

Andreas Steimel

Electric Traction – Motive Power and Energy Supply –

**Basics and Practical
Experience**

**Oldenbourg
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Prof. Dr.-Ing. Andreas Steimel

Electric Traction – Motive Power and Energie Supply

Basics and Practical Experience

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Preface

Intention of this book and synopsis

This book has evolved from the lecture series “Elektrische Bahnen” (“Electric railways”) which has been held at Ruhr-Universität Bochum since 1996. Its primary audience are students of electrical energy technologies, control engineering and mechanical engineering as well as young engineers of electrical engineering, especially in the fields of power electronics, in railway industry and in railway-operating companies.

The book intends to convey mechanical fundamentals of electric railway propulsion, which includes rail-bound guidance, transmission of traction effort from wheel to rail under the influence of non-constant levels of adhesion and the transmission of motor torque to a spring-mounted and thus sliding drive set.

The focal point of the book will be the disposition of electric traction units powered by three-phase induction motors. We shall discuss the stationary and dynamical behaviour of the squirrel-cage induction motor and the principle and construction features of pulse-controlled inverters, as well as scalar and field-oriented control systems and four-quadrant power converters, feeding the DC link of the inverters.

As is appropriate to the lesser importance these drive systems have nowadays, we will consider DC and AC commutator motors only in a cursory fashion, as well as their voltage control. By example, we will take a look at high-performance locomotives, high-speed trains, diesel-electrically powered locomotives and commuter passenger systems.

Since the specific railway energy supply network being separate from the national power utility is a key factor in operating electrical railway systems, chapter 13 will offer a detailed look at the various systems of railway power supply, under special consideration of converter technology in this field as, for example, the line interference of inverter-fed traction units (see chapter 14). Chapter 15 features an abridged overview on the most important systems of field-oriented control of induction motors and about an innovative speed-sensorless control approach for induction motor drives, coming now into the commercial phase. Chapter 16 suggests further reading, while chapter 17 will provide lecture-oriented exercise (including sample solutions).

The Anglo-american reader may notice that the lion’s share of examples has been derived from central European (German, Swiss, Austrian) samples of Electric Traction. This is mainly due to the author’s personal experience as well as the fact that most fundamental research, design and construction of locomotives utilizing power electronics took place in these countries, notably with BBC and Siemens. We wish to apologize that British and American locomotives only feature rarely; however, an approach based on personal experience appeared to be the most sensible way to tackle the subject.

The translation follows the International Electrotechnical vocabulary (IEV, [31]) of IEC and the UIC Railway Dictionary [32]. Corresponding to the dominant use in international technical and scientific literature, the British English term ‘bogie’ will be used for the German word ‘Drehgestell’ and not the term ‘truck’, usual in American English. Finally, please excuse the use of German symbol standards in formulae and diagrams, since the vast number of variables involved would make a complete exchange a daunting task.

Basic knowledge

This book requires the following:

Basic knowledge of construction and operative behaviour of electrical machines and transformers according e.g. to lecture “Grundlagen der Energietechnik” ([V1], Basics of Electrical Power Engineering), basic knowledge of power electronics [V2], basic knowledge of mechanics.

Words of thanks

Every industrial engineer stands on the shoulders of the colleagues before him. So I want to express my gratitude first to my father Karl Steimel, 1956–1967 head of R&D of AEG in Frankfurt/ Germany, one of the indefatigable initiators of development in inverter-fed induction motors drives, and my academic teacher, R. Jötten at TU Darmstadt. Then – only to mention very few – my elder colleagues at Brown, Boveri & Cie. in power electronics as L. Abraham, E. Futterlieb, the late W. Lienau, H. Stemmler and W. Runge, as well as in locomotive engineering W. Teich, J. Körber, M. Schulz and the late R. Gammert, R. Pfeiffer from Technical University Darmstadt and W.-D. Weigel from Siemens Transportation Systems. Next my senior colleague at Ruhr-University Bochum, M. Depenbrock, the inventor of the Four-Quadrant Converter and of Direct Self Control (DSC), and our Ph. D. students working on perfection of DSC and the line behaviour of traction converters and on the development of robust sensorless operation of induction motors. Last but not least thank is to be said to my son Christian for the translation, the secretary and the draughtswoman of our chair in Bochum and the critical readers of the first two editions (in German), ferreting out hidden errors of the first edition.

Table of Contents

Preface	V
1	Basic principles	1
1.1	Definitions	1
1.1.1	So, what is a “railway“?	1
1.1.2	Classification of Railways	1
1.2	Historical development of electrical railwaying	2
1.3	A short overview of railway electrical supply networks	6
1.3.1	Direct-current railway systems	6
1.3.2	Single-phase alternating current railway systems	7
1.3.3	Three-phase three-conductor railway systems	8
1.3.4	Standardized voltages of the train line	8
1.3.5	State of electrification in selected countries	9
1.4	Comparison of traction systems	9
1.5	The European railway industry	10
2	The mechanics of railway transportation	13
2.1	Principles of rail-guidance	13
2.1.1	Gauges	13
2.1.2	Guidance of wheelset in track	14
2.1.3	Frame and bogie	16
2.1.4	Bogies with self-steering wheelsets	20
2.1.5	Curvature-dependant body-tilting equipment	21
2.2	Train resistance	23
2.2.1	Train rolling resistance	23
2.2.2	Train resistance due to curves	24
2.2.3	Train gradient resistance	24
2.2.4	Train acceleration resistance	25
2.2.5	Permanent and starting tractive efforts (<i>F-v</i> diagram)	25
2.2.6	Load transfer	26
2.3	Adhesion, slip-and-slide control	29
2.4	Traveling time loss by acceleration and braking	33
3	Running gear and drive of traction vehicles	35
3.1	Classification of traction vehicles and wheel arrangement	35
3.1.1	Classification of traction vehicle types	35
3.1.2	Wheel arrangement	36
3.2	Mechanical components of power transmission	37
4	Commutator traction motors and their control	47
4.1	DC traction motor	47
4.1.1	DC commutator motor	47
4.1.2	Variation of the terminal voltage by series resistors	52
4.1.3	Control of motor voltage in DC-supplied systems by means of a DC chopper	53
4.1.4	Control of the motor voltage with AC systems by phase-control rectifiers	58

4.2	AC traction motor	62
4.2.1	AC commutator motor	62
4.2.2	Control of motor voltage with the AC commutator motor	63
5	Synchronous traction motors and their control	67
5.1	Synchronous motor	67
5.2	Feeding the synchronous traction motor with a load-commutated inverter	69
6	Induction traction motors and their control	73
6.1	Construction and stationary behaviour of the induction machine	73
6.2	Voltage-source inverter (VSI)	81
6.3	Controlled operation of inverter-fed induction motor	85
6.4	Group supply of induction traction motors	89
6.5	Four-quadrant converter	91
6.6	Inverter circuit and construction technology	96
6.6.1	Forced-commutated thyristor voltage-source inverter	96
6.6.2	Inverter with Gate-Turn-Off (GTO) thyristors	98
6.6.3	IGBT Inverter	100
6.6.4	Three-level inverter	101
6.6.5	Current-source inverter	102
6.6.6	Cooling and constructional aspects	103
7	Electric traction vehicles for main-line service	111
7.1	Electric locomotives with DC traction motors	111
7.1.1	DC chopper control	111
7.1.2	Thyristor phase-angle control	111
7.2	Electric traction vehicles with AC commutator traction motors	115
7.3	Electric traction vehicles with synchronous traction motors	117
7.4	Electric traction vehicles with induction traction motors	118
7.4.1	Locomotives	118
7.4.2	High-speed trains	124
8	Multi-system traction vehicles	129
8.1	Examples with DC commutator motors and synchronous motors	129
8.2	Examples with inverter-fed induction motors	132
9	Diesel-electric traction vehicles	137
9.1	Conventional technologies – hydraulic and electric drive chain	137
9.2	Diesel-electric traction vehicles with three-phase drives	142
9.3	Dual-mode traction vehicles	150
10	Suburban and Light Rail traction vehicles	153
10.1	Metro and Underground trains	154
10.2	Light Rail and Light Rapid Transit vehicles, low-floor technology	157
10.2.1	Conventional tramway carriages and articulated trains	158
10.2.2	Dual-system Light Rapid Transit vehicles	160
10.2.3	Low-floor light rail vehicles	162
10.3	Traction vehicles with energy storage	170

