Chapter 1

Introduction to Railway Systems

Electric traction has become increasingly important for the collective transport of people and goods, since it effectively contributes to the mitigation of congestion and pollution caused by road traffic. In its long history, which began at the end of the nineteenth century, it has experienced remarkable development and, in every era, it promptly made the most of progress in electrical engineering, mechanical engineering, power electronics, and also automation, often creating an incentive for new technology research and a valuable testing ground.

Electric traction has undisputed advantages in areas where levels of performance, safety, environmental compatibility, and economy of service must be guaranteed, such as the rapid transit of urban and suburban populations, long-haul journeys, high-speed rail, and in traversing mountain passes and underwater tunnels.

It should also be noted that the huge investments in infrastructure, equipment, and rolling stock that are required make it very costly to upgrade rail systems with the rhythm that rapid technological progress entails. Moreover, it is exceedingly difficult to radically transform those that may appear "outdated" with others that are modern and efficient. Within these objectives, difficulties arise because of the existence of a multiplicity of types of systems and materials, which place technical and, especially, economic obstacles in the path of a fully interoperable rail. This variety, moreover, makes it difficult to define a culture replete with the present and diffused solutions at an international level.

In the following sections, we will introduce the main features of a rail system that are the basis of differentiation of the various lines around the world.

1.1 TRACTION ELECTRIFICATION SYSTEMS

The term "traction" is intended to indicate the set of phenomena, equipment, and systems that contribute to cause the movement of vehicles; the "electric"

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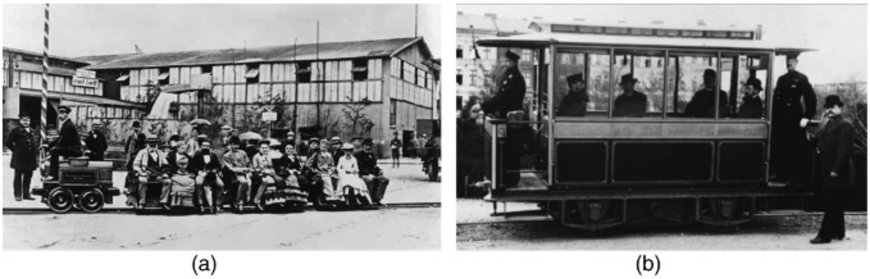
(a) (b)

Figure 1.1 First railroad presented by von Siemens in Berlin in 1879 (a); Lichterfelde tram in 1881 (b). (Reproduced with permission of Siemens AG, Munich/Berlin.)

attribute specifies the mechanical strength for traction that is produced by one or more electric motors. The idea of using electric traction (ET), instead of the thermal characteristic of the steam engine, dates back to the end of the last century with the first direct current motors (DC) derived from the Pacinotti ring (1863). Shortly after the first ET applications, diesel traction proved possible with gasoline, diesel, and gas engines. Diesel engines (diesel cycle) allowed for the construction of powerful locomotives, whereas electric engines had not yet reached the performance necessary to drive heavy vehicles, particularly on long routes.

The first implementation of electric traction motor drive was the small electric railway built, in 1879, by Werner von Siemens for the Berlin Industrial Exhibition (Figure 1.1a): the DC locomotive, with 2.2 kW power, was powered at 150 V and was pulling three small wagons in the exhibition, each with six seats. Two years later, in 1881, Siemens & Halske put into service, at their own expense, the first electric streetcar in Lichterfelde near Berlin, on a line approximately 2.5 km long; the vehicle had an output of 7.5 kW (Figure 1.1b).

Within the span of a few years, there were electric trams in Vienna, Frankfurt, Switzerland, France, and then in the United States, where, in 1886, Van Depoele built a tramway network in Montgomery (Alabama). He accomplished an important step because he used a simple overhead power supply wire on which a metallic contact slid affixed to a wooden grip. The following year in Richmond (Virginia), Sprague perfected the system, using a tubular metallic rod current outlet fitted with a grooved wheel. Besides, he introduced the "nose suspension" for traction drive motors to reduce their mechanical stress. Traction motors were fixed brushes and transmitted the motion to the wheelsets through adapter gear units; the speed adjustment was effected by rheostat and field variation, and a drum "controller" fitted with sliding contacts.

