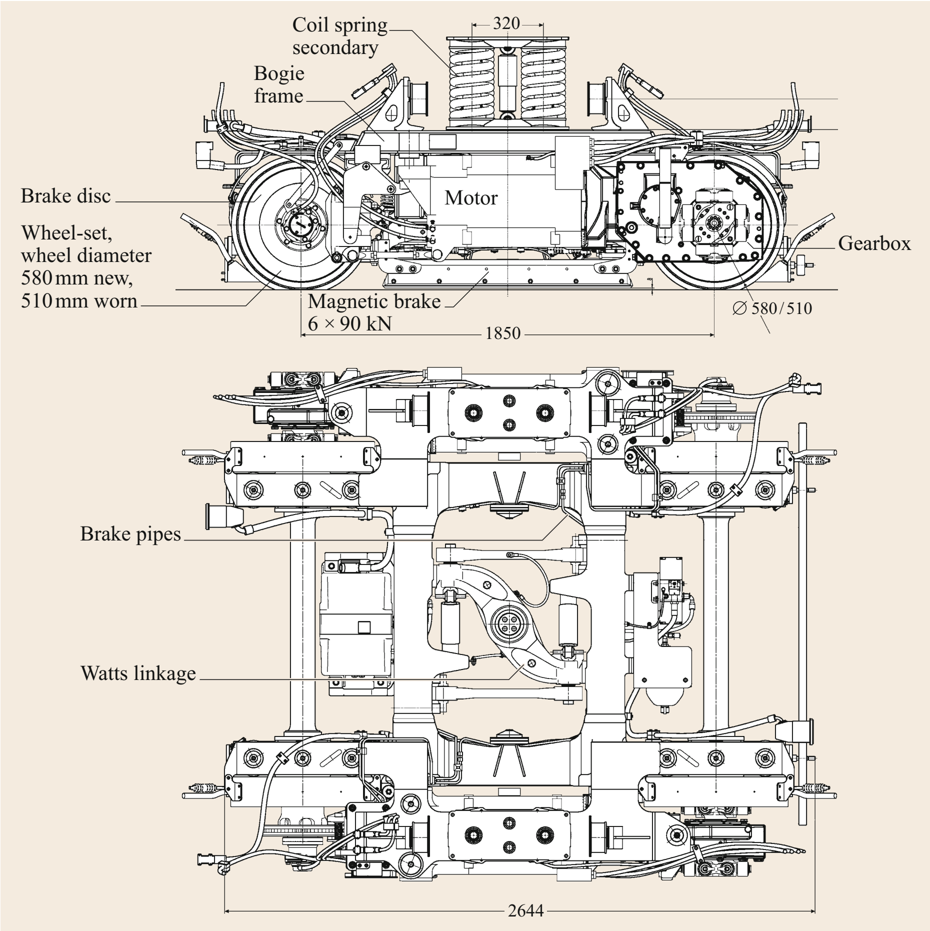


Fig. 23.39 Bogie assembly type S1000 BM1000 tram Marseille MB, weight 4700 kg powered, maximum speed 70 km/h (Bombardier Transportation, Berlin)

23.4 Superstructures

23.4.1 Principle

With articulated vehicles (Fig. 23.40), normally fewer wheelsets than with standard designs are needed. Fewer wheelsets per car length means less weight, less cost, and less noise, but the maintenance process is more complicated.

The body shells are made either from aluminum intrusion profiles [23.9] or from weldable steel in a sheet and stringer design. This design offers more possibilities to adapt the structure to the load requirements and enables simpler repairs (Fig. 23.41).

23.5 Vehicles

Figure 23.42 shows a freight wagon as an example of a very lightweight construction. The empty wagon weighs only 20% of the fully loaded vehicle. For both situations, loaded and empty, the safety requirements must be fulfilled.

To reduce operation expenses, modern metro systems are planned as driverless systems. In this way no space is lost for the driver cabin and all the space may be used for passengers (Fig. 23.43).

Modern tram cars are built in a modular manner so that capacity can be adapted to local needs. This means that the tram shown in Fig. 23.44 can be lengthened or shortened by further bogie and suspended modules.

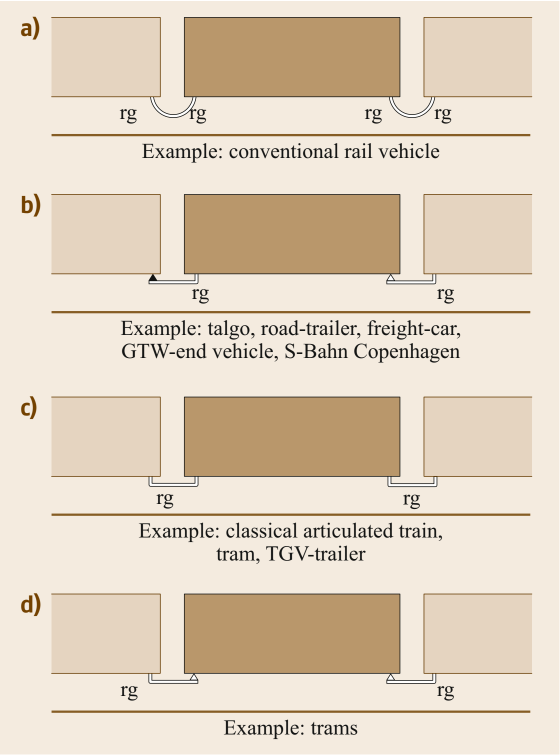


Fig. 23.40 **(a)** Single vehicle (vehicles separable in operation) supported by at least two running gears, rg (single wheelsets or bogies). Articulated vehicles (trains only separable in workshop): **(b)** saddle principle, semi-trailer, one end vehicle with two running gears (GTW – Gelenktriebwagen (German) – articulated vehicle), **(c)** Jacobs principle (bridge vehicle), **(d)** suspended modules