11	Braking technology	173
11.1	Automatic air brake	173
11.2	Magnet rail brake	177
11.3	Linear eddy-current brake	178
12	Uncommon types of railways	179
12.1	Track-guided railways on pressurized rubber-tire wheels	179
12.2	Suspension Railways	181
12.3	Trackless "railway" transportation systems	184
12.4	Magnetic Levitation Railways (MagLev)	188
12.4.1	Support and Guidance	188
12.4.2	Contactless transmission of traction force	190
12.4.3	Converter	193
12.4.4	On-board power supply of vehicles	193
12.4.5	Application Pudong International Airport–Shanghai	194
13	Power supply of electric railways	195
13.1	AC railways operating at $16\frac{2}{3}$ (16.7) Hz	195
13.1.1	Centralized and decentralized supply in Germany	195
13.1.2	Rotary converters	199
13.1.3	Static converters	202
13.2	AC railways operating at 50 Hz	204
13.2.1	Properties, and a comparison to the $16\frac{2}{3}$ -Hz system	204
13.2.2	Autotransformer system	207
13.2.3	Increased operating voltage	208
13.3	DC railways	209
13.4	Contact lines and current collectors	212
14	Line interference	219
14.1	Survey	219
14.2	Emission sources in DC railway systems	220
14.2.1	Voltage harmonics of the substation rectifiers	220
14.2.2	Input-current harmonics of a step-down DC chopper	221
14.2.3	Input-current harmonics of an ASCI	222
14.2.4	Input-current harmonics of a VSI	223
14.3	Emission sources in AC railway systems	224
14.3.1	Voltage harmonics of the power supply	224
14.3.2	Input-current harmonics by phase-angle control	224
14.3.3	Input-current harmonics by inverter input current	228
14.3.4	Input voltage harmonics of the four-quadrant converter	228
14.3.5	Modulation of VSI input-current harmonics by the four-quadrant converter	233
14.4	Impedances of the railway power-supply system	234
14.5	Mechanisms of coupling, psophometric interference current	237
14.6	Track circuits	239
14.7	Suppression of low-frequent interference currents of power-electronic converters	240
14.8	High-frequent disturbance	241

15	Appendix	243
15.1	Control strategies for traction induction motor drives	243
15.1.1	Demands by railway traction	243
15.1.2	Space-phasor representation of three-phase systems	243
15.1.3	Dynamical equivalent circuit diagram of an Induction Machine	244
15.1.4	Field-oriented control	245
15.1.5	Direct Self Control	250
15.1.6	Indirect Stator-quantities Control	255
15.1.7	Conclusion	257
15.2	Speed-sensorless stator-flux-oriented control of induction motor drives in traction	258
15.2.1	Introduction	258
15.2.2	Model of the induction machine	259
15.2.3	Stator-flux oriented control	260
15.2.4	Field-weakening operation	262
15.2.5	Correction of inverter-voltage errors	263
15.2.6	Sensorless identification of speed	264
15.2.7	Stator-resistance estimation	267
15.2.8	Suppression of parasitic DC voltages	269
15.2.9	Operation with infinitely slow change between driving and braking	269
15.2.10	Difference of Indirect Stator-Quantities Control and Direct Vector Control ..	272
15.2.11	Conclusion	273
15.3	Unified Notation of Carriages of UIC and OSShD	274
15.4	Symbols and Abbreviations	276
16	References	279
16.1	Books	279
16.2	Journals	281
16.3	Selected papers from journals and conferences	281
17	Exercises with exemplary solutions	295
17.1	F-v-Diagram of a Universal Locomotive	295
17.2	Mechanical design of a Universal Locomotive	297
17.3	Mean traveling speed of a Metro train	298
17.4	DC traction motor fed by a DC chopper	301
17.5	Two-pulse bridge in half-controllable connection of pairs of arms with sequential phase control	304
17.6	Three-phase induction traction motor for a Universal Locomotive with 6,400 kW	309
17.7	Wheel-tire diameter differences at group supply of traction IM	312
17.8	Four-quadrant converter for a Universal Locomotive 6,400 kW	315
17.9	Stopping distance of a Light Rapid Transit Train with and without magnetic rail brake	319
17.10	Supply of electric railway lines from the 50-Hz utility	321
Index	325

1 Basic principles

1.1 Definitions

1.1.1 So, what is a “railway“?

The most comprehensive definition of a “railway” is, according to DIN 57115 (VDE 0115)¹ part 1: “track-bound and non-track-bound transport systems for passenger and cargo transportation”. A more concise interpretation may be found in the 1962 edition of the Encyclopedia Britannica: “Railway, a mode of land transportation the roadway of which consists of one or more tracks, each having two parallel steel rails. Over these rails move freight and passenger carrying vehicles, or cars, with flanged wheels. The cars are usually pulled or pushed by a locomotive, although they may be self-propelled”.

We shall define a “railway“ in the narrower sense of “a self-propelled track-bound system of transport”. The defining features are track-bound rail guidance and the possibility of creating trains by linking single vehicular units, the iron rails not being necessarily a part of the system. In chapter 12, we will encounter various track-bound systems operating without such rails, which usually are considered key to the concept of “railwaying”.

The principle of track-bound rail guidance (rail-wheel system) allows for transport speeds peaking at 575 kilometres per hour (~360 mph); higher speeds are, in effect, inachievable for land-bound vehicles due to the power requirement rising by the speed to the third power. Regular high-speed train service in France, Germany and Japan operate at speeds of up to 330 kph (over 200 mph). Modern rail systems, on the other hand, allow for composition of trains of up to 20,000 metric tons of weight (4.4 *million* lbs.), which can be safely operated at speeds of up to 60 kph (37 mph) at minimal personnel requirements. Commuter transport may nowadays operate on a fully automatic basis (e.g. without drivers).

1.1.2 Classification of Railways

Railways may be classified by a host of different categories:

- By ownership

National railways and private enterprise railways

Whereas the 19th century had seen a co-existence of national and private railways, Europe and most of the worlds’ countries (excluding the United States of America) nationalized the majority of private rail networks in the years from 1880 onwards to about 1947. This was mainly due to structural and fiscal reasoning, especially in newly emerging national states such as Hungary, Italy and Germany and, later on, former colonies having achieved their independence; furthermore, to provide ample infrastructure for industrialization; finally, to meet the vast transport requirements of the two World Wars and their consequences.

¹ DIN: Deutsche Industrienorm, German Industrial Standard

During the second half of the 20th century, the railways' importance declined due to the rise of individual transport, in the form of the private motor car and lorry, as well as the airplane, whose speed and versatility the railway could not apparently match. Only by the close of the century, a change of mind set in: due to congestion of public traffic by individual transport, track-bound public mass transit becomes more and more appealing. In addition, governmental control proved inadequate to meet the demands to the railway systems; thus, programs of decentralization and deregulation were applied to railway transit. EU Directive 91/440 intended to enable and organize the barrier-free coexistence and competition of governmental and private railway operators. However, due to the massive governmental subsidies given to individual and airborne transport in the latter half of the century, public mass transit is unable to operate economically in most areas and is thus dependent on governmental additional funding.

- By specific task of traffic
Public-service railways (being subject to schedule operation and conveyance obligation);
Non-public service railways (including, for example, factory, harbor and mining railways).
- By importance of traffic
Major networks of national and international long-distance traffic;
Regional networks for a limited area of service;
Minor networks for local service;
Commuter networks for public mass transit in cities and conurbations. These are further specified as tramways or Light Rail Systems, Light Rapid Transit ('Stadtbahnen' in German), underground railways and suburban (mass transit) railways.
- Special transportation systems:
This includes purely touristic systems like funicular and other cable systems, automated cab railways ("people mover") on airport duty and isolated junction lines, for example the Haneda International Airport – Downtown Tokyo or the Pudong International Airport – Downtown Shanghai lines. Finally, there were barge tow railways, the sole surviving example being the system of the Panama Canal Authority.

1.2 Historical development of electrical railwaying

Having had a precursor in the tracks ground into Roman roads (with a width similar to modern standard gauge, 1435 mm or 4ft 8.5in), Europe only saw the return of track systems in the early modern age, in the shape of mining railways: wooden lorries, operating on wide wooden rails and guided by a track nail between the two rails. By the middle of the 18th century, coal-mining companies in England replaced the wooden tracks by iron ones; guidance was achieved by angle irons affixed to the outside of the track. The advantages were most obvious: The rolling friction was greatly reduced, the durability of the rails increased, and this actually laid the groundwork for the use of machine traction. Shortly after, the flanged wheel running on rails of "a mushroom-like" cross-section appeared.