The electric tram, whose power supply had now been increased to 500–600 V, had thus found its almost final configuration, which was used, in fact, for a half century. Around 1890, the system had gained approximately 20 other U.S. cities and was spreading all over the world; in Italy, the Firenze-Fiesole tram was created in 1890. In railways, where steam power still ruled unchallenged, increasingly systemic issues began to surface in the tunnel routes because of the locomotive fumes, which sometimes caused tragic accidents. The problem was acute where the traffic was most intense. This is why electric traction was introduced in 1890 in the urban railways of London and Liverpool and, more specifically, in railways in Baltimore in 1895, on an underground stretch of approximately 5 km between two stations. The electrification system was the same as the tram system, but in view of the high currents involved, it was preferable to replace the contact wire with a large cross-sectional steel wire, arranged in different ways; a solution that quickly resulted in the lateral "third rail" that, particularly in the case of metros, allowed for the adoption of smaller models. The achieved performance was now considerable: in Baltimore, electric locomotives had mass of 90 t and power of 1060 kW. Traction at low-voltage direct current spread in the span of a few years, in addition to the tram and metro segment, to suburban and regional railways, reaching an overall coverage of approximately 20,000 km toward the end of the century.

Therefore, already before 1900, with the development of the railways and, in particular, with the rise of tunnel segments (mountain tunnels, metros, etc.), the introduction of electric traction became necessary to replace steam power and its inherent economic (high cost of coal) and passenger safety (poisoning caused by smoke in the tunnel) issues.

At that time, there were two types of electric motors equipped with the best mechanical properties suitable for traction drive: those with direct current with serial field excitation and those in single-phase alternating current with commutator. The first solution to be adopted was direct current at low voltage (less than 500 V) that did not demonstrate high levels of difficulties. The motors in alternating current, powered at mains frequency, had switching problems at the commutator. Therefore, in order to be used, AC systems had to be powered at lower frequencies (in the United States, the 25 Hz frequency was adopted, whereas in Germany the 15 Hz, that is, a third of the power frequency that at that time was 45 Hz).

The main advantage of alternating current consists in the possibility of adopting a higher voltage supply because interrupting an alternating current is simpler compared with interrupting a direct one. With equal power consumption, this implies not only lower current and therefore lower losses but also lower costs of installation of the contact line (because of the possibility of reducing the section of the conductor, the costs for conductor materials and those for masts, which may be less robust, are also reduced).

Having an AC voltage at a reduced frequency, the reactance of the lines is less than that with mains frequency and the resistance of the circuit is similar to that in direct current, thus guaranteeing low voltage drop. By contrast, however, due to the frequency being different from that of the mains, the power supply needs generating stations exclusively dedicated to the rail or, for interconnection with the grid, converter stations. Years ago, rotating conversion groups were used because power electronics were not sufficiently developed to provide static converters able to cope with this need. However, prior to 1900, the electrical grid was weak and not meshed like the current one and, furthermore, very large loads did not exist, thus the construction of generating stations and high-voltage power lines exclusively dedicated to the railway system was warranted.

Another type of motor that was used for traction was the three-phase asynchronous motor. However, a railway frequency voltage was still required for its operation, namely, a third of the mains frequency. In fact, since high capacity gear units were not available at that time, motors had to be connected to the wheels via kinematic connection with connecting rods and cranks that originated from those of steam locomotives. It followed that the motor rotation speed had to be low and equal to that of the wheels, from which stemmed the need to reduce the power supply frequency. The advantages of this power system were the same as for single-phase electrification in alternating current but, by contrast, had the major disadvantage of needing two overhead conductors (the third phase was provided by the rails), thus introducing major complications especially in proximity of exchanges where there was a need to isolate the overhead conductors to avoid creating short circuits between the phases.

The direct current system had the advantage of having simple and versatile motors and, given the negligible power in use at the time, the fact of having low power supply voltages did not constitute a problem. It is no coincidence that the first applications of DC traction were in tramways and urban transportation, whereas for the electrification of crossing tunnels, where the power involved was greater, the AC system was preferable with much higher rated voltages of approximately 3–4 kV.

Thanks to the progress of power electronics and electromechanical technology, an undulatory current commutator motor was developed after the Second World War by which the vehicle could be powered by a single-phase alternating current line at mains frequency, and the transformation and conversion to direct current were activated onboard. It was therefore possible to break free from the railway frequency and introduce the single-phase electrification system at mains frequency (50 Hz in Europe and 60 Hz in the United States).