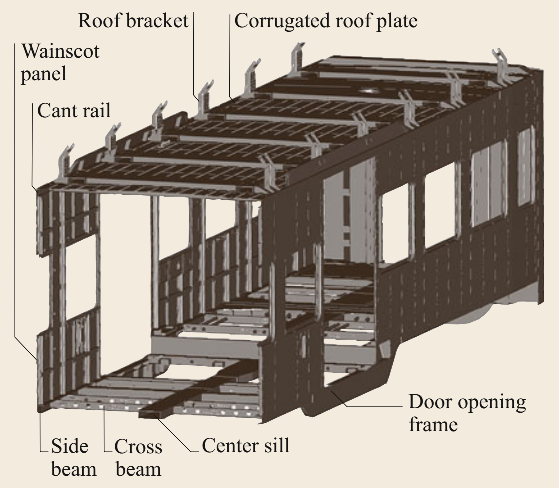


Fig. 23.41 Sheet and stringer design in steel (FTD Fahrzeugtechnik Dessau AG)

Electric locomotives are more powerful than diesel locomotives. To enable free running across borders, they are usually equipped to cover all four electric systems in use in Europe (Figs. 23.45 and 23.46). Modern locomotives also fulfill crash concepts; see Sect. 23.7.2 and [23.10].

Diesel locomotives are increasingly being replaced by hybrid catenary locomotives (Fig. 23.47). Catenary operative expenses are much lower, and regenerative braking can feed the braking energy back to the catenary.

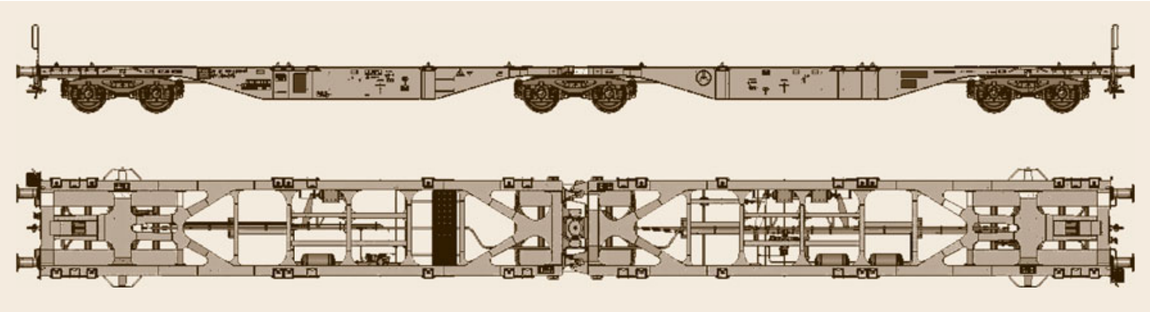


Fig. 23.42 Six-axle, three-bogie articulated flat-bodied Sggmrss-90 unit for container and swap bodies: axle load 22.5 t, load height 1155 mm, length over buffers 29 590 mm, empty weight 27.6 t, V_{max} 120 km/h (with 20 t axle load), bogie type Y25Ls(s)d1 (Trinity Rail Europe)