In 1804, F. Trevithick used Watt's high-pressure steam engine on a rail-bound vehicle for the first time: the steam locomotive was born. From 1810 onwards, such locomotives were in widespread service in coal mines. In 1825, the very first public transport railway was established between Stockton and Darlington in North-East England, George and Robert Stevenson introducing today's 4ft 8.5in standard gauge on this occasion. In 1835, the first such railway opened service in Germany, connecting Nuremberg and Fuerth.

From isolated beginnings, European railwaying downright exploded in the following years; however, a bewildering variety of technical standards was used. By 1850, a necessary trend toward standardization of gauge, coupling system and general size of units emerged, leading to technical standards which allowed for a Europe-wide network of compatible standards. Some countries retained different gauges for strategic reasons, most notably Russia, but also including Spain and Portugal. Minor networks and colonial railways often chose narrow-gauge systems for financial reasons.

In the 1820s, A.M Ampere and M. Faraday had discovered electro-magnetic force and electrical induction, respectively. Subsequently, this led to research how to use this new source of power for railways. As early as in 1836, an electric railcar was tested in Scotland, being powered by electric motors which resemble recent Switched Reluctance Motors. These trials, however, did not yield considerable success, since there still was no effective, reliable and economically sound source of electrical power. Such machines could only operate using early batteries like Volta's elements. Only the discovery of the Electrodynamical Principle by W. von Siemens and Ch. Wheatstone in the 1860s allowed for effectively unlimited amounts of power using generators and thus to increase the output of electrical machines at discretion.

In 1879, Siemens displayed the first electrically powered locomotive at the Berlin Commerce Fair (Fig. 1.1). It was used for transporting visitors on the Fairgrounds, and operated on a direct current (DC) motor of 2.2 kilowatts continuous output, which was fed from a current-carrying rail placed between the two main rails, which in turn re-routed the current from the engine to the generator. Maximum speed attained was 13 kph (8 mph), and the engine's weight came to about two metric tons (4,400 pounds), which means a weight-to-power ratio of 1100 kilograms per kilowatt (modern high-power locomotives attain values of about 14 kilograms per kilowatt!). From 1882 onwards, this direct-current propulsion system was applied to tramways and mining railways, with power being usually supplied via an overhead contact line

The first fully electrified railway was opened in 1895 by the Baltimore & Ohio RR in the United States of America: a five-kilometre city tunnel was electrified using a 675 Volt overhead system; electrical motors of 4-270 kilowatt output were used, thus countering the smoke problem.



Fig. 1.1: First electric locomotive by W. v. Siemens 1879, Berlin

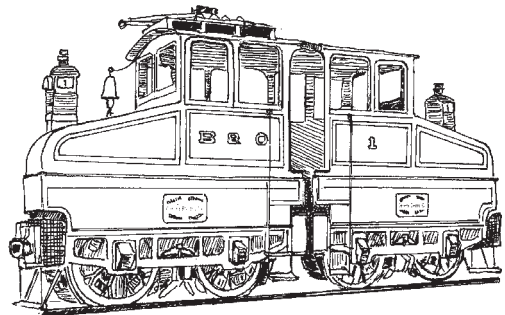


Fig. 1.2: DC locomotive of Baltimore & Ohio Railroad, 1895

The commutator bar voltage, however, limited maximum working voltage to about 750 Volt by the turn of the century. It was only about the time of the Great War that a maximum voltage limit of 1500 Volt was attained; this level is considered a practical economic limit even today. With such voltage, tramways and commuter railways could operate economically. Long-distance railways, however, experienced unacceptable voltage drop, even if using intermittent feeding rectifier units in very short intervals.

As was the case in national power supply, railways were keen on introducing alternating current systems, thus being able to transfer electrical energy at the required high voltage level (since direct current electricity's voltage level cannot easily be transformed). However, there were no traction motors running on AC yet that provided sufficient output levels. But there was already the squirrel-cage induction motor. From about 1890, secondary railways in Northern Italy and later on the Simplon Tunnel were electrified using three-phase alternating current (3AC). In 1903, the "Studiengesellschaft für elektrischen Schnellverkehr" (Research society for electrical rapid transport) held trials using two electric railcars fed from a three-pole overhead system (Fig. 1.3). These vehicles attained speeds of up to 210 kph (130 mph). The 3AC system, however, still suffered from being complicated to construct, especially at intersections and switches, and allowing only a limited number of economic speeds due to the fixed line frequency. As more advanced systems became available, most of the cumbersome three-phase systems had been eliminated by 1970.

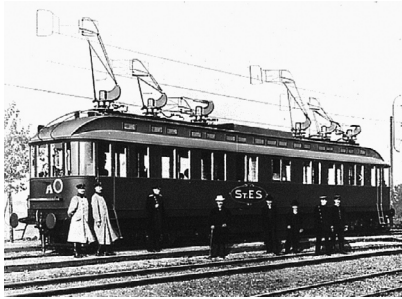


Fig. 1.3: Three-phase high speed experimental railcar by AEG 1903; 210 kph

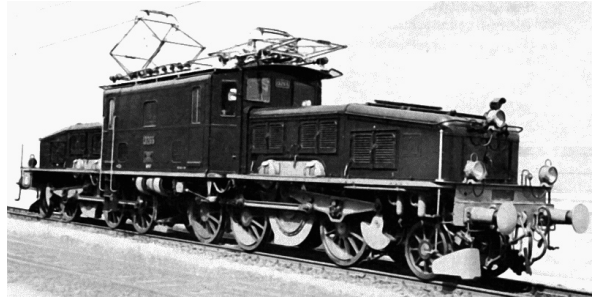


Fig. 1.4: SBB Ce 6/8 II for single-phase AC 15 kV/16²/₃ Hz; 1920; 1650 kW

In 1903, H. Behn-Eschenburg, engineer at Maschinenfabrik Oerlikon/Switzerland succeeded in applying ohmic commutation-pole shunts to the series-wound commutator motor, thus achieving compatibility with alternating current feed. In 1905, trials at Seebach-Wettingen near Zurich met with success. In 1912, the German Länderbahnen of Prussia, Hesse, Bavaria and Baden signed an "Agreement on the execution of electrical railway transport", setting standards for single-phase alternating voltage (1AC) for traction at 15 kV and 16²/₃ Hz. This low special frequency was necessary to achieve sparkless commutation of the series-wound commutator motor. Shortly afterwards, Austria, Sweden, Switzerland and Norway introduced this system as well. Fig. 1.4 depicts the famous "Krokodil" electrical locomotive of the Swiss Federal Railway (SBB) used on the Gotthard Pass route in 1920.

A railway supply network separate from the national utility grid operating at proprietary frequency, however, was a burden many railway companies were unable to shoulder. Early experiments of using the 50-Hz "national" frequency for traction did not yield satisfying results until 1936, when the German electrical industry tested various prototype locomotives at the Höllental trial line in the Black Forest, of which those with mercury-vapor rectifiers proved most successful.

After the Second World War, that region was part of the French occupation zone; French engineers got to study the new system and learned of its advantages and peculiarities, using it then for electrification of the Lorraine–Nord France coal railways (Fig. 1.5), introducing a nominal voltage of 25 kV. From thereon, the 50-Hz system was adopted all over the world, using this frequency unless the national network operated at 60 Hz.

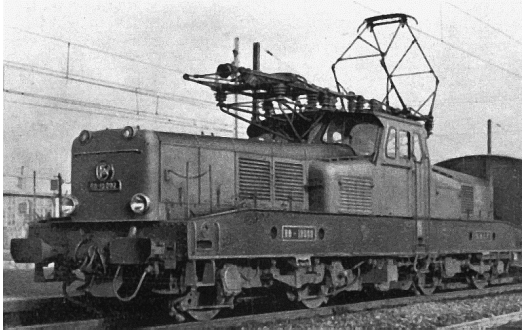


Fig. 1.5: 50-Hz goods locomotive of SNCF, Japan series 12 000, 1950, 2650 kW, 85 metric tons



Fig. 1.6: Shin-Kansen High Speed Train of national railroad, Series 0; 220 kph

Nowadays, high-speed trains like the “Shin Kansen” of Japan (Fig. 1.6) and the French “Train Grande Vitesse” (TGV) attain maximum speeds in excess of 200 mph.

