Worldwide Development of Propulsion Systems for High-Speed Trains

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This survey starts with a brief overview of train speed records during the last century followed by a list of types of vehicles suitable for high-speed operation. Some rules applied in various countries for the utilization of adhesion between wheel and rail are presented. At high speeds air drag is the dominant part of total train resistance, and tables and curves showing this resistance versus speed are given for a number of modern high-speed trains. The impact of vehicle cross section and shape on train resistance is discussed. Relations among tractive effort, train speed, and required power at rail make it evident that, for speeds in the range of 200 to 400 km/h, this power must be of the order of 4000 to 10 000 kW. A number of high-speed trains, locomotives, and power cars are then described in some detail. The conventional adhesion-dependent wheel-on-rail technique is likely to be used in the future for maximum speeds of up to 300 and possibly 350 km/h. Because of their high power requirements, diesel-powered trains may be restrained to about 200 km/h; gas turbines can be used to perhaps 250 km/h. Straight electric propulsion is conceivable up to the limits of adhesion, maybe 350 km/h. For higher speeds, use of an adhesion-independent magnetic levitation system appears to be inevitable. So much power is required for these high-speed trains that a three-phase propulsion system has to be adopted. All recently developed high-speed trains have been designed for three-phase propulsion.

Despite ever-increasing competition from airline and highway transportation, railroads in a number of countries are still optimistic about their ability to conquer for themselves, on a commercially sound basis, a significant part of the high-speed transportation market. This survey will focus on the technical development of propulsion systems for guided transport using either wheeled vehicles on rail or some type of levitated vehicles on track.

During the last few decades, railroads and traction vehicle manufacturers have become increasingly aware that, at high speed, air resistance to movement is dominant and has to be reduced as much as possible to minimize power requirements and energy consumption. Figure 1 shows how the shape of the front end of some high-speed traction vehicles has changed over the last 30 years, shifting gradually to a lower and more streamlined contour. This and many other developments, primarily the availability of much more powerful propulsion systems, has shown remarkable results.

The very first electric locomotive was demonstrated at a trade fair in Berlin in 1879 (Figure 2). It could run around a short track at a maximum speed of 13 km/h. Almost exactly

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FIGURE 1 Changes in shape of front ends of high-speed traction vehicles.

100 years later, on December 21, 1979, a Japanese magnetically levitated vehicle attained the highest speed ever recorded for guided transport, 517 km/h.

Figure 3 shows some but not all of the speed records set between 1903 and 1985 by either wheeled or magnetically levitated vehicles. On October 28, 1903, a German coach powered by three-phase slip-ring motors reached a speed of 210 km/h. On June 21, 1931, the "rail blimp," a German "Schienenzeppelin" using a diesel-driven propeller ran at 230 km/h, and on May 11, 1936, the first high-speed German electric locomotive (E 03) achieved 200 km/h. Then the French National Railways (SNCF) entered the race. On February 21, 1954, a CC 7121 electric locomotive ran at 243 km/h, and on March 28 and 29, 1955, two locomotives, the CC 7107 and the BB 9004, both attained 331 km/h, a record that was going to last for a long time.

Interest in high-speed traction vehicles using gas turbines as prime movers started to grow in the mid-1960s, especially in France, and such a vehicle ran at 230 km/h on June 13, 1967. After further development, a gas-turbine-powered precursor to the French Très Grande Vitesse (TGV) trains reached 318 km/h on December 8, 1972. Also in France, the "Aerotrain," running on an air cushion and propelled by a gas turbine, set a new world record of 425 km/h in May 1974. In England the diesel-driven High-Speed Train (HST) attained 225 km/h on June 11, 1973. Since the first oil crisis in 1973–1974, efforts to develop high-speed trains have been almost exclusively devoted to electric locomotives, power cars, or magnetic levitation (Maglev) vehicles using electric energy. In the first category, the long-standing record of 331 km/h (from 1955) was finally broken on February 26, 1981, when a French

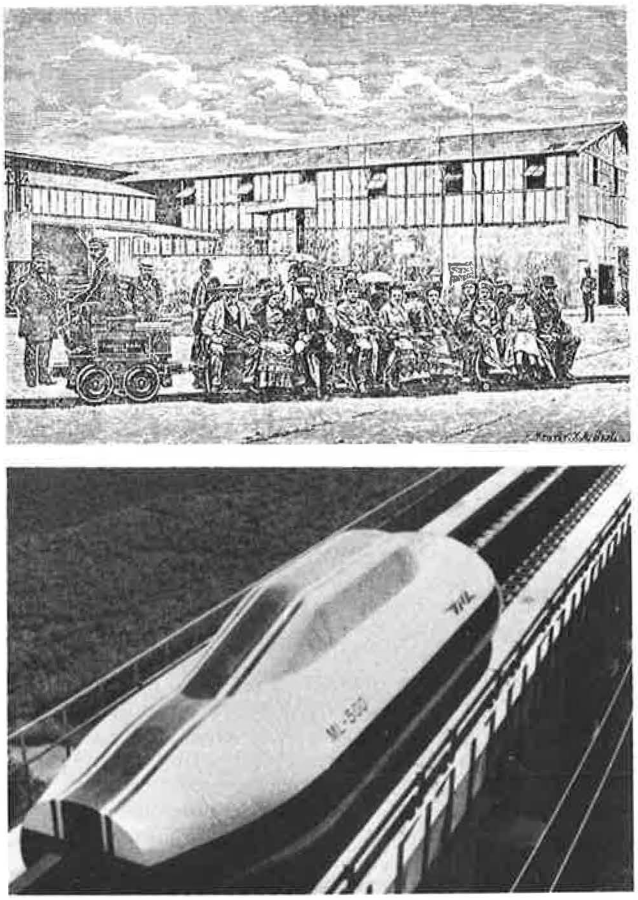

FIGURE 2 A century of progress: May 31, 1879, Berlin, Germany, 13 km/h (*top*) and December 21, 1979, Miyazaki, Japan, 517 km/h (*bottom*).

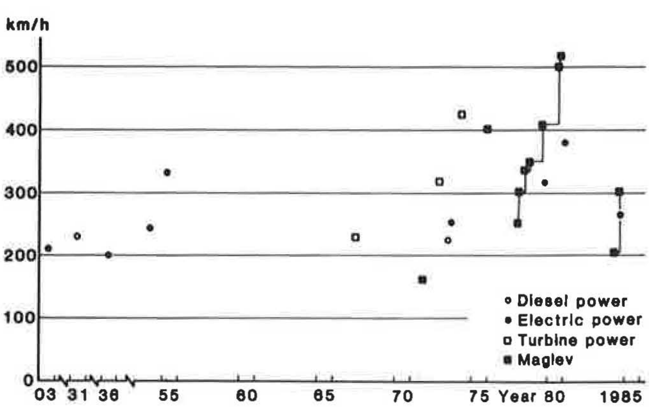

FIGURE 3 Some speed records of guided transportation.

electric TGV train ran at 380 km/h. In the Maglev category, rapid development in Japan of repulsion-type Maglev vehicles resulted in the speed record being increased for the same vehicle (ML 500) from 301 km/h on March 10, 1978, to 517 km/h on December 21, 1979. In Germany, where development of Maglev vehicles is concentrated on the attraction type with a long-stator synchronous motor, a similar attempt to increase maximum speed was begun and then postponed until the Maglev test track in Emsland was completed.

Figure 4 highlights the most important aspects of vehicles for high-speed guided transportation. These aspects can be (and have been) combined for various types of propulsion as will become evident later in this paper. However, before propulsion development is described in detail, some general items such as adhesion, train resistance, power requirements, and body tilting will be discussed.

It is well known that the adhesion between wheel and rail varies considerably depending on physical conditions (such as dry or wet rail) and also that it is affected to a certain extent by vehicle speed, track curvature, and other parameters. A rather typical example follows.