Currently, the motors used in modern vehicles are all in alternating current of an induction or permanent magnet synchronous type with inverter drive, for which, in essence, the need to have a suitable voltage for the motor was eliminated. The vehicle is equipped with converters that adapt the line voltage at the inverter input, which controls the traction drive motor; this results in the advantage of interoperability between the various electrification systems.

Today, the most efficient system is the mains frequency single-phase system, suitable for both the regional and suburban transport lines and for high-speed (HS) lines. For the latter, given the high power used, it is essential to have high voltages, in order to limit the absorbed current. If these are too high, they generate uptake problems between the pantograph and overhead line preventing the speed exceeding 250 km/h.

DC electrification systems are still widely used in road-bound urban transport systems, such as metros, streetcars, trolley buses, and so on, with voltages of approximately 750–1500 V and preferable to those at alternating current for their lower impact on the medium-voltage power supply networks. They are also used at higher voltages even for regional railways.

Given the wide use of DC traction, and not just in the railway area, the search for innovative systems that are able to ensure the good power supply quality of traction vehicles, as well as the reduction of interference on the AC network, is increasingly important. In addition to these objectives of purely technical nature, energy savings linked to the recovery of energy during braking play an increasingly important role. Therefore, it is necessary to provide bidirectional power supply systems, also able to receive power from the traction vehicles and to release it back into the electrical network or store it in appropriate storage systems to then allow it to be reused.

1.1.1 DC Electrification

The first major applications of DC electrification date back to 1860 when the first electric machines for tramway traction, with voltage of approximately 500 V DC, were built. After 1890, DC electric traction was also applied to metro railways, with gradually increasing voltages (750, 1500, and 3000 V), with priority to line development in tunnels, where diesel traction had serious problems due to the persisting fumes.

The power supply systems in direct current gave the possibility to derive the power supply directly from the primary lines at mains frequency without introducing unbalances, with contained power factors and distortions, and without the risk of unwanted flux on the contact lines. In addition, the limitation of voltage drop due only to the resistive components of the line impedances and the simplicity of the parallel operation of substations with the bilateral power supply of the segments, combined with the absence of induced voltages in the neighboring lines of the rail network, were advantages that, to date, still make this kind of power supply preferable in many applications.

The success of DC for the power supply of railway lines is due, among other things, to the unique tractive effort of the commutator motor with series excitation.

The first applications of systems with ground electric power supply were those of tramways in Paris and Berlin in 1881. In 1890, it was also introduced in the London metro with power supply from two additional rails compared with line rails.

In order to have a traction power greater than that sufficient solely for the urban and suburban systems, it was necessary to elevate the values of the power supply voltage up to DC 1500 V, and subsequently up to DC 3000 V. The voltage of DC 1500 V was found to be the maximum cost-effective voltage to be generated with the rotating conversion systems installed in the power supply substations of the railway networks. This also prevented an excessively complex connection of the traction drive motors to enable correct operation in the starting phase.Thanks to the experience gained in the United States since 1914 by the Chicago and Milwaukee and St. Paul railroads on electrification at DC 3000 V; in Italy, the secondary line to the standard Torino-Ceres gauge was electrified at DC 4000 V in 1920. Not everyone believed that it was the appropriate time for the continuous use of such high voltage. France, which already had some lines supplied with a low-voltage third rail, preferred not to exceed 1500 V in the electrification of the Pau–Tarbes of Paris–Orléans segment, and adapted the third rail at 1500 V from Chambéry to Modane. Similarly, in the Netherlands, Japan, Australia, and elsewhere, DC at 1500 V was adopted.

In other systems, such as in Italy, with the aim of also allowing relatively heavy traffic on electrified lines, the DC 3000 V was adopted right from the start, as soon as the overall electrification policy of the entire network was implemented. This system has thus supplanted other systems that were developed, such as the three-phase railway frequency, which, particularly following the destruction caused by the Second World War, was reconstructed in DC 3000 V. The DC 3000 V system occurred although, due to the needs of the installed onboard motors, it was necessary to keep two traction motors connected in series, and at least four connected during the starting conditions. These problems were then overcome by the advent of electronic drives that permitted the adjustment of the motor voltage regardless of the power supply. In addition to this, in the first applications, the conversion substations, which were made with rotating systems, were particularly burdensome and complex. The first example of this voltage level was created in the United States by the aforementioned Chicago–Milwaukee–Saint Paul railway line, in which a synchronous motor that was configurable as asynchronous, two 1500 V dynamos connected in series, and the exciter of the synchronous motor and that of the two dynamos were all assembled on the same axis, all at a rated power of 2 MW with ample possibility of overload.