1908 saw the advent of the diesel locomotive, designed by R. Diesel and the Sulzer company of Switzerland (Fig. 1.7). It yielded 1500 hp using a direct drive without gearing or clutch. Due to difficulties of starting up a heavy train using compressed air carried on board, this new technology first proved unsuccessful. Only in the 1930s, the success of Electro-Motive Division of General Motors in introducing diesel-electric drive technology in the U.S. and the introduction of the hydraulic flow converter in Germany allowed for economical use of the diesel motor in railway traction.

In 1971, the first successful diesel-electric locomotive with three-phase drive technology, produced by BBC and Henschel (Fig. 1.8) took up operations. Frequency converters now allowed (by variable frequency/variable amplitude feed) to employ the robust squirrel-cage induction motors in place of the cost- and maintenance-heavy commutator motors.

In 1979, three-phase drive technology was applied to overhead-system locomotives in the shape of the first high-performance universal locomotive, the class 120 of the DB (Deutsche Bundesbahn). Ever since 1990, this technology is general standard for high-speed trains (Fig. 1.10) and heavy and/or fast goods trains as well as most commuter service railways.

[B2], [B4], [B7], [B8], [B11], [B12]; [1]...[5].

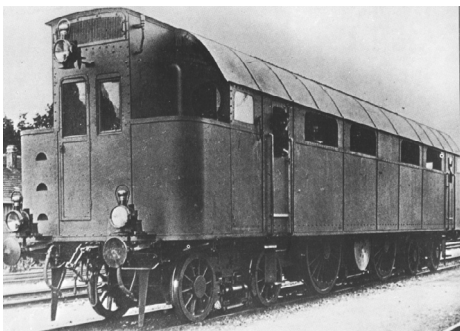


Fig. 1.7: Sulzer-Klose-Henschel diesel locomotive 1912 with direct drive; 1000 kW



Fig. 1.8: First diesel-electric locomotive with three-phase drive technology DE 2500 by BBC and Henschel 1971; 1840 kW

(Bombardier Transportation)



Fig. 1.9: Full-electric high-performance locomotive class 120 of DB; 1979, 5600 kW
(Bombardier Transportation)

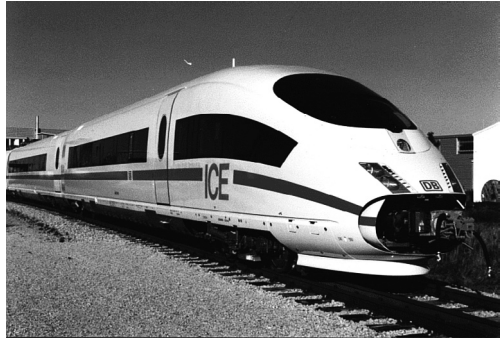


Fig. 1.10: Electric High-Speed Train ICE3 class 403 of DB AG; 1999, 8000 kW, 330kph

1.3 A short overview of railway electrical supply networks

As indicated in the historical overview, the type of electrical supply network chosen – direct current, single-phase alternating current or three-phase alternating current – is of vital importance for the system “Electric Railway” and is thus inextricably linked to the evolution of traction technology. Therefore, this subchapter will provide a short overview on the various railway power systems of Europe, their development and current state. chapter 13 will focus on the various railway power systems *en détail*.

1.3.1 Direct-current railway systems

Tramways and underground railway systems run preferably on direct current (DC) voltage of 600–750 V; suburban commuter and city railways usually operate at voltages of 750–1500 V, this being due to the simple vehicle technology. 750 V is used in South-East England (Kent). In South and Southwest France as well as in the Netherlands, stemming from the suburban lines of the great capital terminal stations extended networks of 1500-V main-line systems have developed. Though their limitation of power (less than 5 MW per train) is a distinctive drawback, it is unlikely however, that they will be replaced by more efficient power supply systems. Fig. 1.11 depicts these direct current railways of $U_N = 1.5$ kV by hatching from top left to bottom right, the 750-V lines from bottom left to top right.

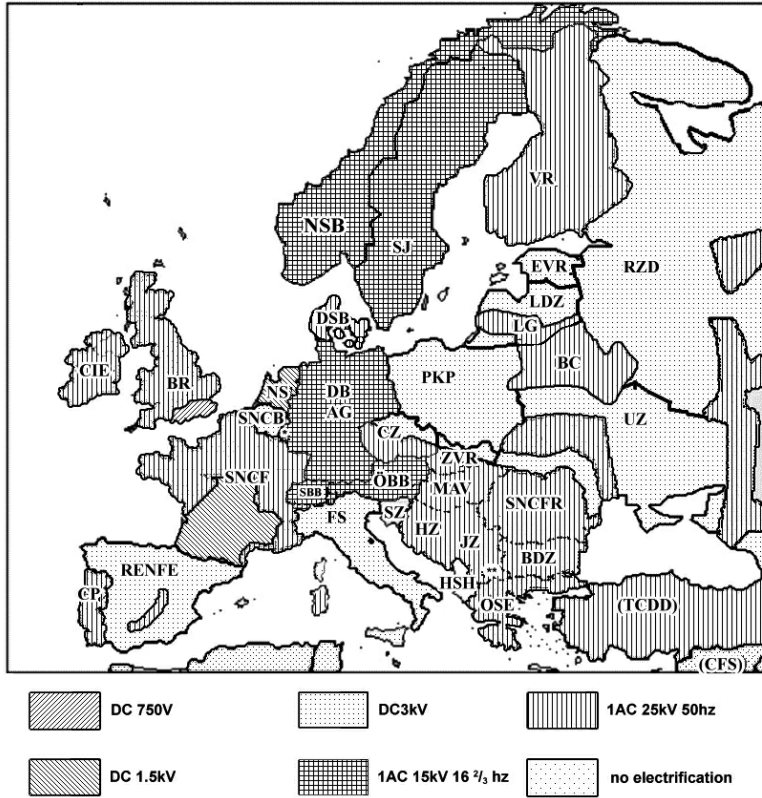


Fig. 1.11: Railway main-line power-supply systems in Europe (abbreviations of names of railway authorities cf. subchapter 15.2; *: CFL; **: MZ)

During the 1920s, Belgium, Italy, Spain and the Soviet Union, drawing on U.S. experience, established 3-kV DC long-distance networks, this system being adopted by Poland, northern Czechoslovakia, India, South Africa and Brazil after the Second World War. European areas using this system are narrowly dotted in Fig. 1.11. This system always used two drive motors in series until the three-phase drive technology superseded the commutator motor.

1.3.2 Single-phase alternating current railway systems

Fig. 1.11 shows the areas using the 1AC 15 kV/16 2/3 Hz alternating-current system for long-distance railways as chequered areas, including Sweden, Norway, Germany, Switzerland and Austria. This system has been in use since 1912.

Those regions utilizing 25-kV/50-Hz electrification are depicted using vertical hatch. Special notice should be taken of the 50/60-Hz high-speed or heavy-duty new lines in Japan, France, Spain and the Netherlands, which cut a swathe through vast areas of 1500-V DC-run railways (3 kV in Spain). A key of the abbreviations of the railway companies can be found in subchapter 15.2.

The various lengths of system network in 2003 were:

Table 1.1 Network line lengths and proportion of electrical railway systems (2003)

DC 1500 V	15,318 km / 9,497 miles	6.5 %
DC 3000 V	72,104 km / 44,704 miles	30.3 %
AC 15 kV/16 2/3 Hz	32,392 km / 20,083 miles	13.6 %
AC 25kV/50 (and 60) Hz	106,437 km / 65,991 miles	44.8 %
Others	11,349 km / 7,036 miles	4.8 %
Total	237,600 km / 147,312 miles	100.0 %

The 50-Hz system is experiencing the largest growth nowadays.

1.3.3 Three-phase three-conductor railway systems

The only three-phase public railway systems still in existence in Europe today are the Jungfrau-bahn and the Gornergrat-Bergbahn in central Switzerland. Apart from that, various “people mover” airport railways are operated as low-voltage three-phase three-conductor systems.

1.3.4 Standardized voltages of the train line

As electrification grew apace, the former vapour heating of passenger trains was replaced by electrical systems. Due to security reasons, it is obviously rather inappropriate to use the 15/25 kV supply voltage directly; thus, the main transformer branches off a lower voltage for the train line. The standardized overhead-line voltages have been allotted specified voltages for the train line according to UIC 550 (cf. Table. 1.2).

High-speed trains like the ICE use proprietary train lines of DC 500...700 V; this is favourable when considering inverter-fed compressor motors for air-conditioning equipment. If fed from a diesel-engine generator, trapezoid voltages AC may occur (cf. subchapter 9.1). In the U.S., three-wire systems using 3AC 480 V/60 Hz are common; those were introduced early on with regards to the power demand of train air conditioning, so-called Head-End Power systems.