Measurements in Japan, under wet conditions, on a test bed, and in actual service at speeds up to about 250 km/h, resulted in a wide range of adhesion values as shown in Figure 5 (*1*). The Japanese National Railways (JNR), according to Nouvion (2), applied as a design rule for their high-speed trains on the Shinkansen network a utilizable adhesion of

$$\mu = \frac{136}{v + 85}$$

where v is vehicle speed measured in kilometers per hour. It should be recognized that all Shinkansen trains so far have used a propulsion system with direct-current traction motors permanently connected in series. This is a condition generally known not to improve the possibilities of utilizing available adhesion between wheel and rail.

Figure 6 shows some rules applied in various countries for the utilization of adhesion. Curve A is generally employed in Central European countries such Germany, Austria, and Switzerland and is the result of numerous running tests up to 160 km/h in 1943 with a German Class 19 electric locomotive. This locomotive had an axle arrangement 1′ Do 1′ with driving wheels 1540 mm in diameter and used parallel-connected alternating-current single-phase commutator-type traction motors. The findings were originally published in 1944, but because many copies were destroyed during the events at the end of World War II, the results were published again in 1950 (*3*). Analytically, the Curtius-Kniffler formula can be written as

$$\mu = \frac{7.5}{v + 44} + 0.161$$

with v expressed in km/h. It should be observed that the results were obtained with a locomotive that had an idle axle at each end.

Curve B is according to Nouvion (*2*) and is the rule applied in France in the 1950s and 1960s for electric locomotives "in normal service without antislip devices."

Curve C shows results of experiments in Germany with trains hauled by the first German electric locomotive geared for 200 km/h (Class 103).

From the late 1960s, the SNCF applied for their electric traction vehicles the design rules (2)

$$\mu = 0.24\,\frac{8 + 0.1\,v}{8 + 0.2\,v}$$

Wheeled vehicles on rails

Steam power	Mechanical transmission
Diesel power	Hydraulic transmission
Turbine power	Electric transmission
Electric power	Direct current, single-phase, three-phase

Levitated vehicles

Air cushioned	Short-stator motors
Magnetically levitated	Asynchronous
Repulsion system	Synchronous
Attraction system	Long-stator motors Synchronous

FIGURE 4 Types of vehicles for guided transportation.

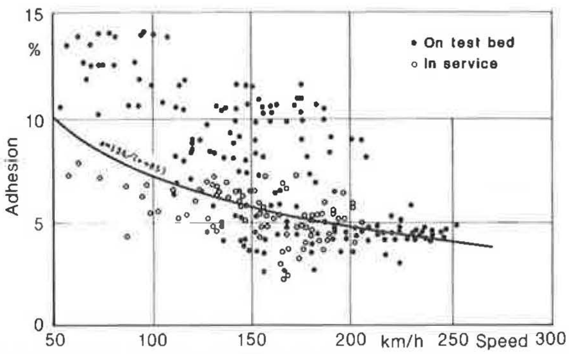

FIGURE 5 Adhesion under wet conditions (Shinkansen).

for individually driven axles and

$$\mu = 0.26 \frac{8 + 0.1\,v}{8 + 0.18\,v}$$

for locomotives with two-axle "monomoteur" trucks. The speed (v) is measured in km/h. These rules were considered valid up to at least 250 km/h.

An adhesion of 10 percent ($\mu = 0.10$) was utilized when the French electric locomotive BB 9004 set a world speed record of 331 km/h on March 29, 1955 (*4*).

To define the propulsion system for a traction vehicle able to run at a specified speed (v), it is necessary to know, in addition to the utilizable adhesion, the total resistance (R) of the train to motion. In free air (no wind) and on level track, it is generally accepted that this total train resistance can be expressed by an equation of the type

$$R = A + Bv + Cv^2$$

where the coefficients A, B, and C are of such magnitude that at very high speeds the term Cv^2 dominates. It is therefore of particular interest to study how the coefficient C depends on various design factors so that means can be found to reduce the value of C and thereby the significant part of total train resistance. Experience has shown that C is practically proportionate to the cross-sectional area of the train and to a factor that takes into account mainly the shape of the leading end (the nose) and the trailing end of the train.

The following table gives the cross sections (expressed in m^2) for some of the high-speed trains to be discussed in detail later:

Train	*Cross Section*	*Reference*
APT prototype	8.05 or 7.8	*5* and *6*
HST	9.12	*5*
ICE	10.3	Calculated
Shinkansen 0	10.4 or 13.35	*7* and *8*
Shinkansen 200	12.5	*7*
TGV 001	9.15	*9*
Class 103 locomotive	10.9	*10*

As mentioned earlier, the cross section alone does not determine the C coefficient. Total aerodynamics must be considered (including shape and degree of protruding trucks). C. J. Baker (*11*) has given the following typical "train drag coefficients" for three of the trains mentioned and a typical British freight train:

Train	*Coefficient*
TGV	1.5
APT prototype	2.05
HST	2.11
British freight train	5 to 15

Figure 7 (*12*) shows the cross sections of some high-speed trains compared with the limiting profile according to the Union Internationale des Chemins de Fer (UIC). The trend toward smaller cross sections for modern trains is evident.

The actual cross section dimensions of the German Inter-City Experimental (ICE) train are shown in Figure 8 (*13, 14*).

Recent investigations by SNCF in France have shown that a 10 to 14 percent reduction in drag coefficient can be achieved by introducing underbody skirts on high-speed passenger trains (*15, 16*).

It has been mentioned before that total train resistance R (the resistance of a train in motion in free air and on level track at a speed of v) may be expressed as

$$R = A + Bv + Cv^2$$

The coefficients A, B, and C depend on such parameters as axle load, number of axles, cross section of the train, and shape of the train; their values also depend on the units selected in the preceding equation. In the following, R will be

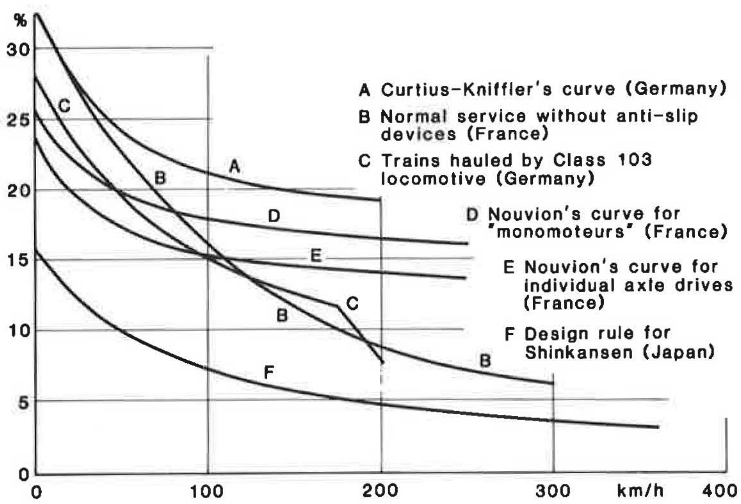

FIGURE 6 Some rules for use of adhesion.

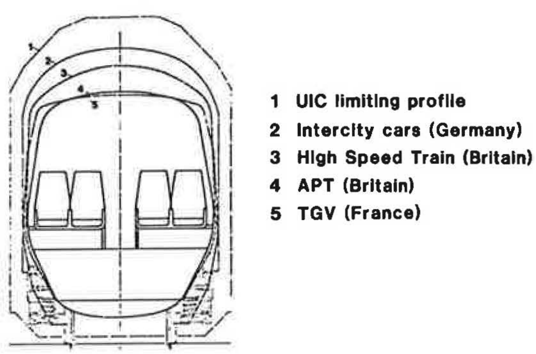

FIGURE 7 Cross sections of some high-speed trains.

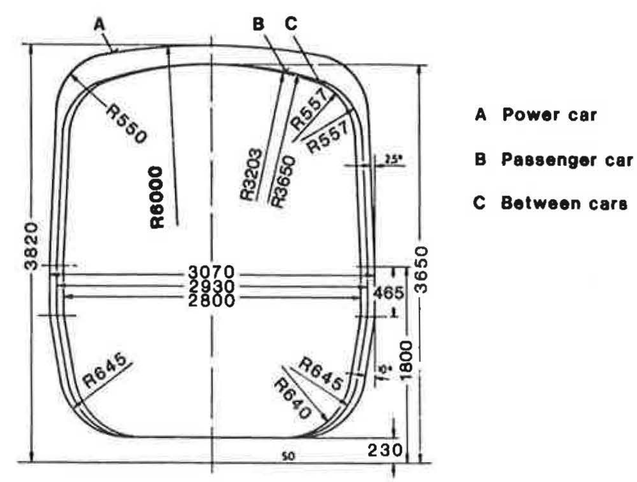

FIGURE 8 Cross section of InterCity Experimental.

expressed in kilonewtons (kN) and v in kilometers per hour (km/h).