The main power supply limit in direct current consists of the maximum applicable voltage limit. Currently, in fact, it is technically difficult to succeed in developing switches capable of withstanding continuous reestablishment voltages higher than 6 kV. Applications have been researched requiring the implementation of a circuit breaker using some SCR static switches at the AC/DC interface point. In this case, in fact, it is sufficient to stop the control pulses of the thyristors in order to break the current. Such systems, regularly used in systems for high-voltage DC electricity transmission, have not found practical application in the railway area, essentially due to the simultaneous development of single-phase AC systems equally suitable for linear density high power applications (Figure 1.2).

Figure 1.2 DC railway electrification system in Italy.

1.1.2 Single-Phase Electrification at Railway Frequency

In electric rail traction, it is very important to be able to adopt high line voltages because only then can adequate power with sufficiently low current values be transmitted to trains. During the early decades of the twentieth century, the problem was solved with various solutions that, in individual nations, were affected by the influence of special guidelines and technical and economic interests.

In German-speaking countries and initially in the United States, single-phase alternating current was chosen, which made it possible to reach voltages of 10–15 kV and power the traction motors, with conveniently reduced voltage, with a transformer installed onboard the locomotives. On the other hand, the advantage of being able to use single-wire contact lines influenced the choice of the single-phase commutator motor as a traction vehicle motor. This motor, created for DC applications, when operating in alternating current manifests transformative electromotive forces that make it difficult to switch to the commutator. Therefore, in an attempt to reduce the effects, it was necessary to adopt power supply frequencies lower than the mains frequency. As a result, 16 and 2/3 Hz systems were developed in systems with mains frequency of 50 Hz, and 20–25 Hz in systems of 60 Hz.

Figure 1.3 AC railway electrification system at railway frequency in Sweden: (a) primary lines and (b) railway line.

In the United States, in 1906, the New York–New Haven line chose the 25 Hz frequency, with 11 kV. In Europe, the single-phase traction at 6300 V–25 Hz was applied to the Hamburg suburban network and the 5500 V–15 Hz to a private Bavarian railway.

In 1911, the Prussian railways electrified the Dessau–Bitterfeld segment at 10 kV–15 Hz; the tests were successful and were the basis for the agreement of 1912 between the German railway authorities for the adoption of single-phase traction at 15 kV and 16 and 2/3 Hz, which was then introduced in Switzerland, Austria, and, subsequently, in Sweden and Norway (Figure 1.3).

1.1.3 Single-Phase Electrification at Mains Frequency

The use of single-phase alternating current allows for the voltage level of the contact lines to be increased, thereby reducing the current values drawn by the pantograph, and at the same time ensuring the most appropriate values for the power supply of the motors through the simple use of transformers. Furthermore, the somewhat limited current values of the trains in such systems allow for the single-wire contact line to be maintained and for the creation of much lighter and cost-effective contact lines than those for direct current that fit more easily with the mechanical requirements for good collection of current. The adoption of the mains frequency makes the direct connection of the power supply lines to the mains network possible without having to use conversion systems that are not simple transformers. On the other hand, the AC current power supply at mains frequency has demonstrated problems with unbalances induced on the power supply rail from the rail load, which by its nature is a single-phase load. To reduce these unbalances, however, various substation connection

Figure 1.4 AC railway electrification system at mains frequency in (a) the United States and (b) Japan.

specifications have been suggested that, however, result in the loss of the bilateral power supply possibilities and require connection to high-voltage systems, therefore not suitable in urban areas.

The great advantage that the adoption of single-phase mains frequency systems have in relation to the possibility of greatly simplifying substations was advantageously used only when, thanks to the advent of electronic systems, it was possible to overcome the problems relating to the use of a commutator motor. Essentially, after Second World War, an impetus led to the systematic development of networks supplied by AC power at mains frequency. Therefore, the system, which has now also been relaunched in countries that previously adopted DC power, has now reached greater development than that of DC power at 3000 V, covering approximately a third of electrified lines in the world (Figure 1.4).