Table 1.2 Train line voltages

Railway electrical system	Nominal voltage
AC 15 kV/16 ² / ₃ Hz	1AC 1000 V
AC 25kV/50 (and 60) Hz	1AC 1500 V, 3000V* in Eastern Europe
DC 1500 V	DC 1500V
DC 3000 V	DC 3000 V

*Due to ease of transition to the DC 3-kV used in Eastern Europe and the CIS, cf. Fig. 1.11!

1.3.5 State of electrification in selected countries

The state of electrification regards only the quota of electrified network length to total network length, NOT the quota of transport capacity.

Table 1.3 State of electrification in 1990

Country	State of electrification
Denmark	7 %
Germany	42 %
Switzerland	99 %
Europe (on average)	37 %
USA	1 %
Soviet Union	36 %
South Africa	36%

1.4 Comparison of traction systems

The following table 1.4 lists a number of advantages and disadvantages of electric traction when compared to diesel traction, for main-line traffic.

Table 1.4 A comparison of electrical and diesel-electrical traction

<p>Advantages of electric traction, compared to diesel traction</p> <ul style="list-style-type: none"> • In general, lower energy cost • Preservation of limited oil reserves • Usability of hydroelectric power and low-yield coal • Environment-friendly operation, lower noise • Possibility of energy recovery when braking, less wear of brake shoes (especially for three-phase drives!) • Higher partial efficiency (nominal efficiency off primary energy source is comparable!) • No need for carrying the power generator on the vehicle unit, thus more than double power at same weight (ca. 7 MW at wheel-rim with a four-axle locomotive of G = 85 t, compared to 3.5 MW at wheel-rim for a diesel-electrical locomotive of G = 130 t!) • Service speed over 200 kph and heavy mass transit only viable with electric traction • Possible overload of electrical machinery can be utilized • Lower maintenance cost • Higher number of operational hours due to easier maintenance and no need for pre- heating the engine • In total, cheaper traction units <p>Disadvantages</p> <ul style="list-style-type: none"> • High initial cost for catenaries and power-supply network <p>Rough guideline values for economic limits of track electrification</p> <ul style="list-style-type: none"> • Traffic work is $12 \cdot 10^6$ t/a, for a train of 1350 metric tons, per hour, on level routes; less in mountainous areas! • Energy consumption of about 300...400 MWh/(a·km), depending on price of diesel fuel
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Figs. 1.12 and 1.13 show typical efficiencies of an electric line-fed locomotive and a diesel-electric locomotive, with the respective amounts of loss resp. partial efficiencies. It becomes obvious that electric traction does NOT offer a higher coefficient in itself, if the whole chain starting with the initial thermal energy of the primary fuel is considered. Recuperation is not taken into account, as it is extremely difficult to figure, being too dependent on too many different parameters.

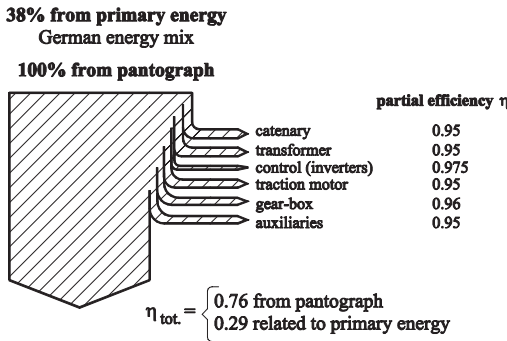


Fig. 1.12: Energy usage of a line-fed electric locomotive

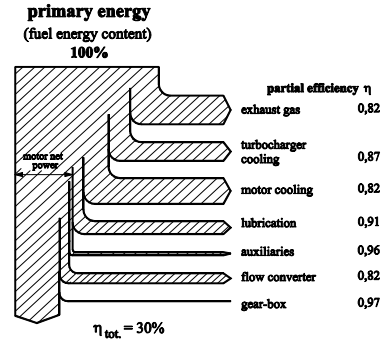


Fig. 1.13: Energy usage of a diesel-hydraulic locomotive [B18]

1.5 The European railway industry

Ever since the beginning of the 1990s, the European railway industry had to face constant change; the restructuring of the railway organisations (deregulation, privatization) led first to a decline in orders and in consequence to collapses and amalgamation; partially the production was transferred to low-wage countries, mainly East Europe.

Engineering industry divisions formerly responsible for the supply of the mechanical components of traction units (incl. Henschel, Krauss-Maffei, Krupp, and SACM) were integrated into the transportation divisions of the electrical large-scale industrial companies (like ABB, AEG, ALSTOM and Siemens), the latter now acting as leaders of system technology. In 2001, Bombardier, until then having their focus on coaches and aircraft engineering, acquired ADtranz from the Daimler-Chrysler Group.

In the big groups, factories concentrated their production portfolio on their “core competences”; so the bogie production of Bombardier Transportation was combined in Siegen (D), that of Siemens Transportation Systems in Graz (A), at the place of the former SGP.

As the railways gave away much of their former own technological competence, the way was now free for standard products, following “platform” strategies as known from automobile industrie. Much bigger lots could be produced then known from the seventies and eighties of the twentieth century. Corporate enterprises such as Mitsui Rail Capital Europe and Angel Trains entered the new business of leasing of rolling stock, eventually taking over e.g. the Siemens division “Dispolok” built up for that purpose in the late nineties. Table 1.5 provides a “snapshot” of the railway industry in 2006 (including some corporate history).

Table 1.5 European Traction Unit Manufacturers (2005/06)

	ALSTOM Transp. (FRANCE)	BOMBARDIER TRANSPORT.		SIEMENS TS (GERMANY)
		ADTRANZ (SWITZERLAND, GERMANY, SWEDEN)	BOMBARDIER (CANADA)	
Business volume (in billions of €) *)	5.1	5.0		4.5
Employees *)	26,000	28,600		18,865
Origins (selected!)	ALSTOM = Thomson-Hou- ston + SACM Belfort; MTE Schneider, DeDietrich (F) FIAT Ferrov. (I) Linke-Hofmann- Busch (D) GEC Traction (UK) Until 1998: GEC- Alsthom	ABB-Henschel = ASEA (S) + BBC (CH, D, I) includ. Oerlikon, Sècheron (CH), TIBB (I) NEBB (N) + Henschel (GER) + BREL (UK) + AWTS (AEG incl. LEW Hen- nigsdorf, MAN, MBB, Waggon-Union (D); Pafawag (PL); Westing- house TS (USA) Matranovak (HU)	B. Mass Transit (CAN) B. Transit USA Talbot (D) DWA (D): Ammendorf Bautzen, Görlitz, Niesky (Manage- ment-Buy out in 2005) Division BN (B) ANF-Industrie (F) Bomb.-Wien (A) Prorail Ltd. (UK)	Siemens VT (TS) Krauss-Maffei Krupp VT DÜWAG Uerdingen (D) SGP (A) MATRA S.A. (F) VATech ELIN, (A)

*) World-wide)

Figs. 1.14 and 1.15 give an overview about the market situation; the whole railway product market is about 72 bn. €, that for rolling stock about 25 bn. €, and splits according to the diagrams into the following segments.