Perhaps the most recognized investigation of train resistance of freight and passenger trains in North America is one published in 1926 by W. J. Davis, Jr. (*17*), and the preceding equation is therefore often called Davis' equation. However, the classification of train resistance into three terms, one independent of speed, one proportional to speed, and one proportional to the square of speed, was first proposed in France in 1885. In general, the investigations performed by Davis were limited to speeds not exceeding 145 km/h.

Peters has stated (*18*) that, although the skin frictional drag is not exactly proportional to the square of the vehicle speed, experience has shown that, up to 300 km/h at least, the Cv^2 term expresses quite adequately the aerodynamic resistance, so terms of higher powers of v may be neglected.

Over the years, numerous tests and theoretical investigations have been made to determine the coefficients in this equation for various types of trains. Table 1 gives some results, mainly for trains capable of running at speeds of 200 km/h or more.

Rappenglück (*12*) gives a number of rather general equations for calculating total train resistance as dependent on total mass of train, total length of train, axle load, and some other parameters.

The impact on train resistance of various nose shapes for the Shinkansen trains has been investigated (*26*). The difference in resistance between a "conventional" French passenger train and the TGV Sud-Est is shown in Figure 9.

Tests on models of the experimental German high-speed train R/S-VD (later ICE) for determining components of train resistance are described by Neppert (*27*). The impact of various components on total train resistance of the TGV Sud-Est as a function of speed, particularly at 260 km/h, is shown in Figure 10 (*24*).

When total train resistance is known (adjusted for gradient, impact of wind, tunnels, etc.), the power required for driving the train at a specified speed can be calculated.

In the international system of units, the relationship between force (F), speed (v) (in the direction of the force), and power (P) required can easily be expressed as

$$P = Fv$$

TABLE 1 RESULTS OF TESTS AND INVESTIGATIONS

Train	*A*	*B*	*C*	Reference
SNCF CC 6500 + 10 standard coaches	7.70	0	0.000960	19
JNR 8-unit Sanyo Shinkansen	5.46	0.0705	0.000666	20
SNCF TGV 001	1.04	0.0180	0.000258	9
BR British passenger train with 10 Mk II cars	6.60	0.0111	0.001424	21
BR APT train with 2 power cars and 12 coaches	9.60	0.0447	0.000782	21
SNCF RTG (total of 5 vehicles)	2.07	0.0234	0.000595	22
SNCF BB 16500 + 7 coaches	5.34	0.0355	0.000883	22
SNCF TGV Sud-Est (total of 10 vehicles)	3.90	0.0407	0.000632	22
DB Class 120 + 6 passenger cars	9.30	0.0279	0.001045	23
SNCF TGV Sud-Est	3.82	0.0390	0.000632	24
BR APT train with 2 power cars and 12 coaches	9.78	0.0442	0.000780	12
BR HST (2 power cars + 8 coaches)	2.85	0.0180	0.000772	25
BR APT (2 power cars + 12 coaches)	6.72	0.0270	0.000777	25
SNCF TGV Sud-Est (2 power cars + 8 coaches)	3.90	0.0410	0.000632	25
JNR Shinkansen (total of 12 cars)	7.71	0.1410	0.000982	25
BR British freight train (locomotive + 20 cars)	15.60	0.1530	0.002590	25

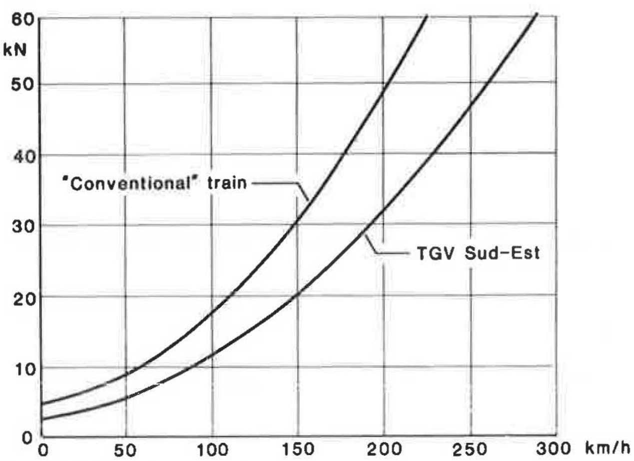

FIGURE 9 Impact of shape on train resistance.

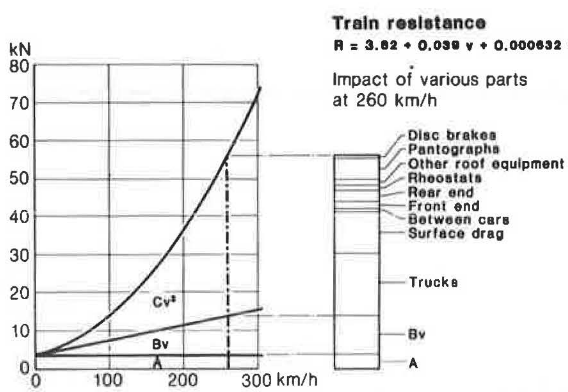

FIGURE 10 TGV Sud-Est.

with P in watts, F in newtons, and v in meters per second. Applying a factor of 1000 to each side yields

P (in kW) = F (in kN) $\times$ v (in m/sec)

Applying another factor of 1000 to each side yields

P (in MW) = F (in kN) $\times$ v (in km/sec)

Finally, because 1 hour = 3600 sec, the relationship can be written

3600 P (in MW) = F (in kN) $\times$ v (in km/h)

In the case of high-speed trains, F corresponds to the tractive effort, v to the speed of the train, and P to the power required at the wheel-rail interface. This relationship is illustrated by the four hyperbolas in Figure 11. The lower left corner of the figure may be considered a nomogram in which the tractive effort (using the vertical scale) can be obtained at the intersection between a vertical line representing the adhesion weight of the train (total weight on driving axles) and a skew line representing the adhesion coefficient presumed to be available at the driving wheels. When the tractive effort has been found, a horizontal line can be drawn to the right. The hyperbola that intercepts this horizontal line where it crosses the vertical line representing the train speed indicates the power required.

Figure 12 shows some examples of curves representing tractive effort versus speed for some vehicles that have actually been built or at least have been projected. Curve A relates to the German electrical multiple-unit train set ET 403, the first of which was delivered in 1973 (*28, 29*). Curve B represents the French electric locomotive Class 26000 (Sybic) with three-phase synchronous traction motors and intended for 200-km/h passenger trains as well as for lower-speed freight trains (*30, 31*). Two prototype locomotives were delivered at the end of 1984, and 44 series-production locomotives have been ordered by SNCF.

Curve C refers to the French high-speed train TGV Atlantique (*31, 32*), the first 73 sets of which SNCF ordered in 1985. They will run at a maximum speed of 300 km/h and are driven by three-phase synchronous traction motors.

The Class 103 with the characteristic shown in Curve D was the first German electric locomotive projected to run at speeds of 200 km/h. The first prototype was delivered in 1965. As were all main-line electric locomotives in Germany at that time, it was powered by single-phase commutator-type motors (*33*).

A British project for a high-speed train with two power cars and 14 coaches is described by Ford (*34*). The speed in open air would be 300 km/h but in a tunnel only about 190 km/h. Continuous power output is planned to be no less than 10 MW for the train that will be powered by three-phase induction motors. Curve E shows its characteristic.