1.1.4 Three-Phase Electrification at Railway Frequency

The use of the three-phase alternating current has substantially been justified by the possibility of using the three-phase asynchronous motor for traction, with its high qualities of strength and economic feasibility and its potential to be powered directly even at voltages of a few kilovolts.

In 1895, the tramways in Lugano, Switzerland, experimented with the three-phase low frequency system. The locomotives were equipped with motors built according to the rotating field patent of Galileo Ferraris, thus asynchronous three-phase squirrel cage motors. The system was also proposed for railway traction with power plants and primary lines operating at 16.7 Hz, called railway frequency. The voltage of approximately AC 3000 V was selected, even if restricted to crossing lines, in Europe and in the United States. During the early years of the twentieth century, after some successful experiments in Hungary and successful applications in Switzerland, in 1896–1899, on the other segment of Lugano and in the Burgdorh–Thun line, the latter at 750 V–40 Hz, three-phase electric traction was also adopted in Italy. The choice of using the high line voltage, set at the very high value, for those times, of AC 3000 V, mainly fulfilled the will to disengage all the electric traction passenger and goods services, which required the use of locomotives with power up to 1000–1200 kW. The limit of the current collected from an overhead contact line, estimated at approximately 300 A, required the above-stated voltage.

The special frequency solutions were chosen to obtain running speed of 50–60 km/h and even lower, with motors having an acceptable number of poles (in practice 6 or 8), without resorting to adapter gear units, still not considered reliable for high powers. Therefore, motion transmission was via rod–crank kinematic connection, which was due to torque ripple and, thus, from power absorbed by the motors. This ripple sometimes caused interference in the three-phase power supply system and the telecommunication lines parallel to it.

Already in the early 1900s, however, the three-phase system showed its limits, particularly regarding the difficulties of locomotive speed control (being rigidly fixed to the rotation speed of the asynchronous motor running speed) and maintenance of the two-wire contact line that, moreover, made it problematic to overcome the speed of 100 km/h due to mechanical issues. In fact, the “rigidity” of the tractive efforts of the three-phase locomotives and the inability to adjust the speed to the actual needs of the service and the track were one of the main disadvantages of the system, not offset by the robustness and reliability of the asynchronous traction motors and ease by which downhill regenerative braking could be carried out, at speeds slightly higher than those for synchronism. The other weak point, namely, a bipolar contact line, did not allow the speed of 90–100 km/h to be exceeded; this constituted a heavy limit compared with the same steam locomotives that reached a speed of 120–130 km/h.

For these reasons, all countries that had initially adopted the three-phase system abandoned it within a few years, with the exception of Italy that, given the need to take advantage of the large hydroelectric resources available and at the same time reduce coal imports, continued with the application of this power supply system. Therefore, in the early decades of the 1900s, while the three-phase alternating current 3400 V electrified network was expanding in Italy, the single-phase AC with voltages ranging from 11 to 15 kV at 16.7 Hz became predominant in the other countries that had chosen alternating current.

Today, this type of power supply system has been completely abandoned and it will not be described in the remainder of the book for this reason. Only particular applications still survive supplied with three-phase systems at mains frequency (Figure 1.5).

Figure 1.5 Particular three-phase AC railway electrification system at mains frequency for the Corcovado Railway in Rio de Janeiro, Brazil.

1.2 TYPES OF ELECTRIC POWER SUPPLY IN RAILWAY LINES

The technologies available in the various eras of development of electric traction, especially regarding the transmission of power, voltage levels, and speed control of traction drive motors, have led, over time, to the adoption of different technological solutions that persist to this day.

In classic urban transport trolley buses, trams, and metros, DC traction at 600–750 V or 1500 V is always used. The 750 V system is also used in metros on tires adopted in Paris, Montreal, Mexico City, Santiago, Lyon, and Marseille.

On the other hand, for the above-stated reasons, the railway area has a wide variety of systems; the most significant are the following:

- DC at 750 V in Britain (2000 km) with third rail power supply;
- DC at 1500 V in Japan, France (6000 km), the Netherlands, and so on;
- DC at 3000 V Russia (27,600 km), Italy (10,500 km), Poland, Spain (6400 km), South Africa, Brazil, Czech Republic, Slovakia, Belgium, and so on;
- Single-phase alternating current at the special frequency of 16.7 Hz at 15 kV, in Germany, Sweden, Switzerland, Norway, Austria: in total, the single-phase European network at 16.7 Hz covers over 33,000 km. In the United States, the 25 Hz frequency with 11–12 kV was adopted for single-phase alternating current electric traction;
- Single-phase alternating current at mains frequency of 50 or 60 Hz, at 25 kV, in Russia (26,800 km), France (7000 km), Japan, India, former Yugoslavia, China, Great Britain, Hungary, Finland, and so on, and on European high-speed networks where the railway frequency does not exist.