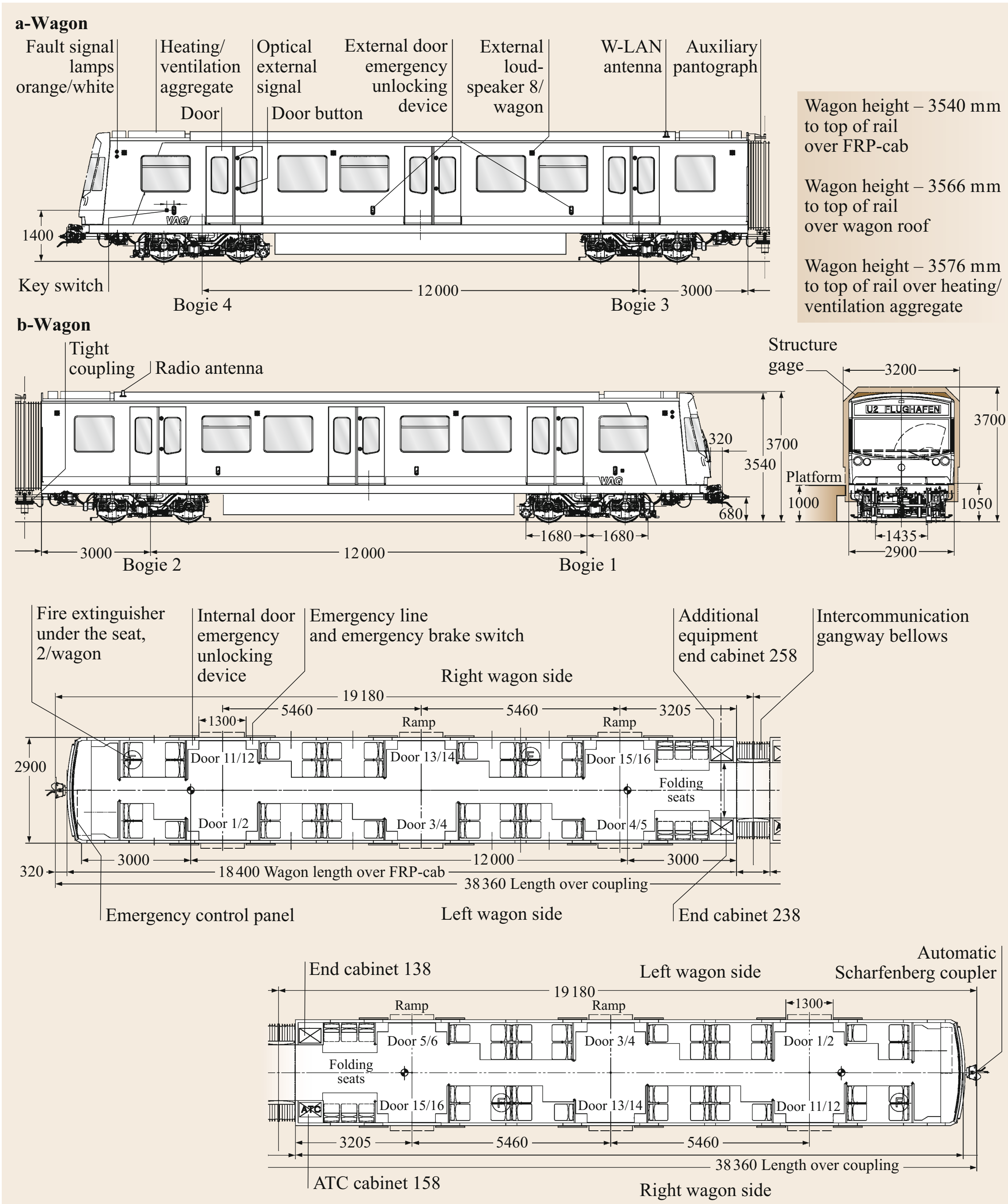


Fig. 23.43 DT3 RUBIN (automatic, driverless metro system) Nürnberg with auxiliary driver desks, but no cabs. Body-shell aluminum extrusion profiles, empty weight 59.2 t, loaded weight 98.4 t, 82 seats, capacity 424 passengers (6 /m^2) (Siemens Transportation Systems, Erlangen) (ATC – automatic train control, FRP – fiber-reinforced plastic)

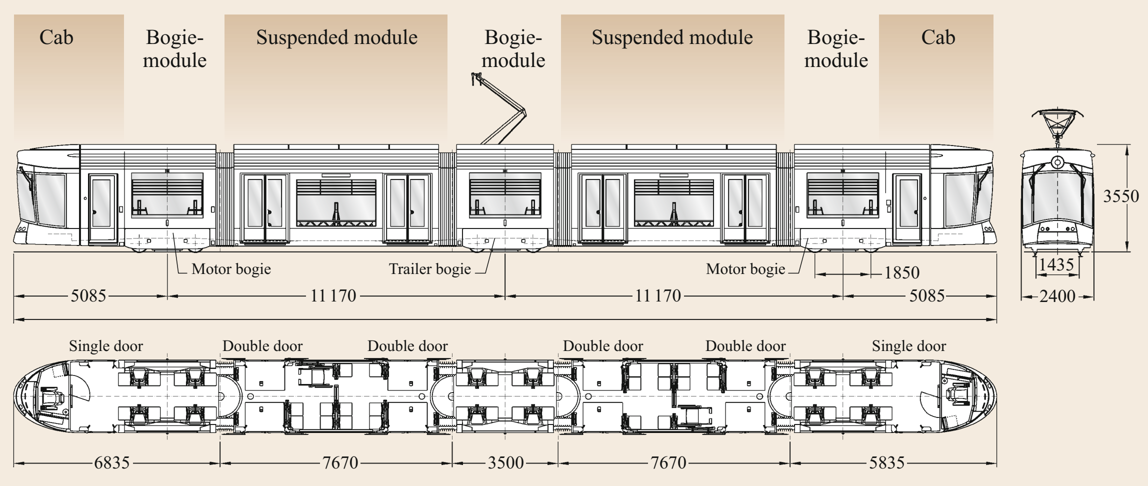


Fig. 23.44 Type of vehicle: Bombardier Flexity outlook, model Marseille: bidirectional, length 32.5 m, height 3.5 m, width 2.4 m, floor height above top of rail (low floor entrance) 320 mm, wheel diameter new/worn 580/520 mm, gauge 1435 mm, car weight (empty) 40 t, car weight (loaded) (4 pass./m^2) 54.3 t, maximum axle load 11 t, minimum horizontal curve radius 25 m, minimum vertical curve radius, crest 450 m, minimum vertical curve radius, sag 350 m, maximum speed 70 km/h, maximum gradient 80‰, nominal current supply: 750 $V_=$, regeneration of energy, low voltage: 24 $V_=$, four three-phase asynchronous motors, motor power: 4 × 115 kW, air-cooled motor, two powered bogies/one trailer bogie, rubber/metal primary suspension, coil spring secondary suspension, eight sanders, antislip, antiskid system, electrical service brake: regenerative, mechanical service brake: disc brake, magnetic brake: 6 × 90 kN (Bombardier Transportation)