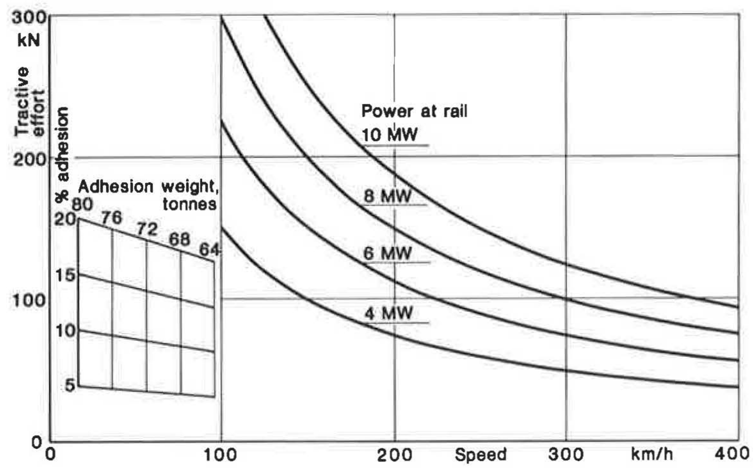

FIGURE 11 Relations among tractive effort, speed, and power at rail.

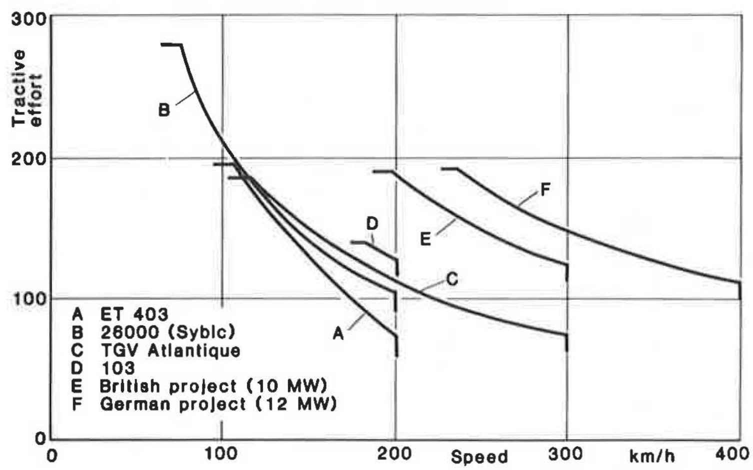

FIGURE 12 Relations among tractive effort, speed, and power at rail for six selected trains.

As early as 1974 a train with 12 driven axles and a total power of 12 MW was being planned in Germany (*35*). Its characteristic is shown by Curve F. The train would be driven by three-phase induction motors with a maximum rotational speed of 4500 r/min and weighing only 1150 kg per motor rated 1000 kW. The axle load would then be limited to 15 tonnes.

Attempts to increase the maximum speed of trains by providing more traction power will result in an appreciable reduction in journey time only if the higher speed can be maintained for long distances. Unfortunately, most of the existing railroad systems are troubled by numerous speed restrictions, mostly due to curvature, and realignment of these curves is usually very costly and may be prohibitively expensive. Therefore, during the last two or three decades, a good deal of effort has been put into endeavors to provide the vehicles themselves with means that would enable them to traverse existing curves at higher speeds than are possible with conventional vehicles.

In general, the maximum speed limit in a curvature (after attention has been paid to safety, risk of derailment, overturning the train, or overloading the outer rail) is determined by considerations of passenger comfort. The main cause of discomfort is unbalanced centrifugal force. Centrifugal force can be countered by superelevation of the track, but the amount of superelevation may be limited by slower trains using the same track or the track having been built at a time when there was no need for the higher speeds considered necessary today.

Attempts were made in the 1950s to counteract excessive centrifugal force on passengers by suspending the carbody in such a way that it could turn around a longitudinal axis above the center of gravity, enabling the body to swing like a pendulum when traversing a curve. Passengers then experience a slight increase in weight but little transverse force. Experiments with natural, passive, or pendular tilt were performed in France (*36*) (Figure 13), Germany, and the United States (on the Chesapeake & Ohio Railroad). This type of tilting was also used on the turbotrains designed by United Aircraft and introduced between New York and Boston and in Canada in 1968.

The early French experiments with tilting vehicles, beginning in 1956, are described elsewhere (*36, 37*) and shown in Figure 13. Tests with assisted tilt demonstrated that it was possible to run a vehicle over a curve with a cant deficiency of up to 300 mm.

In Germany, a diesel multiple-unit train was provided with a tilting mechanism for use when traversing curves; the servo

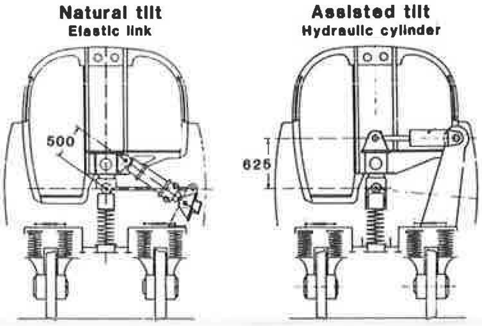

FIGURE 13 French experiments with a tilting coach.

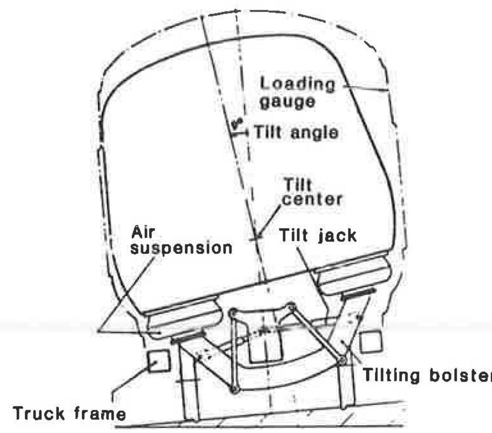

FIGURE 14 Tilting arrangement for prototype APT train.

system was arranged so that air bellows supporting the carbody were inflated on the outside of the curve and deflated on r/min inside, thus tilting the body relative to the truck toward the inside of the curve (*38, 39*). In this case the maximum tilt was 4.4 degrees.

In Japan, two experimental nondriving trucks with a pendulum-type suspension were built and tested in 1968 (*40*). After some improvements of the truck had been made, an experimental three-unit narrow-gauge electric train set Kumoha 591 with pendular tilt was built and tested (*41*). The system used for tilting is described in the *Railway Gazette* (*42*) and is based on the body being mounted on rollers giving a relatively high axis of rotation so that no powered tilting is considered necessary. The tilting is limited to 6 degrees. Tests on the Kumoha 591 set are described elsewhere (*43*). A similar pendular tilting system was used for the JNR prototype gas turbine train completed in 1972 (*44*). After 3 years of testing of the Kumoha 591, a design was approved for series production and the first six-car set went into service in 1973. Later, nine-car sets were also built, and the train was reclassified as Series 381.

The idea of tilting the carbody by power controlled by some sort of servomechanism came to the fore in the late 1960s and early 1970s, mainly in Britain, France, Germany, Italy, Japan, Spain, Sweden, and the United States. This type of tilting is called active, assisted, controlled, or powered tilt.

British Railways first introduced the concept of powered tilting on its Advanced Passenger Train (APT) (*42, 45*). One reason was that a pendular nonpowered suspension for tilting the body would inevitably have had a rather long response time. The technique suggested for APT is described elsewhere (*46, 47*) and shown in Figure 14. After many years of difficulties with various versions of tilting equipment for the APT, the project was finally abandoned and most power cars and trailers scrapped in 1986.

In Italy, the State Railways (FS) in 1970 authorized expenditure for building a prototype tilting-body electric train set (*48*) with an intended maximum speed of 250 km/h. The pantograph was to be carried on a framework mounted solidly on the truck, and the coach bodies with their vestibuled connections were to be free to tilt within this framework (*42, 49, 50*) as shown in Figure 15. Testing of the first car began in early 1972. Maximum tilting was 10 degrees. After comprehensive tests on the single car type Y0160, it was decided in 1974 that a four-unit high-speed train with a hydraulically operated tilt control device for a maximum tilt of 10 degrees should be developed. The design is described by Messerschmidt (*51*). The train is designated as ETR 401 and entered public service in July 1976. A similar four-car train set was also built in Spain under license from Fiat and delivered in 1976 (*52*).