Around the world, the development of electrified railways is greater than 200,000 km (Table 1.1), namely, 17.2% of the global railway network.

Table 1.1 Electric Traction Railway Coverage Around the World

DC mains		
Up to 1 kV	7,650 km	96,980 km (47.3%)
1–2 kV	20,440 km	
Over 2 kV	68,890 km	
AC single-phase mains		
15 kV–16 and 2/3 Hz	32,940 km	105,050 km (51.2 %)
25 kV–50/60 Hz	72,110 km	
Other systems	3,000 km	3,000 km (1.5%)

1.3 TRACK AND TRAIN WHEEL

Figure 1.6 schematically represents a track consisting of two rails supported on sleepers (treated wood, concrete, or steel) and anchored to them by means of appropriate baseplates. In railway lines, the sleepers are in turn anchored in a ballast of crushed stone or on concrete platforms equipped with elements that limit the transmission of vibrations. When crossing bridges, the tracks may be laid directly on the structure, with appropriate measures implemented to allow for controlled thermal expansion.

A typical rail cross section is shown in Figure 1.7: Recall that there is a set of standardized profiles, characterized according to linear mass, ranging from light rails with linear mass from 21 to 36 kg/m, to heavy ones from 50 to 60 kg/m used in trunk railway and metro lines.

The track is made from sections of rail of length *l* connected by joints that allow for some movement due to thermal expansion.

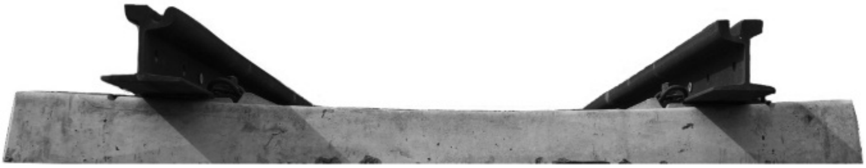

Figure 1.6 Basic representation of a track.

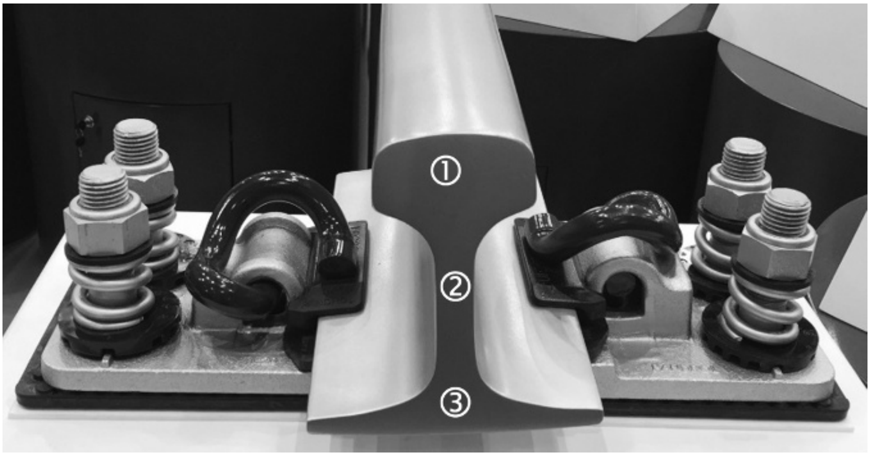

Figure 1.7 Section of a rail with linear mass of 60 kg/m (cross section = 7886 mm^2; moment of inertia $J_x = 3055\ cm^4$; moment of inertia $J_y = 513\ cm^4$) clamped on a sleeper: (1) head, (2) web, and (3) foot.

Table 1.2 Distribution of World Railway Networks According to Gauge

Gauge	km	Extension %
Narrow, up to 914 mm	21,900	1.8
Narrow, 950–1067 mm	213,300	17.9
Normal, 1432–1445 mm	703,200	59.1
1498–1524 mm (Russia)	150,200	12.6
Broad, 1580–1676 mm	102,100	8.6
	1,190,700	100

Source: From Railway Directory, London 1993.