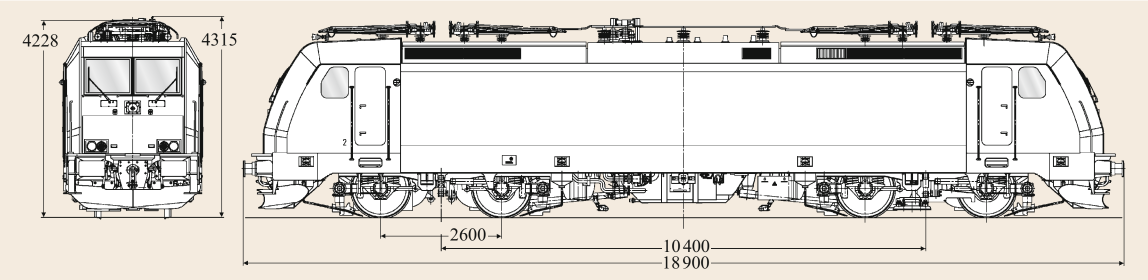


Fig. 23.45 Bombardier Traxx locomotive family, freight and passenger locomotive: weight 86 t, power 5600 kW, max. traction force 300 kN, speed 140, 160 or 200 km/h

23.6 Coupling Systems

As trains are formed from several vehicles, the coupling device used between the vehicles is essential. It transmits not only high forces, but also data channels. Coupling and uncoupling must be done very reliable (Figs. 23.48–23.50).

23.6.1 Coupling

The cone-and-funnel shape of the coupler front face profile ensures a generous gathering range both horizontally and vertically and allows automatic coupling on curves, even with vertical mismatch and very low speed. Minimal force is required for successful coupling.

23.6.2 Coupled

The coupler faces and the locking system form a rigid connection both vertically and horizontally. The parallelogram arrangement of the coupler link provides

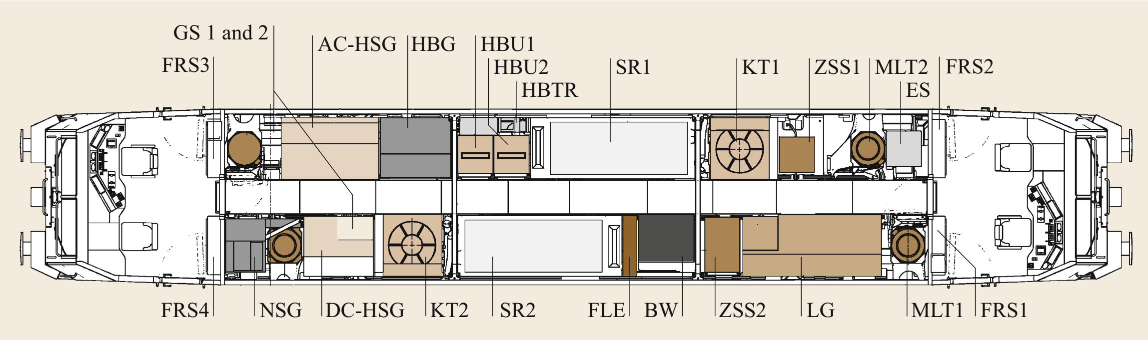


Fig. 23.46 Bombardier transportation (GS 1 and 2 – various nonpermanent equipment (inventory) such as track shoes, earthing rod gloves, tools, etc.; AC-HSG – high-voltage AC cell; AC – alternative current; HBG – auxiliary power distribution and battery charger; HBU1 and 2 – auxiliary converter; HBTR – auxiliary energy supply transformer; SR1 and 2 – traction converter; KT1 and 2 – cooling tower with blower; ZSS1 and 2 – signal equipment (automatic train control); MLT1 and 2 – traction motor blower; ES – electronic control equipment; NSG, NSGAT – low-voltage DC distribution; DC – direct current; DC-HSG high-voltage DC cell; FLE – fire detection and extinguishing equipment; BW – braking resistor; LG – compressed-air supply and braking equipment; FRS 1, 2, 3, 4 – cab rear wall cabinets)