Recent developments related to the tilting trains ETR 401 and ETR 450 in Italy are discussed elsewhere (*53*). The ETR 450 is designed for a maximum speed of 250 km/h. Fourteen of these trains have been on order since May 1985. The axle load is limited to 12 tonnes.

Experiments with air spring tilting in Sweden started in 1970 using a system in which the centrifugal acceleration in a curve was electronically measured and the corresponding tilting angle monitored. Full reaction time was reported to be 1.5 sec. Since 1973, a development project X15, involving both radial-steering trucks and carbody tilting, has been carried out. The results of this development are described by Nilstam (*54*) and shown in Figure 16. Ford (*55*) makes a comparison between this project and the failed APT in Britain. On the basis of experience gained, the Swedish State Railways in 1986 ordered from ASEA 20 six-car trainsets Class X 2 with a maximum service speed of 200 km/h. These trains will be powered by three-phase induction traction motors; they will use radial steering trucks; and all vehicles in the train, except the power car, will be fitted with a hydraulic tilting system. Maximum tilt will be 6.5 degrees. The X 2 trains are described elsewhere (*56*).

As early as 1949, the American Car & Foundry Company designed and built a demonstration train based on patents owned by the Spanish Tren Articulado Ligero Goicoechea Oriol (TALGO). A TALGO train is characterized by independently rotating wheels, only one pair of wheels at the rear end of each car, a very low point of inertia, extremely low weight, and a link connection between the carbodies. The first trains went into regular service in July 1950 between Madrid and the Spanish-French border and became quite popular. Similar trains were also supplied to the New York–New Haven Railroad in the United States.

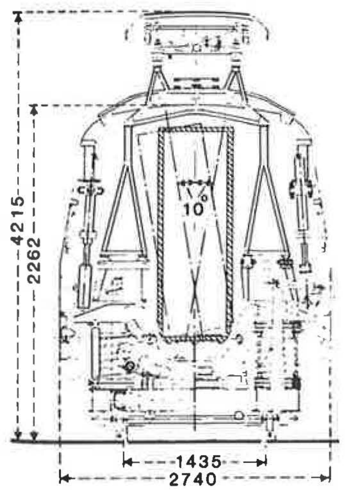

FIGURE 15 Tilting coach for 250 km/h (Italy and Spain).

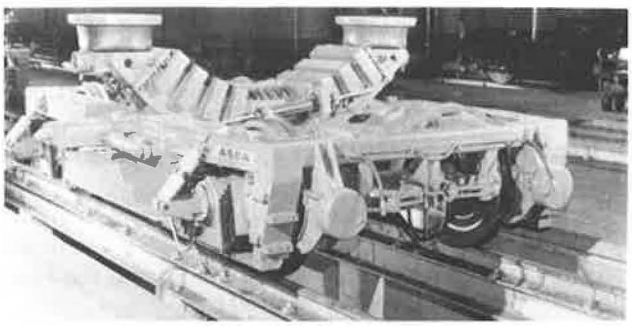

FIGURE 16 Radial steering truck with hydraulic carbody tilting (experimental train X15 in Sweden).

In July 1976, a prototype TALGO trainset with pendular body tilting was delivered in Spain by CAF and Fiat, and tests with speeds up to 200 km/h were performed at the end of 1976. These tests are described by Lumpie (*57*).

A new generation of TALGO trains (Talgo Pendular) was introduced in Spain in 1980 after having been tested at speeds of up to 230 km/h. They are described elsewhere (*58, 59*).

Selected high-speed trains, locomotives, and power cars are described next.

DETAILED DESCRIPTIONS

High-Speed Train (HST) in Britain

In the British Railways Board Report for 1969, two speed ranges to be attained operationally in the next decade were outlined. One was a "high-speed" train operating at 160 to 200 km/h with existing forms of traction and signaling, and the other was a "very high-speed" train to be designed according to the APT concept (*60*). On September 21, 1970, it was first publicly announced that a high-speed diesel-powered train was under development at British Rail's Technical Centre in Derby. A comprehensive description of this HST was published by Janota and Dannatt (*61*). Figures 17 and 18 show the general layout of its diesel-electric power car and a cross section of its mechanical transmission, respectively.

In commercial service, the HST will normally comprise five Mark III passenger coaches, two catering vehicles, and one power car at each end. The nine-car formation has a tare weight of about 365 tonnes. Each power car in service order weighs about 66 tonnes, corresponding to an axle load of 16.5 tonnes. The principal components of an HST power car are described next.

The diesel engine is a 12-cylinder Ruston Paxman Valenta type 12RP200L developing 1678 kW (UIC rating) at 1500 r/min. It drives a combined main/auxiliary three-phase 12-pole alternator rated at a maximum power of 1480 kW in the main part and 313 kW in the auxiliary part. The four frame-mounted direct-current traction motors are each rated 343 kW. They are permanently connected in series-parallel and operate in full field throughout the entire speed range. Alternator and traction motors are made by Brush. Stanier (*62*) and Sephton (*63*) give rather complete reports on the HST.

After the prototype HST had been thoroughly tested, British Rail announced in 1973 that 27 HSTs had been ordered, followed the next year by an order for 32 more. The first production-type HST went into service between London and Bristol on October 4, 1976.

Experience gained with the production trains has been reported elsewhere (*64*). Of particular interest was that fractures started to develop on the production trains (they had not occurred on the prototype). This may be one reason for some of the Valenta engines reportedly being replaced by Mirrlees V12MB190 diesel engines. British Rail currently has a fleet of 95 HSTs.

In March 1980, the New South Wales Public Transport Commission ordered four seven-car trains similar to the HST, but in Australia classified as XPT. They are, however, geared for a maximum speed of 160 km/h instead of 200 km/h as is the case for the HST.

Advanced Passenger Train (APT) in Britain

As mentioned earlier, in the mid-1960s British Rail had already started to investigate a high-performance, lightweight

Maximum speed	200 km/h
Diesel engine rating	1678 kW at 1500 r/min
Diesel power for traction	1455 kW
Wheel diameter	1020 mm
Weight of power car	66 tonnes

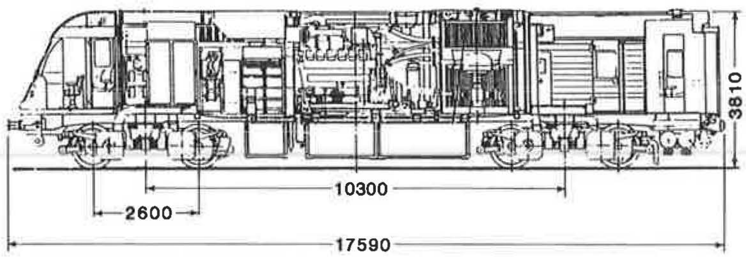

FIGURE 17 Diesel-electric power car for the high-speed train (Britain).

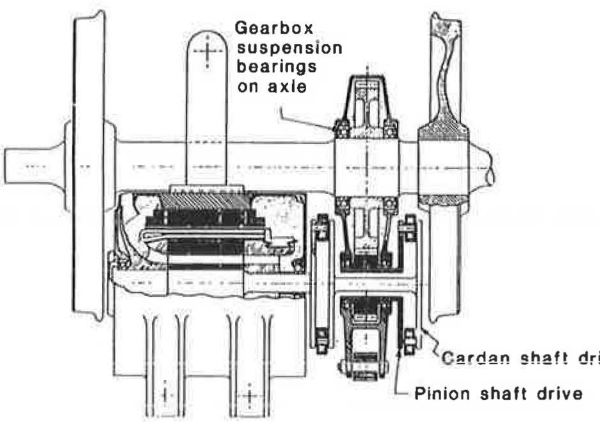

FIGURE 18 Mechanical transmission of HST.

train, later to be named the Advanced Passenger Train. It was intended to be able to run at maximum speeds well above 200 km/h on existing track in Britain, thereby avoiding the considerable costs of major civil engineering reconstruction of track. Some type of power-controlled tilting would be necessary to achieve this. Several types of propulsion were studied, and originally it appeared likely that a rail traction version of an aircraft gas turbine plus a simple mechanical transmission would be chosen for the APT (*65*).