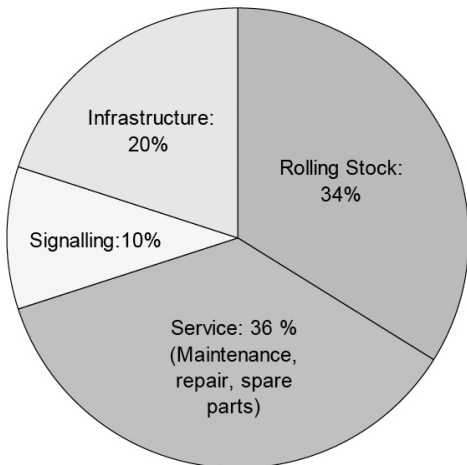


Fig. 1.14: Overall market volume of railway material, as of 2003-2005
(UNIFE-Study 2015)

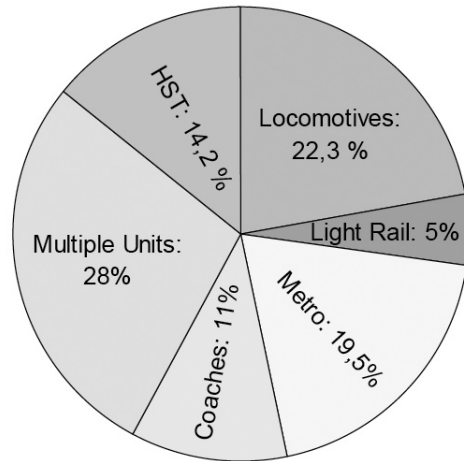


Fig. 1.15: Breakdown of rolling stock (2006-2015)
(UNIFE-Study 2015)

Table 1.7 Further manufacturers of traction units (in excerpt)

<p>Europe: AnsaldoBreda, Naples, Italy Balfour Beatty Rail GmbH – Power Systems, Frankfurt and Munich, Germany Brush Traction Ltd., Loughborough, UK Cegielski, Poznan, Poland Construcciones y Auxiliare de Ferrocarriles S.A (CAF), Beasain and Zaragoza, Spain ELIN EBG Traction, Vienna, Austria (Siemens) Ganz Tranelectro Traction (formerly Ganz-MAVAG), Budapest, Hungaria Riga Carriage Building Works, Latvia Skoda, Prague, with CKD Vagonka, Ostrava, Czech Republic Stadler Rail Group, Bussnang and Altenrhein/Switzerland; Pankow, Germany TALGO S.A., Spain Voith Turbo Lokomotivtechnik GmbH, Kiel Vossloh SFT (incl. MaK and Kiepe Elektrik, Düsseldorf; acquired the Valencia works for diesel-electric locomotives from ALSTOM in 2004), Germany Windhoff, Rheine; Schöma, Diepholz, Germany (small locomotives, special vehicles)</p> <p>Worldwide: General Electric (GE) Transportation Systems, Erie, Pa., U.S. General Motors, Electro-Motive Division (EMD), London/Ont., Canada; formerly also Lagrange, Ill., U.S.A. Hitachi, Kawasaki, Mitsubishi, Toshiba, Tokyo Denki, Japan Union Carriage & Waggon Co. (UCW), South Africa Daewoo, Hyundai, South Korea Chittaranjan, BHEL, IndiaZhuzhou, PRC</p>
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Table 1.8 Leading associations/accords/authorities

UIC/IEV	Union Internationale des Chemins de Fer, Paris (International Railway Association)
ERRI OSShD	European Railway Research Institute (fm. ORE) Organisazija sotrudnitschestwa shelesnych dorog (Organisation for Cooperation of Railways (East European states, CIS and Iran)
RIC	Regolamento Internazionale delle Carrozze (Accord on the mutual use of passenger and luggage cars in international transport), January 1 st , 1950
RIV	Regolamento Internazionale delle Veicoli (Accord on the mutual use of cargo cars in international transport), January 1 st , 1958
TSI	Technical Specification on Interoperability. Guideline 96/48/EC of the European Council on Interoperability of the trans-European high-speed railway system. Official Journal of the E.C. No. L 235, September 17 th , 1996, p. 6 ff.
UNIFE VDV VDB	Union of European Railway Industries Association of German Transport Undertakings, Cologne Association of the German Rail Industry, Frankfurt/Main
EBA	Eisenbahn-Bundesamt, Berlin (technical supervision authority)

2 The mechanics of railway transportation

2.1 Principles of rail-guidance

2.1.1 Gauges

As mentioned in the historical overview, subchapter 1.2, the later European Standard Gauge of 1435 mm (distance between inner edges of rail tops) had been introduced by the railway pioneer George Stephenson. As early as the middle of the 19th century, it was adopted as the standard gauge for European railways. It is also found in the US and the PRC, Korea and Australia as well as on the new Japanese and Spanish high-speed mainlines.

“Standard gauge” (in the wider sense as compared to “narrow gauge”, discussed below) also includes the gauge range from 1524 mm to 1676 mm (5 ft and 5 ft 6 in, respectively), which were chosen as standard gauge in various countries. The 1524-mm gauge, widely called “Russian Gauge”, had been introduced in Czarist Russia due to strategical concerns. In Ireland, 1600-mm gauge was designated standard in the middle of the 19th century; from there, it proliferated to various Australian federal states and Brazil. 1665-mm gauge is mainly found on the Iberian peninsula, with the only fractionally larger gauge of 1676 mm being used in South America and the Indian subcontinent. Even larger gauges have been used on the North American Erie Railroad (New York-Great Lakes) and the Great Western Railway from London to Devon and Cornwall in the United Kingdom, those using 1800-mm and 2134-mm gauge, respectively. Both railways, however, had been converted to European standard gauge by the end of the 19th century to eliminate the drawbacks associated with using deviating gauges, most notably the impossibility of transfer for cars, thus requiring costly transshipping.

Besides the standard gauge railways, which have been most successful and numerous in the industrialized countries, various smaller gauges have seen use in various Third World countries and minor railways, the so called “narrow gauge”. “Metre Gauge” (of 1000 mm, or 3 ft 3 in) has been widely used in Europe for minor (secondary) railways and suburban lines, as well as in a number of former European colonies. 1067-mm gauge (3 ft 6 in) is common in various former British colonies in central and southern Africa, as well as in India, Indonesia, Japan and South America. The great success this gauge enjoyed in South Africa has given it the moniker of “Cape Gauge”. In contrast, the 1100-mm gauge of the Brunswick tramway must be regarded as exceptional.

Smaller gauges are commonly used on railways of minor importance, for example 600 mm (2 ft) with field and military railways, 750 mm and 760 mm with German or Austrian and former Yugoslav minor railways, respectively. 900 mm (2 ft 11 in) is a typical mine railway gauge, whereas 914 mm (3 ft) is common in Central and South America.

Narrow gauge railways have several advantages: Apart from considerably lower initial investment cost, they prove far easier to construct in difficult, rough and mountainous terrain. The

major drawbacks, however, are noticeably lower service capability and the easily underestimated cost of transshipping when using narrow gauge in conjunction with standard-gauge railways. As traffic volume increased, these transshipping costs regularly and quickly outweighed the low initial and maintenance cost that made narrow gauge so attractive.

A typical example is the re-gauging of the 760 mm Bosnia-Herzegovinian railway line from Sarajevo to Ploce on the Mediterranean, which was concluded in the 1960s.

As well as the various service capabilities inherent in the various gauges, various typical wheelset loads have been associated to these gauges. Whereas modern standard gauges (1435...1676 mm) can easily manage axle loads from 21 metric tons (Europe) to 35 metric tons (U.S.), for economic reasons, narrow gauges can only shoulder wheelset loads of 16 metric tons for meter gauge, dropping to some 9 metric tons for gauges of about 750 mm. Smaller field railways only served axle loads of only a couple (3.5 usually) metric tons.

Table 2.1 A selection of gauges

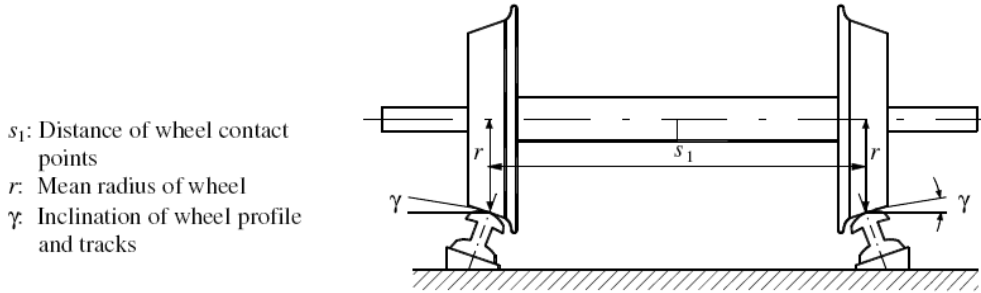
381 mm	Exhibition railways, some public railways in the UK
600 mm	Minor, field and military railways
750 mm	Minor railways
760 mm	Minor railways in Austria and former Yugoslavia (“Bosna Gauge”)
900 mm	Mining railways, for example in lignite strip mining
914 mm	Minor railways in Central and South America
1000 mm	Minor and colonial railways, “meter gauge”
1067 mm	Many railways in Central and Southern Africa, India, Indonesia, Japan; called “Cape Gauge” in South Africa
1100 mm	Brunswick tramway
1435 mm	“European standard gauge”, U.S., Northern Africa, Australia, China, Japanese and Spanish newly-constructed high-speed lines
1524 mm	CIS, Finland, Iran, Panama
1600 mm	Australia, Brazil, Ireland
1665 mm	Spain, Portugal
1676 mm	Argentina, India, Pakistan, Bangladesh, Sri Lanka, Chile

2.1.2 Guidance of wheelset in track

The system “wheel-track” that is key to railway technology has to meet three requirements:

- transmission of the vehicles’ weight to the rail
- transmission of traction power from the traction unit to the rail
- guidance of the vehicle in lateral direction both on straight and curved tracks

Wheelset loads were already mentioned in the previous section; subchapter 2.2 will discuss the transmission of traction power. This section shall discuss vehicular guidance (formerly, the term “axle” was common for “wheelset”, with some technical terms being derived from that).



s_1 : Distance of wheel contact points
 r : Mean radius of wheel
 γ : Inclination of wheel profile and tracks

Fig 2.1: Geometrical designations of the wheel set on track

As can be derived from Fig. 2.1, the wheels sport a conical running profile, which concurs to the horizontal at an angle of γ . Accordingly, the tracks are mounted at an angle of γ ($\tan \gamma = 0.025 \dots 0.04$).