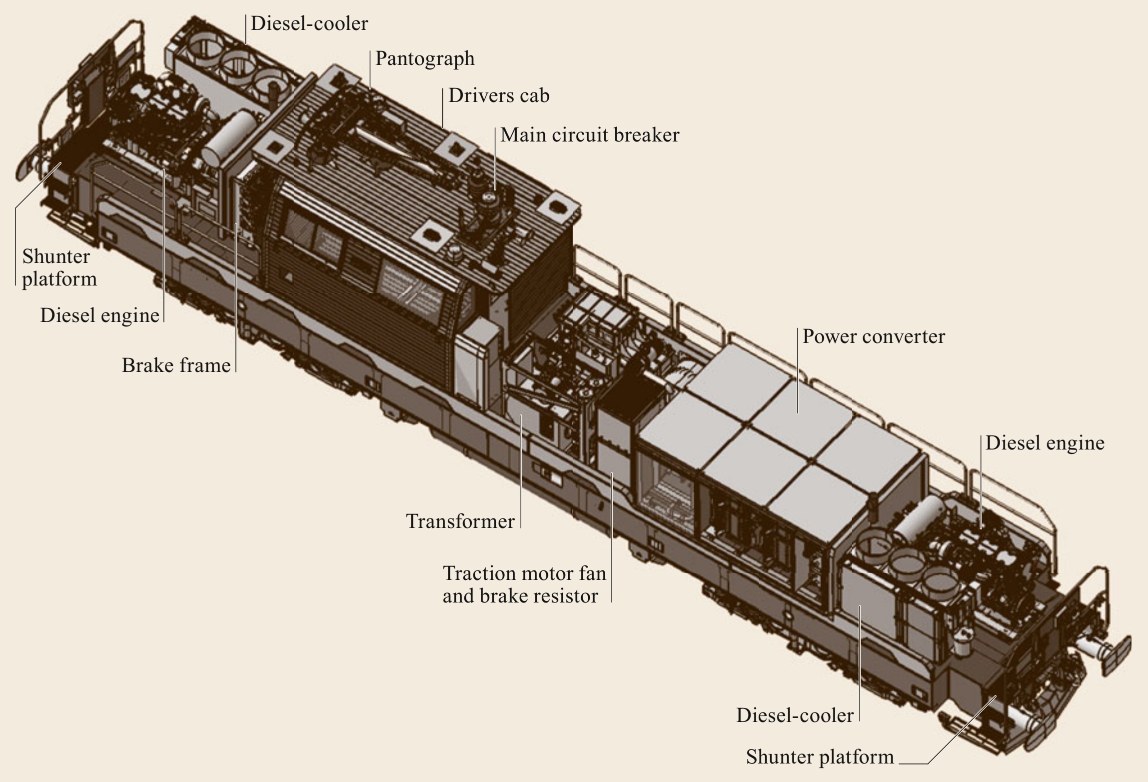


Fig. 23.47 Alstom Hybrid Loco Prima H4 bi-mode, power from catenary (16.7 Hz, 15 kV or 50 Hz, 25 kV) 2000 kW, Diesel 2 × 500 kW, traction force 300 kN, mass 80 t, mass with ballast 90 t, length over buffers 18 750 mm, width 2955 mm, height 4478 mm, bogie center distance 10 500 mm, wheelset distance in bogie 2500 mm, gauge 1435 mm, wheel diameter new 1000 mm, worn 920 mm, min. curve radius 80 m, max. speed 120 km/h, tank capacity 3000 L, operating temperature range −25 °C to 40 °C, multiple operation up to four locomotives (with permission from *ALSTOM* Schienenfahrzeuge AG, Neuhausen am Rheinfall, Switzerland)

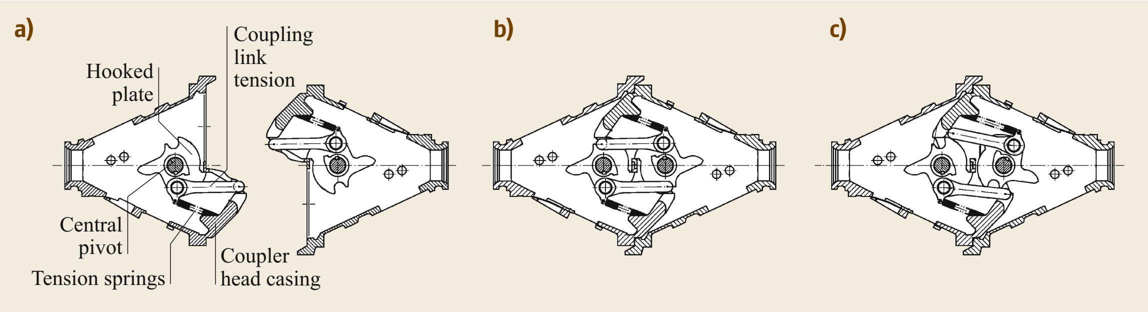


Fig. 23.48a–c Scharfenberg coupler, working principle (Voith Turbo): **(a)** ready to couple, **(b)** coupled, **(c)** uncoupled