Evaluation of the APT using two skeletal dummy power cars started at Derby early in 1971, and it was decided to build an experimental four-car train to be tested on a track 21 km long (*66*).

Initial trials planned for the experimental version APT-E are described elsewhere (*67*). The APT-E is also discussed in detail by Wickens (*68*) and in *Rail Engineering International* (*69*). The gas-turbine-driven APT-E took to the rails for the first time on July 25, 1972. At the same time, it was decided that detailed design work was to start on the prototype straight electric version APT-P; an order was placed with ASEA for the electric traction equipment for this version.

Gunston (*70*) gives a comprehensive description of the APT-E. Problems with the gas turbines and heat exchangers on the APT-E started almost immediately after completion. Both the gas turbines and the suspension system had to be modified. Some of these problems are described elsewhere (*71*). The tilting problems have also been discussed (*46*).

For a while in the mid-1970s, a degree of optimism returned, and the APT was treated in some detail by Jones (*21*). The APT-E attained 240 km/h on July 27, 1975, and 245 km/h on August 10 the same year. Figure 19 is a picture of this train.

Six power cars for the electric power car version APT-P were in the meantime being built at Derby (*47*). The power transmission is shown in Figure 20 and described elsewhere (*47, 72–74*).

Technical faults continued to plague the APT into the 1980s. The worst affected components were reported to be the tilt system (liable to lock a particular carbody into one position) and the friction brakes (which had a tendency to become applied on one axle only leading to overheating). Criticism of the whole project increased, and it was finally abandoned in 1986.

Light Rapid Comfortable (LRC) Train in Canada

It was announced in June 1969 that a Canadian consortium had started (in 1967) to develop a high-speed lightweight train incorporating many features of the Turbotrain design, but to be powered by diesel engines. The consortium consisted of

FIGURE 19 Advanced Passenger Train in Britain.

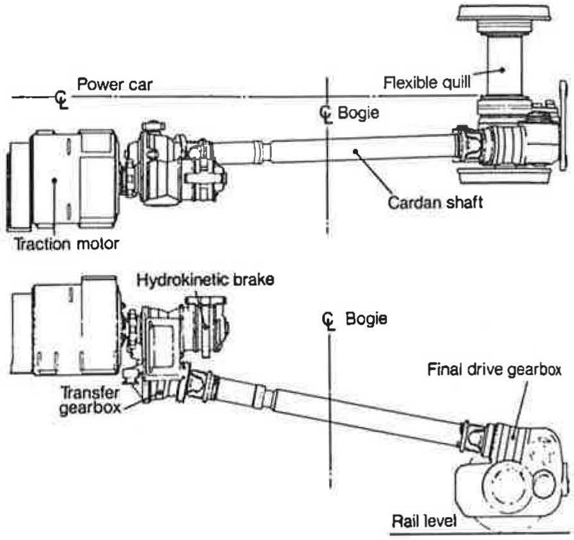

FIGURE 20 APT power transmission.

MLW-Worthington Limited, Alcan Aluminium Limited, and Dominion Foundries & Steel Company.

The LRC is a trainset consisting of either one power car (locomotive) and five coaches, or two power cars (one at each end) with ten coaches between them. The train is designed for a maximum speed of 193 km/h.

A prototype LRC coach was displayed to the public on October 5, 1971 (*75*). Later, a power car was designed and built by MLW Industries (*76–78*). At the end of 1974 the power car and the coach were tested at Pueblo where they reached an average speed of 156 km/h during a 1762-km test. They then entered service between Toronto and Sarnia on March 3, 1975. A Canadian train speed record was set on March 10 of that year when the LRC reached 205 km/h (*79*).

Late in 1977, the Canadian government ordered for VIA Rail 22 LRC power cars and 50 coaches from Bombardier-MLW.

Amtrak decided to lease two LRC trainsets, each consisting of one power car and five coaches, and both had entered service by the end of October 1980. However, Amtrak decided in the middle of 1982 not to use them further and returned them to Canada. This coincided with VIA Rail's ordering 10 more LRC trainsets. The first ones had been in revenue service between Montreal and Toronto since October 25, 1981.

Rather comprehensive descriptions of the LRC trains are available elsewhere (*80, 81*). The main dimensions of the power car are shown in Figure 21. Characteristic particulars are described next.

The power car is geared for a maximum speed of 193 km/h, and the continuous power at rail is 1492 kW. The total length over couplers is 19 406 mm, the truck wheelbase is 2896 mm, and the wheel diameter is 1016 mm (new). A power car weighs 99 tonnes. It has a low profile, a low center of gravity, and a front end designed for low air resistance. Its cross section is only 9.57 m^2. The underframe is designed with a depressed box for accommodating the diesel engine. The fuel tank has a capacity of 7272 liters. There is no provision for tilting of this carbody.

The diesel engine (one per power car) has a gross power rating of 2163 kW and delivers 1715 kW for traction to the three-phase alternator at a constant speed of 900 r/min (idling speed is 400 r/min). It is an MLW series 251 turbocharged four-stroke, 12-cylinder Vee engine with a bore of 228.6 mm and a stroke of 266.7 mm. Cylinder blocks, cylinder heads, and the turbocharger are water cooled.

The output from the main alternator is rectified by diodes and supplied to four axle-hung direct-current traction motors made by Canadian General Electric.

Each coach has a length over couplers of 25 908 mm and a weight (with 75 percent passenger loading) of about 42 tonnes. It is provided with Dofasco's hydraulic system for tilting the coach body up to a maximum of 10 degrees of which usually only 8.5 degrees are utilized.

Traction Vehicles Powered by Gas Turbines (some in combination with diesel engines)

Attempts to use gas turbines in traction applications started in the 1930s. It was reported in 1947 (*82*) that, at that time, 21 different organizations were known to be supporting

Maximum speed	**193 km/h**
Diesel engine rating	**2163 kW**
Diesel power for traction	**1715 kW**
Wheel diameter	**1016 mm**
Weight of power car	**99 tonnes**

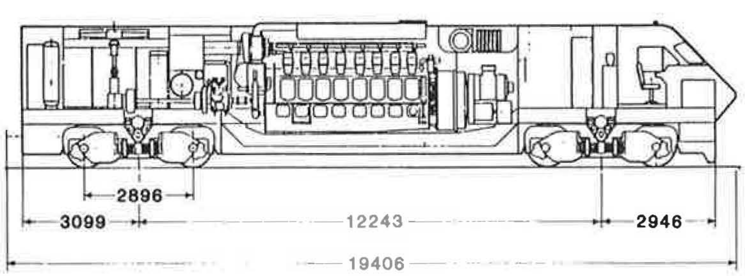

FIGURE 21 LRC diesel-electric power car.

development of gas turbine locomotives. Especially in the United States this development was directed toward both oil- and coal-burning turbines, but the locomotives envisioned (although some were intended for passenger services) had maximum speeds far below those addressed in this paper.

Brown Boveri in Switzerland built a 1640-kW oil-fired gas turbine locomotive in 1941 and followed up this pioneering work in the mid-1940s with a 2982-kW DoDo gas turbine–electric unit. In October 1946, Britain's Great Western Railway (now British Railways' Western Region) ordered from Brown Boveri and SLM a gas turbine locomotive, number 18000, with a continuous power from the turbine at the generator coupling of 1864 kW. It was delivered early in 1950 (*83*). The maximum speed of the locomotive was 145 km/h. The rotational speed of the turbine was 5800 r/min and that of the generator 875 r/min. The axle arrangement was (A1A) (A1A).

The second locomotive of this type in Britain was delivered to BR by Metropolitan-Vickers early in 1952 (*84*). It was a CoCo locomotive also geared for a maximum speed of 145 km/h and was powered by a Metropolitan-Vickers open-cycle gas turbine rated 2237 kW at 7000 r/min and driving three main generators running at 1600 r/min.

An attempt by BR to burn coal in a gas turbine locomotive with a direct mechanical transmission for low speed (80 km/h) appears to have failed in 1954, and it was not until 1967 that BR announced new interest in gas turbine traction (*85*)—the projected Advanced Passenger Train in its first version. It was to use an oil-burning gas turbine and hydraulic tilting of the coach bodies to attain a planned maximum speed of about 240 km/h. The APT project was finally abandoned in 1986 for a number of reasons. A rather comprehensive description of the experimental APT-E train is given by Wickens (*68*).