When running through a curve, the wheelset, moved by centrifugal force, shifts outwards until the way covered on the larger reference circle diameter is equal to the longer way covered on the outer track, avoiding slip and thus wear of the wheel profile, at least in wide curve radii. Thus, railway vehicles can eschew the use of a differential gear which is indispensable for road vehicles.

If on a straight track the wheelset is shifted to the right, the right wheel moves upwards and runs on a larger reference circle diameter than the left, which in turn moves down, running on a smaller reference circle diameter, and vice versa. By revolving on the larger reference circle diameter, the right wheel experiences higher peripheral speed, resulting in a movement of the wheelset towards the centre of the track. This so called “sinusoidal running” was described in 1880 by Klingel [7], [8]; it has a typical wavelength, which results from the distance of the wheel contact points s_1 , the radius of the wheel r and the inclination of the wheel profile of $\tan \gamma$ at

$$\lambda = 2\pi \cdot \sqrt{\frac{s_1 \cdot r}{2 \cdot \tan \gamma}}, \tan \gamma = 0.025 \dots 0.04 \tag{2.1}$$

The conicity of the wheel thus results in automatic centering of the wheelset on the track.

On the other hand, this desirable reset causes oscillation of the wheelset, the strength of which is dependent on the speed of the vehicle. The frequency of the oscillation is at $f = v/\lambda$, v being the translatory speed of the wheelset. Thus it is imperative under all circumstances that this frequency does not incite the intrinsic oscillation of the wheelset. As is generally known, the resonance frequency of the mechanical pendulum is proportional to the root of the quotient of rigidity and mass. Heavy wheelsets further burdened by electrical motors result in lower frequency limits or higher spring rigidity, this in turn causing high recoil strength and high stress applied to the wheelset–track system; wear becomes inevitable. Thus, in order to reach high speeds, it is absolutely necessary to reduce the mass of the wheelset (e.g. by light construction and hollow axles) as well as using fully de-coupled drives (see subchapter 3.2), if one wishes to operate at low recoil strengths.

Greater wavelengths, and thus higher velocity limits, can practically not be achieved by using flatter wheel cones, since tire wear will quickly result in a S-shaped profile that has sequentially much higher conicity; this in turn results in a non-linear oscillation with, again, shorter dominant wavelength. To counter this effect, the Deutsche Bahn fits all vehicles with the so-called DB II-Wear Profile as standard. This system, derived from Prof. H. Neumann’s work [9] provides for a constant stable behaviour over the running time of the wheelset.

However, a traction unit uses more than one wheelset, which are mounted in a frame, bogies nowadays [B33]. Thus, coupled oscillations both of the wheelset and the bogie frame occur. To control these oscillations more easily, it has proven advantageous to de-couple them from one another. For this reason, a laterally-elastic spring suspension mates the wheelset to the bogie frame. Still, the sinusoidal oscillation and disturbances of the track alignment cause oscillations of the wheelset, and in turn, of the bogie – the latter being mainly rotary. In order to achieve higher speeds safely, a low moment of inertia is required.

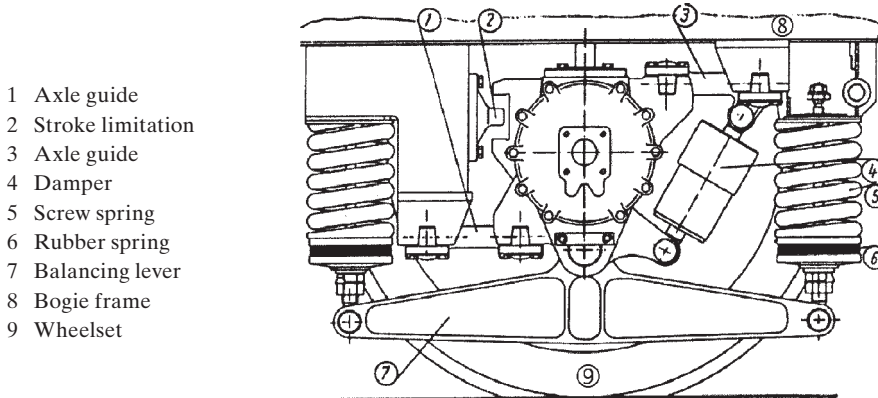


Fig. 2.2: Wheelset guidance including axle-guides and dampers (lemniscatic guidance)

Fig. 2.2 depicts a modern system of wheelset guidance, including axle-guides and dampers. The bogie frame (8) is mounted to the axle-bow cage via two Flexicoil screw springs (5) and a balancing lever (7), the springs forming the “primary suspension”. The stress of tractive and braking effort is transmitted via two axle guides (1 and 3) from the bogie to the axle-bow cage. This type of axle guidance is called “lemniscatic guidance”. The axle guides allow for a certain amount of lateral shift of the wheelset; the recoil strength for the lateral suspension is supplied by the screw springs, which are mounted fast to the bogie frame. For dampening of the vertical oscillations, a damper (4) and a rubber spring (6) are used; excessive movement is prohibited by the stroke limiter (2).

2.1.3 Frame and bogie

Fig. 2.3 shows the three translatory and the three rotary degrees of liberty that apply to a vehicle. Similar degrees of liberty apply to the wheelset and the bogie.

Up to the 1920s, electric locomotives of higher power output were constructed along the same principles as steam locomotives: A centrally placed high-power motor drove the wheelsets via parallel-crank drives and coupling rods (cf. subchapter 3.2).

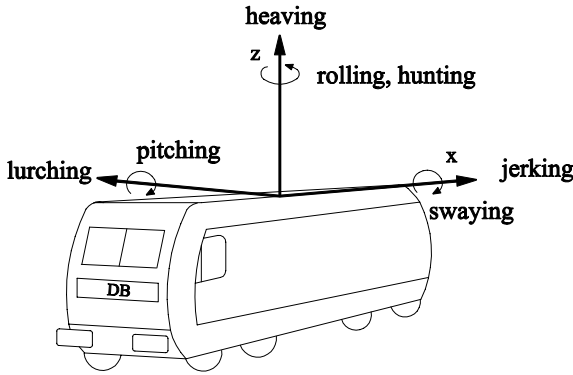


Fig. 2.3: Translatory and rotary degrees of liberty of vehicular movement and their denomination

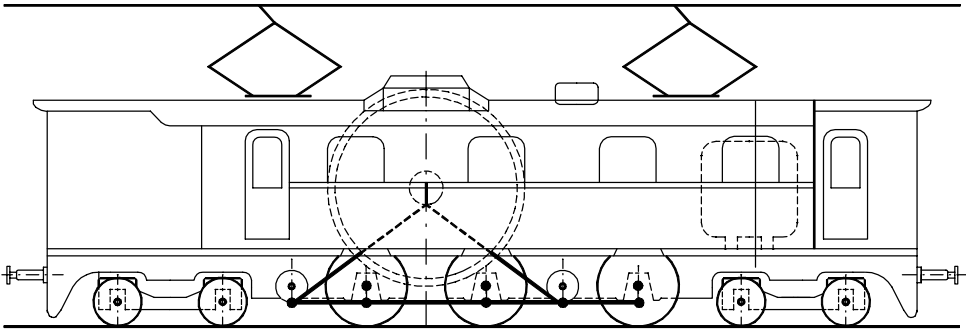


Fig. 2.4: Rigid-frame express locomotive Class E 06 of the DRG (1922)

See Fig. 2.4: To support the then considerable total weight of the electric equipment and to improve the running behavior at high speeds, idler wheelsets or bogies were used. Later on, the single-axle drive with high-speed motors and gears replaced the direct rod coupling.