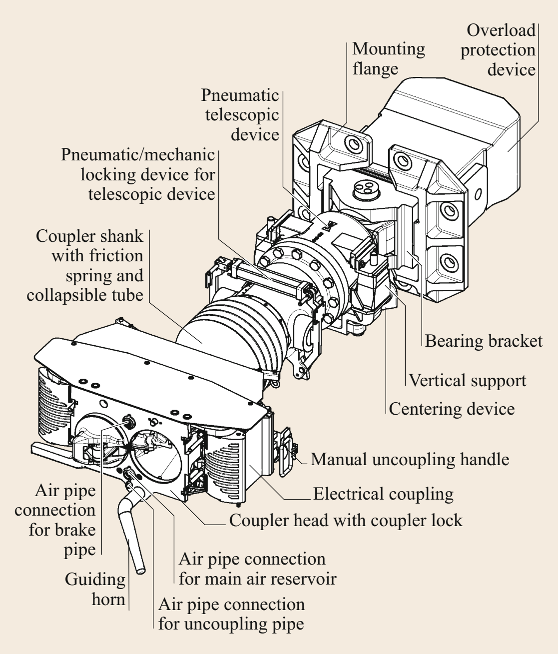


Fig. 23.49 Scharfenberg coupler for high-speed trains ICE 3 (ET-415/417)/Velaro S (AVE S 103)/Talgo 350 (AVE S 102) (Voith Turbo)

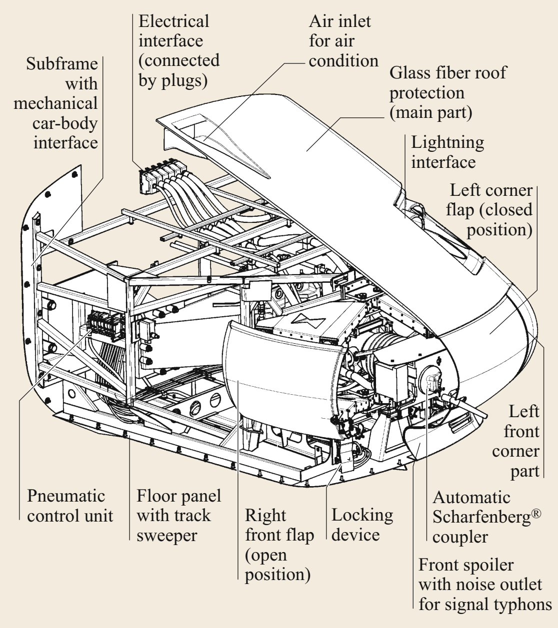


Fig. 23.50 Scharfenberg front nose for high-speed trains Talgo 350 (AVE S 102) (Voith Turbo). Technical data: overall length 2985 mm, overall hight 2042 mm, overall width 2866 mm, weight 1020 kg (without coupler), maximum train speed > 350 km/h, aerodynamic loads ± 11 kPa, mechanical carbody interface 10 screws M 16, front flaps opening angle 64°, material of outside parts, GRP (glass fiber-reinforced plastic) sandwich laminate, fire protection according to DIN 5510 S4

uniform distribution of the draft load. This coupler link design ensures minimal wear and maximum coupler longevity. The rigid and slack-free connection enables jerk-free acceleration and braking, and offers optimum ride comfort. It also prevents the cars from overriding one another in the case of an accident.

23.6.3 Uncoupling

The geometry of the coupler lock enables automatic uncoupling even under traction load. Automatic uncoupling is ensured when misaligned, even on gradient changes. The uncoupling operation is irreversible. Schaku's safety philosophy does not allow recoupling, unless the cars have moved apart and the couplers have separated.

23.7 Safety

23.7.1 Active Safety Systems/Brakes

Brakes transform the kinetic energy of a train into other forms of energy. There are three principal tasks for a brake: bringing the train to a halt (stop braking), maintaining the speed of the train on a gradient (downhill braking), and preventing a stationary train from moving (park braking).

From the mechanical point of view, brakes can be categorized into adhesion-dependent and non-adhesion-dependent brakes. The former type always work via brake moments to wheels, whereas the latter are track brakes or aerodynamic brakes. Adhesion-dependent brakes may be friction brakes (tread or disc brakes) or dynamic brakes (electrodynamic brakes, where a motor works as a generator, or hydrodynamic brakes, which have a hydraulic retarder).

For safety reasons, all rail vehicles must be equipped with an indirectly acting pneumatic brake and the brake pipe must run through the entire train (Fig. 23.51).

The indirectly acting brake operates according to the following principle: If the full brake pressure (typically 5 bar) is available and the brake pipe is at that pressure, then the same pressure is present in the supply air reservoir and the brake cylinder is released by a mechanical spring in the brake cylinder. If the brake pressure is reduced, for instance, by the brake operating device, then the distributor valve connects the supply air reservoir to the brake cylinder and the brake is applied.

The brake is released by increasing the brake pipe pressure again. Then the distributor valve releases the pressure from the brake cylinder into the atmosphere and simultaneously refills the supply air reservoir with the brake pipe pressure. Because of this indirect or automatic behavior, the brakes are also applied if the train breaks apart and the pipe is separated.

Also, the brake can be applied from any location along the brake pipe, for instance, by a control van or by an emergency brake device.

The disadvantage of an indirect brake is that it takes a long time for application (up to 30 s for freight trains) and release (up to 60 s for freight trains). Therefore, vehicles that must be controlled quickly and precisely, for instance, locomotives, must be equipped with an additional direct brake device.