In Germany, the Deutsche Bundesbahn (DB) initiated studies on the feasibility of using gas turbines for railroad traction in 1963, but at the beginning they thought mainly in terms of a combined diesel and gas turbine system (CODAG) with a small gas turbine providing boost for rapid acceleration and gradient ascents. Such a locomotive, V 169, was built and completed in May 1965 (*86–88*). This locomotive used a Maybach 16-cylinder Vee-type diesel engine model MD 870 rated 1603 kW at 1600 r/min for main traction and, in addition, a General Electric two-shaft gas turbine model LM 100 rated 671 kW. Power was transmitted to all four axles of the locomotive through a Voith hydraulic gearbox with two torque converters. The maximum speed of the V 169 (later renamed Class 219) was only 130 km/h, but the basic concept was so successful that DB ordered eight locomotives of an improved version, Class 210 (*89*). The first of these was delivered at the end of 1970. Main traction was provided by an MTU diesel engine model MA12V956TB rated 1864 kW at 1500 r/min boosted by an AVCO Lycoming gas turbine model T53-L 13 with a continuous rating of 742 to 913 kW depending on altitude and environmental temperature.

The next move of DB was to order three power cars Class VT 602 (*90–94*), with gas turbines as prime movers, intended for a maximum speed of 160 km/h. The turbine was an AVCO Lycoming model TF35 with a continuous rating of 1864 kW replacing the 820-kW diesel engine previously installed in this type of power car. However, fuel consumption and maintenance cost did not meet DB's expectations, and DB decided in 1978 to abandon all attempts to use gas turbines for rail traction.

In January 1966, the U.S. Department of Commerce awarded a contract to United Aircraft Corporation (UAC) for the development of two gas-turbine-powered trainsets, each consisting of three articulated cars. Propulsion was to be accomplished by specially modified Pratt & Whitney Aircraft model ST-6B turbines, and the cars were to have a pendulum suspension system enabling their bodies to tilt (*95*). The Canadian National Railways (CNR) became interested but preferred a longer trainset (seven cars). Both trains are described elsewhere (*96, 97*). During tests in New England at the end of 1967, the first Turbotrain attained a speed of 275 km/h. The three-car trains for the New Haven Railroad had a total power of 2035 kW; the seven-car trains for CNR had a power of 1193 kW. The Canadian Turbotrains entered service in December 1968 but had to be withdrawn after only a few weeks because of severe weather conditions. The first Turbotrain in New England entered service on April 8, 1969.

Although the Turbotrains also encountered a number of problems in the United States, the U.S. Department of Transportation, in January 1971, signed a new contract with UAC for the production of four additional Turbotrain cars. On January 29, 1973, the department announced that it had ended its sponsorship of the Turbotrain demonstration and turned the program over to Amtrak. The two trains used in the U.S. demonstration had been acquired by Amtrak for continued use. Almost at the same time, Amtrak decided to lease from France two gas-turbine-powered trains of the RTG class (*98*).

Rohr Corporation was granted a license by ANF Frangeco to build RTG Turbotrains in North America. In July 1974, financing was approved for Amtrak to buy seven trainsets of the RTG design. In the United States these trains have been named Turboliners (*99*). The first of the seven Turboliners ordered from Rohr went into service between New York and Buffalo in September 1976. Amtrak decided early in 1980 to sell the three trouble-plagued UAC Turbotrains "for the best possible price." VIA Rail in Canada withdrew its remaining Turbotrains from service on October 31, 1982.

In 1967 a project for fundamental research on the suitability of gas turbine propulsion for high-speed trains started in Japan. The following year a gas turbine was installed in an obsolete diesel railcar that was then run on a test track. Results were encouraging, and tests continued on Japan's narrow-gauge (1067-mm) main-line tracks at speeds of up to 130 km/h (*100*). The turbine had an output of 746 kW at 15 000 r/min. A mechanical transmission with a total gear ratio of 1:17.94 was used. Later, two different turbines (*101*) were tested. After the successful conclusion of these tests, the JNR ordered, in 1971, a three-car gas-turbine-powered train (*43, 44, 102*). The prototype unit was completed in March 1972. The gas turbine used could be either an Ishikawajima model IM 100-IR rated 783 kW at 21 300 r/min or a Kawasaki model KTF-14 rated 761 kW at 18 500 r/min. A number of these trainsets are now in service in Japan.

As early as 1966, the French National Railways (SNCF) decided to seriously look at the idea of using gas turbines for

Maximum speed	**200 km/h**
Main turbine power rating	**2200 kW per train at 20480 r/min**
Hydraulic transmission	**Voith L 411**

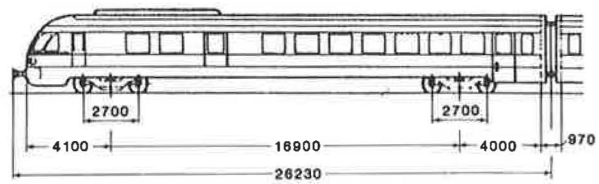

FIGURE 22 Power car of the RTG turbotrain (France).

FIGURE 23 Gas-turbine trainset Turboliner (United States): maximum speed 200 km/h, rated turbine power 1700 kW.

rail traction (*103*). An experimental vehicle TGS (Turbine à Gaz Special) was built and tested in 1967. An order was placed in 1968 for 10 turbine trains ETG (Element automoteur à Turbine à Gaz), and these were tested in 1969 and entered revenue service in 1970. Also in 1970, the first six Rame à Turbine à Gaz (RTG) trains were ordered, and they went into commercial service in 1972. The first turbine train for very high speed, the Très Grande Vitesse (TGV) 001 was delivered in 1971.

It appears to be fair to state that, in the early 1970s, France had become the acknowledged pioneer of gas turbine traction for high-speed trainsets. Therefore the French vehicles briefly mentioned previously will be described in somewhat more detail.

The TGS was the result of rebuilding a standard diesel-driven two-car trainset X4300/X4500. One of the cars retained its Poyaud diesel engine rated 330 kW, and a gas turbine drive Turmo III C3 from the Turbomeca Company was installed in the other car. It had a rated output of 820 kW. Numerous high-speed tests were performed with the TGS from April 1967 until December 1972. The maximum speed attained (with an experimental turbine Turmo X) was 252 km/h on October 19, 1971. After conclusion of the tests, the TGS was converted into a trainset for party excursions.

The first 10 ETGs were ordered by SNCF in July 1968 as a result of the successful tests on the TGS. Each ETG consists of four cars: at one end a diesel-powered rail car, at the other end a gas-turbine-powered rail car, and, in between, two non-powered coaches, all permanently connected. The train is designed for a maximum speed of 180 km/h. The turbine used on the ETG is Turbomeca model Turmo IIIF, which is a direct development from a turbine used for a French helicopter. It is a two-shaft turbine, which makes it possible to reduce fuel consumption at partial load in comparison with what it would be for a single-shaft turbine. In this application, the output rotating speed of the turbine is 5700 r/min and the power is limited to 820 kW. The power is transmitted to the wheels through a Voith L411rU hydraulic transmission. The ETG trains are described elsewhere (*104–108*).

The RTG trains (Figure 22) (*106, 109–111*) are designed for a maximum speed of 200 km/h and are powered only by gas turbines. Each train consists of a power car at each end and three intermediate nonpowered coaches. There is one Turbomeca Turmo IIIF gas turbine, which drives the wheels through a Voith hydraulic transmission, in each power car. The first RTG train was delivered on December 1, 1972. The trainset RTG01 was equipped with a special high-speed gear and attained a speed of 260 km/h on January 22, 1974. The RTGs are the base for the Turboliners in the United States (Figure 23) and also for turbine trains delivered to Iran and Egypt.