The track foundation can be significantly improved by reducing the distance between the sleepers and increasing their mass, or by laying them in concrete; this allows for the joints to be eliminated, as the rails can be butted and welded in place, thus achieving long uninterrupted welded rail sections with significant benefits for the ride quality of the rolling stock.

In electric traction lines, the track is normally used as the negative conductor of the power supply line; since the joints give rise to a significant additional electric resistance, they are short-circuited by means of flexible copper cable ties

Figure 1.8 Broad gauge in regional Spanish railway lines.

welded to the adjacent rail pieces. There is a clear advantage, also from this point of view, in eliminating the joints or, at least, in reducing their number.

The distance between the inner faces of the rails at the head is called the gauge: The most common one used in approximately 60% of the world's railways (Table 1.2) is 1435 mm; at the extremes, there are narrow gauge and broad gauge railways: 1520 mm is used in Russia; 1600–1668–1676 mm in Spain (Figure 1.8), Portugal, Latin America, and India.

Wheels have a steel rim that rests on the upper surface of the rail head, and it has a guiding flange (Figure 1.9). The wheels are normally of rigid construction, consisting of a rim (tire) fitted to a steel body as shown in Figure 1.10, or forged in a single solid unit.

Figure 1.9 Steel wheels with rounded flange for railway and subway applications.

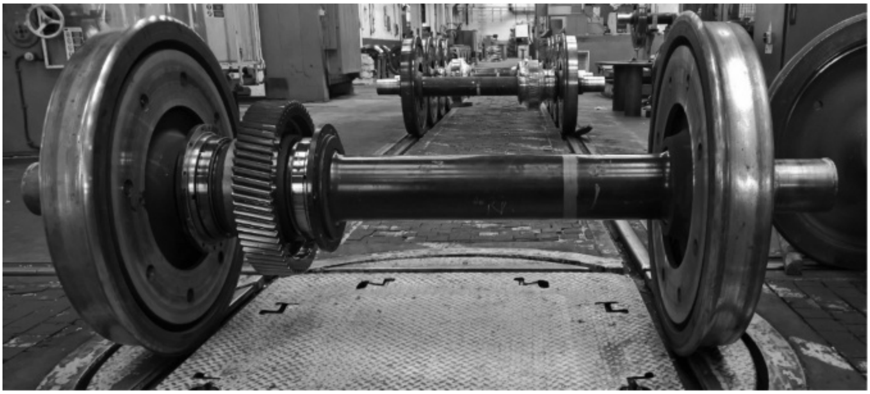

Figure 1.10 Wheelset for railway applications.

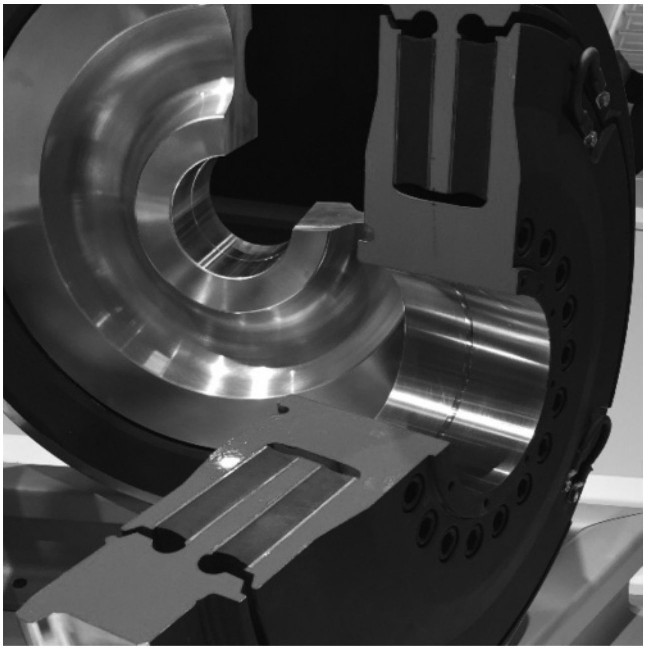

Figure 1.11 Elastic wheel with flat flange for tramway applications.

In trams elastic wheels may be used with rubber segments fitted between wheel and tire. Two wheels and an axle constitute a wheelset, as shown in Figure 1.11; the wheelset is automatically guided by the tire flanges; this system is very effective and enables the formation of convoys that may be very long, as they are drawn or pushed on the tracks.