Brake actuators may operate through one-sided (Fig. 23.34) or two-sided (Fig. 23.35) brake blocks. Because of wear and noise demands, modern brake blocks are no longer made from cast iron but from composite materials.

Higher thermal capacity can be achieved by disk brakes: either wheel disk brakes (Figs. 23.36 or 23.37) or shaft disc brakes (Fig. 23.30).

To reduce the braking distance further, rail brakes can be used as they are not dependent on the wheel–rail friction coefficient (Fig. 23.52). If the brake is not used, pneumatic cylinders lift the brake to avoid contact because of track irregularities. The magnets are excited by direct current from batteries. The friction force between

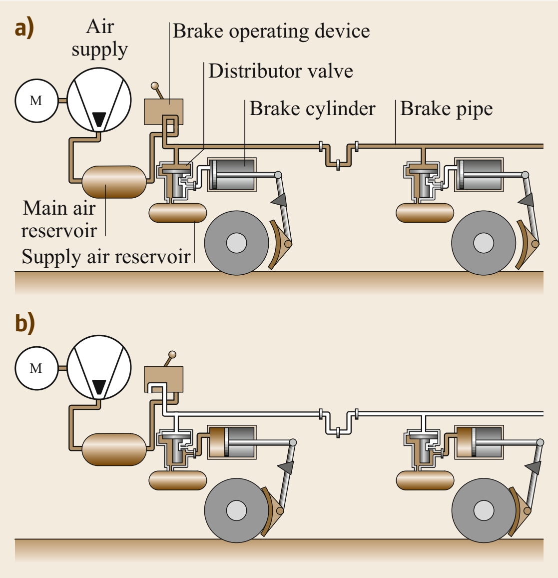


Fig. 23.51a,b Indirect (automatic) train brake. **(a)** Release position, **(b)** brake position

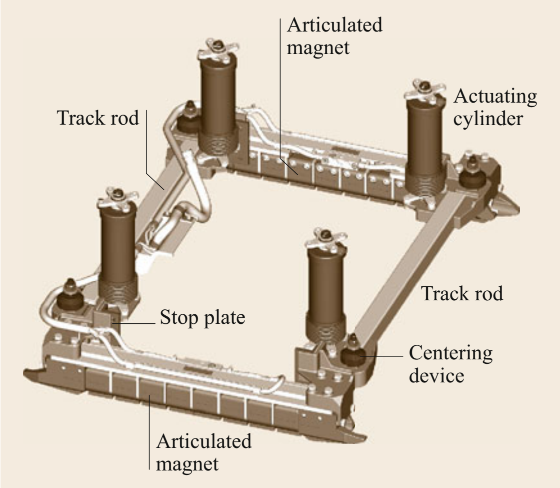


Fig. 23.52 Track brake, speed up to 200 km/h

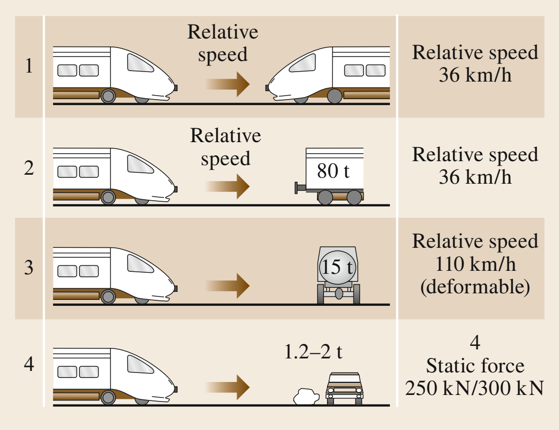


Fig. 23.53 Crash scenarios, main definitions of EN 15277 2016 (weights are given in units of metric tons)

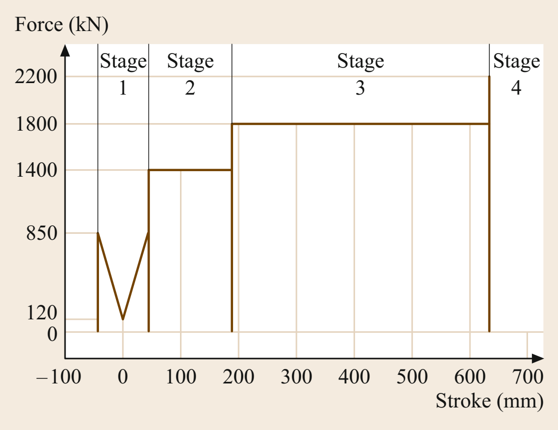


Fig. 23.54 Energy absorption of the coupler from Fig. 23.49. Overall length 2345 mm, telescopic stroke 200 mm, weight 960 kg, vertical swing ±6°, horizontal swing ±20°, tensile strength 850 kN (braking strength 1000 kN), compressive strength 1400 kN (braking strength 2000 kN), minimum coupling speed 0.6 km/h, admissible impact speed allowing buffer to regenerate: 5 km/h, admissible impact speed before coupler tear-off: 20 km/h. Energy absorption capacity. Stage 1: friction spring 120–850 kN, 44 mm stroke; Stage 2: collapsible tube 1400 kN, 145 mm stroke; Stage 3: collapsible tube 1800 kN, 445 mm stroke; Stage 4: shear-off elements 2200 kN; total energy absorption 1025 kJ

the magnet and the rail because of the magnetic forces causes the brake force.