The idler-free bogie system which is almost exclusively used today (Fig. 2.5) was first employed on tramways operating at low speeds. In the 1930s, this system was introduced with main-line locomotives of some 2 MW and speeds of 80 kph (50 mph). In the 1940s, the first high-speed high-performance locomotive was constructed in Switzerland; it reached a maximum speed of 120 kph (75 mph) and a nominal power of 3 MW (cf. subchapter 7.2). This engine must be considered the ancestor of all modern locomotives, which are able to attain speeds of up to 357 kph (220 mph).

A bogie combines two (seldom three today) wheelsets of the traction unit, the respective drive motors and the power transmissions (cf. subchapter 3.2). It revolves around a circular pivot mounted in the vehicle frame, allowing for rotation around the z and y axes and translating the resulting forces in the directions of x and y.

The weight force (z-axis) is transmitted via springs, the “secondary suspension”. Today, the voluminous pivot is often not physically existent, its tasks being fulfilled by coupling rods and the screw or spiral suspension springs (“Flexicoil”), which are mounted fixedly in the girder under-frame and the bogie frame, taking up the bogie rotation by torsion.

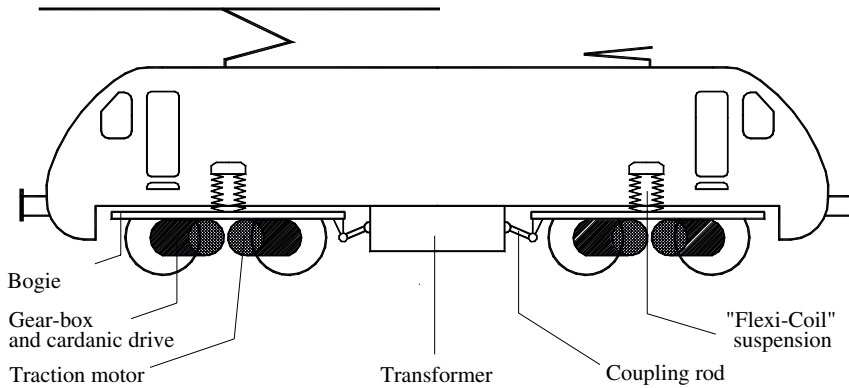


Fig. 2.5: Schematic illustration of a bogie locomotive with "Flexicoil" suspension

As has been proven with passenger carriages, bogies greatly improve running quality, since they halve the effects of track-induced thrusts in y- and z-direction on the vehicle and reduce the running resistance (cf. subchapter 2.2) in curves. Vehicles of short wheelbase (lengthwise distance of axles) have lower striking angles of the wheelset (i.e. wheelset group) and thus experience lower drag in curves; additionally, since the bogies align themselves radially towards the centre of the curve, the striking angle is further reduced.

The thrusts, however, do regularly cause inherent oscillation by the z- and y-axes, which proved the key problem hindering widespread introduction of the bogie for high-speed traction units; a striking example is the drive bogie of the express locomotive BR 103 of the DB (Fig. 2.6). At the time of construction (1965), to achieve the demanded power of 7 MW required the use of 6 motors of 1180 kW each, these being rigged as triple assemblies in two bogies. A single bogie weighed in at 31 metric tons, the wheelbase measuring 4500 mm. This resulted in a high axial moment of inertia, which led to low-frequency oscillations; due to the given wheelbase kinematics, these already occurred at speeds of just above 200 kph (125 mph) and could only be controlled by equipment of extra dampers.

The problem was effectively alleviated only by the introduction of the three-phase drive technology: due to higher number of revolutions, the power of the motor (while keeping the weight) was raised so rapidly, that outputs of 6–7 MW can be achieved by four drive motors, allowing for the use of twin-wheelset bogies. Fig. 2.7 shows the BR 120's bogie assembly: the weight is down to a mere 16.1 metric tons at a continuous output of 2 x 1400 kW.

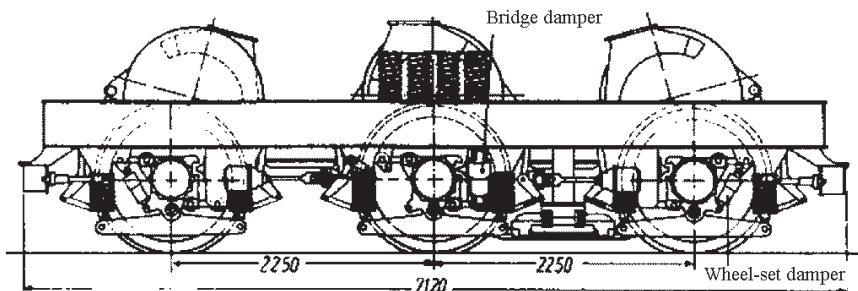


Fig. 2.6: Drive bogie of with three wheelsets (Class 103 DB), without central pivot

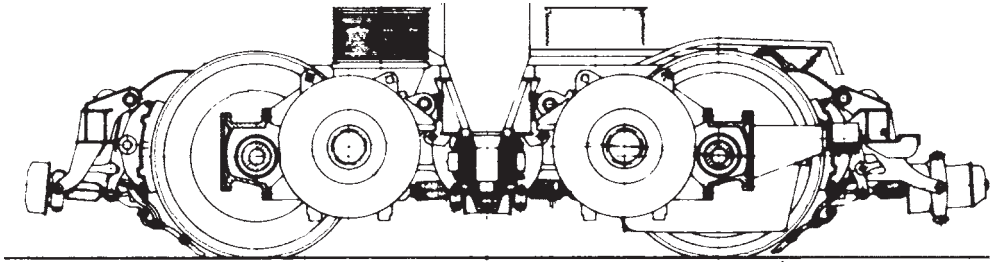


Fig. 2.7: Modern drive bogie with two wheelsets and a central pivot (Class 120 DB)

The relatively small traction motors can be mounted close to the pivot, the wheelbase is reduced to just 2.8 m (9 ft 1/5 in), thus greatly reducing inertia. Similar locomotives achieved speeds of 357 kph (225 mph, “Taurus” Class 1216 of ÖBB).

Even more advanced is the bogie model used on the French high-speed train TGV (Fig. 2.8). The drive motors have been removed totally from the bogie and are mounted laterally in the bridge girder, driving the wheelsets via cardan shafts. The weight of the bogie, while yielding 2 x 1100 kW, sank to 11 tons. On trials, such trains achieved speeds of 575 kph (360 mph). The German ICE HSTs use a similar drive concept, but with a concentric cardanic hollow shaft (subchapter 3.2).

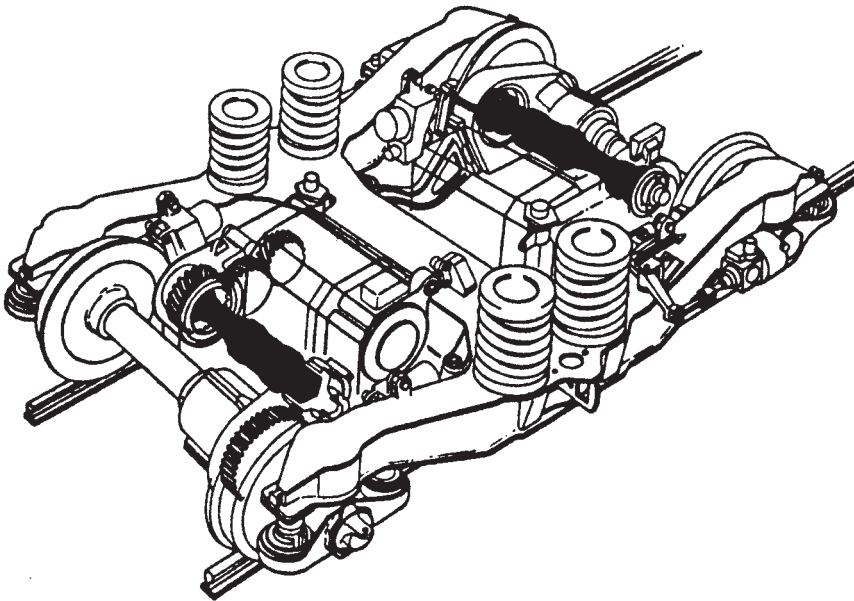


Fig. 2.8: Drive bogie of the TGV with traction motors mounted in the bridge girder

The “Integrated Complete Drive” is a compromise; it is discussed in detail in subchapter 3.2.