For trams, the lifting device can be avoided because of the lower speeds (Fig. 23.39).

23.7.2 Passive Safety

Though the active safety provision of railway systems is very high due to the implementation of signals, brakes, and train control systems [23.11], collisions cannot be totally avoided. Therefore, it makes sense to reduce the potential human factor through the use of safety devices.

For various crash scenarios (Fig. 23.53), one must ensure that no severe injuries occur to passengers or staff.

Crash Scenarios

- Scenario 1: collision between two identical trains (single-unit train sets or defined formation) at a relative speed of 36 km/h.
- Scenario 2: collision between a train (single-unit train sets or defined formation) and a railway vehicle equipped with side buffers at a speed of 36 km/h. The railway vehicle shall be a four-axle freight wagon with a mass of 80 t.
- Scenario 3: collision at a speed of 110 km/h, on a level crossing, with an obstacle equivalent to a 15 t specially defined lorry.
- Scenario 4: collision with a small or low obstacle such as a car or animal, which shall be addressed by defining the characteristics of an obstacle deflector.

To fulfill these scenarios, a certain energy-absorbing capacity must be achieved by the couplers and body shells. Figure 23.54 shows an example of energy absorption.

23.8 Air Conditioning

For high-speed rail vehicles, closed body shells with fixed windows are essential for safety reasons. Air conditioning is therefore a must. For environmental reasons, air is also used for cooling purposes (Figs. 23.55 and 23.56).

23.8.1 Process Air Loop

In the cooling circuit, the process air is first expanded in the motorized air cycle machine (MAM), and thus cooled. The cold process air then passes through the

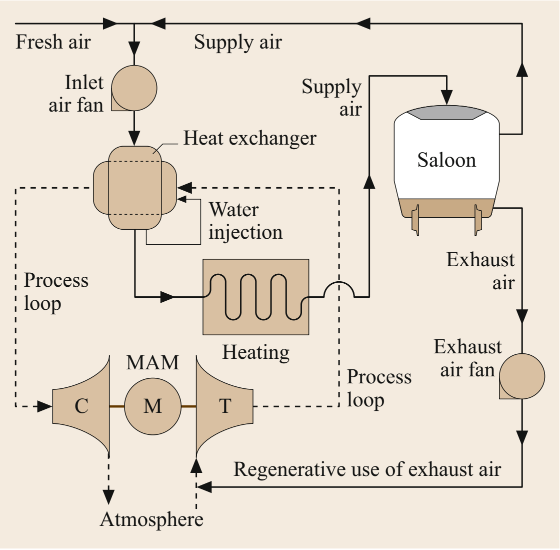


Fig. 23.55 Air cycle concept (Liebherr) (C – compressor; M – motor, T – turbine, MAM – motorized air cycle machine)

downstream heat exchanger to chill the air supply to the passenger saloon. Subsequently, the now heated process air is taken in by the turbocompressor and released to ambient.

The cooling process is controlled by the air cycle machine speed. The cooling power is thus infinitely variable between 0 and 100%.

Supply Air Loop

The supply air is a mixture of ambient fresh air and recirculated air from the vehicle. The supply air fan delivers the supply air through a supply air filter to the heat exchanger, where the required temperature reduction is performed in cooling mode.

The conditioned supply air is passed through an air silencer to the passenger compartment. In heating mode, the MAM is turned off so that the cooling process is deactivated. Controlled operation of the main heater adds the required amount of heat to the air flow.

To balance the air flow to the saloon, an amount of air equivalent to the amount of fresh air added must be exhausted. The cooling energy contained in the exhaust air will be used regeneratively in the process loop to improve the system's efficiency.

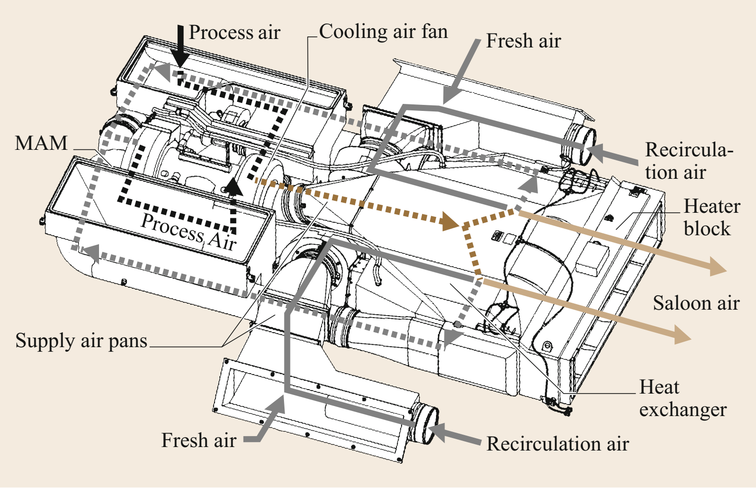


Fig. 23.56 Components and air flow (Liebherr). Roof-mounted air-conditioning unit for high-speed trains, weight 550 kg

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