The experimental gas-turbine-powered train TGV 001 was ordered in July 1969 and delivered in April 1972. It is made up of five cars mounted on six trucks. The end cars each incorporate a driving cab and house the power equipment. The TGV 001 has much better streamlining than the ETG and the RTG, is lower, and has a center of gravity 300 mm lower. In each power car there is a pair of Turmo IIIG gas turbines side by side, which together drive a single alternator through reduction gears. Silicon rectifiers supply power to the direct-current traction motors on the driven axles. The Turmo IIIG is rated at 940 kW per unit. The traction motors are self-ventilated, compensated, and compound wound, and are rated 310 kW continuously with a maximum rotational speed of 3000 r/min.

The TGV 001 is shown in Figure 24 and described elsewhere (*112–117*). On December 8, 1972, it reached a maximum speed of 318 km/h.

Figure 25 shows cross sections of some gas turbines intended for rail traction applications. The development of such gas turbines is described elsewhere (*118–120*).

The high-speed vehicles described so far have all, except the APT-P, used a thermal prime mover mounted on the vehicle. However, a vast majority of high-speed trains today get electric power from a catenary. They can be trains hauled by electric locomotives, power cars, or multiple-unit trains in which all, or practically all, axles are driven. Some selected examples of such trains that are designed for maximum speeds of at least 200 km/h are discussed next.

In the early 1960s France already had four different classes of electric locomotives capable of running in regular service at these high speeds (*2, 121*). Also in the early 1960s, locomotive-hauled high-speed trains appeared to be the preference in Germany, Italy, and the USSR; Japan favored multiple-unit trains of the Shinkansen type.

Maximum train speed	300 km/h
Turbine power rating	4 x 1100 kW at 20800 r/min
Alternator rating	2 x 2250 kW at 4000 r/min
Traction motor rating	12 x 310 kW at max. 3000 r/min
Wheel diameter (new)	900 mm
Maximum axle load	16 tonnes

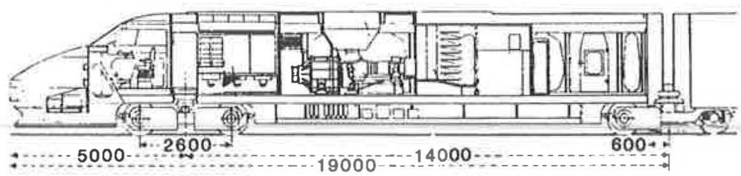

FIGURE 24 Power car of articulated train TGV 001 (gas turbines, alternators, direct-current traction motors).

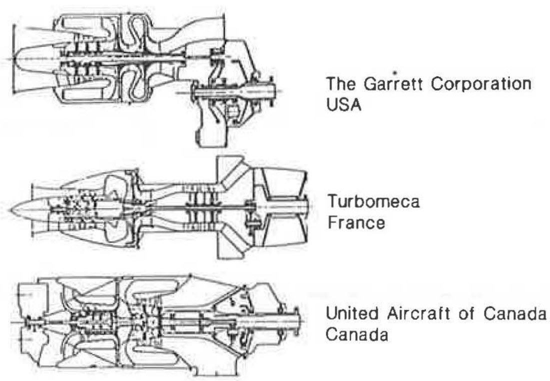

FIGURE 25 Gas turbines for traction.

Electric Locomotive Class 103 (Germany)

In 1962 the German Federal Railway (DB) awarded a contract for four prototype locomotives of a new type (now named Class 103) able to haul trains at a maximum speed of 200 km/h. The first of these locomotives ran in scheduled service between Munich and Augsburg in the summer of 1965. Later 145 series-production locomotives were ordered with deliveries from 1970 on. Siemens had responsibility for the electrical part, Thyssen-Henschel for the mechanical part.

Class 103 is in many respects a further development of the older Class 110; it has a CoCo axle arrangement and is geared for a maximum speed of 200 km/h. The continuous power at rail is 7080 kW according to International Electrotechnical Commission rules. Power supply is from 15 kV at 16²/₃ Hz. The weight of the locomotive in working order is 114 tonnes, corresponding to an axle load of 19 tonnes. The transformer has a continuous rating of 6250 kVA and uses a 39-step high-voltage tap-changer. The spring-suspended 12-pole single-phase commutator motors are each rated 1240 kW continuously at 645 V and 1518 r/min. The wheel diameter (new) is 1250 mm and the gear ratio 1:1.74. The principal dimensions of the locomotive are shown in Figure 26 and general descriptions are given elsewhere (*33, 122–124*).

Electric Locomotive Class E 444 (Italy)

Four prototype locomotives, E 444.001 through E 444.004, with a maximum speed of 180 km/h were delivered from Savigliano in 1967. The Italian Railways (FS) then ordered series production of 113 locomotives with a maximum speed of 200 km/h. The first of these locomotives were delivered in 1970. They all originally had resistance control and field-weakening in steps. In 1975 locomotive E 444.005 was modified for chopper control.

The E 444 is a BoBo locomotive geared for a maximum speed of 225 km/h although only 200 km/h is utilized in service. The continuous power at rail is 3760 kW and power supply is from 3-kV DC. The weight of the locomotive in working order is 81 tonnes, corresponding to an axle load of 20.3 tonnes. The axle-hung direct-current traction motors of model T750 have six series-wound main poles, six interpoles, and a compensation winding. The wheel diameter (new) is 1250 mm and the gear ratio is 40:77 = 1:1.925. The principal dimensions of the locomotive are shown in Figure 27 and general descriptions are given elsewhere (*125–130*).

Electric Locomotive Class ChS200 (USSR)

After the end of World War II, the USSR decided to build domestically electric locomotives for freight transportation only. Electric locomotives for passenger services were imported mainly from the Czechoslovakian manufacturer Skoda. From 1958 to 1972, Skoda delivered to the USSR at least 944 locomotives of Class ChS2 (including those with resistance braking, ChS2T). These CoCo locomotives for 3-kV DC, as well as the corresponding locomotives ChS4 and ChS4T for 25 kV at 50 Hz, were designed for a maximum speed of 160 km/h and, of course, for the Russian broad gauge of 1524 mm. For further development, with a maximum speed of 200 km/h, it was decided in 1973 to build locomotive consists with a total of eight axles, BoBo + BoBo, of the new Class ChS200. Skoda delivered the first two consists in 1975 and since then has delivered at least 20 more, half of them geared for 200 km/h, half for 160 km/h. Further developments of the ChS200, all for a maximum speed of 160 km/h, are the Classes ChS6, ChS7, and ChS8.

The ChS200 is a BoBo + BoBo consist designed for 200 km/h with a continuous power at rail of 8000 kW. Power supply is from 3-kV DC. The weight of the consist is 152 tonnes, corresponding to an axle load of 19 tonnes. The fully suspended direct-current series-wound traction motors are of Skoda's type AL 4741 FIT. The wheel diameter (new) is 1250

Maximum speed	**200 km/h**
Rated output	**7080 kW**
Power supply	**15 kV, 16 2/3 Hz**
Weight of locomotive	**114 tonnes**

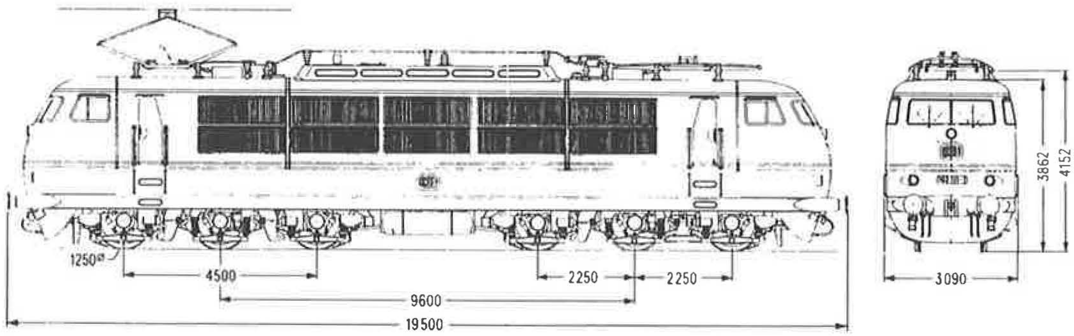

FIGURE 26 Electric locomotive Class 103 (Germany).

Maximum speed	**225 km/h**
Continuous power	**3760 kW**
Power supply	**3000 volts dc**
Weight of locomotive	**81 tonnes**

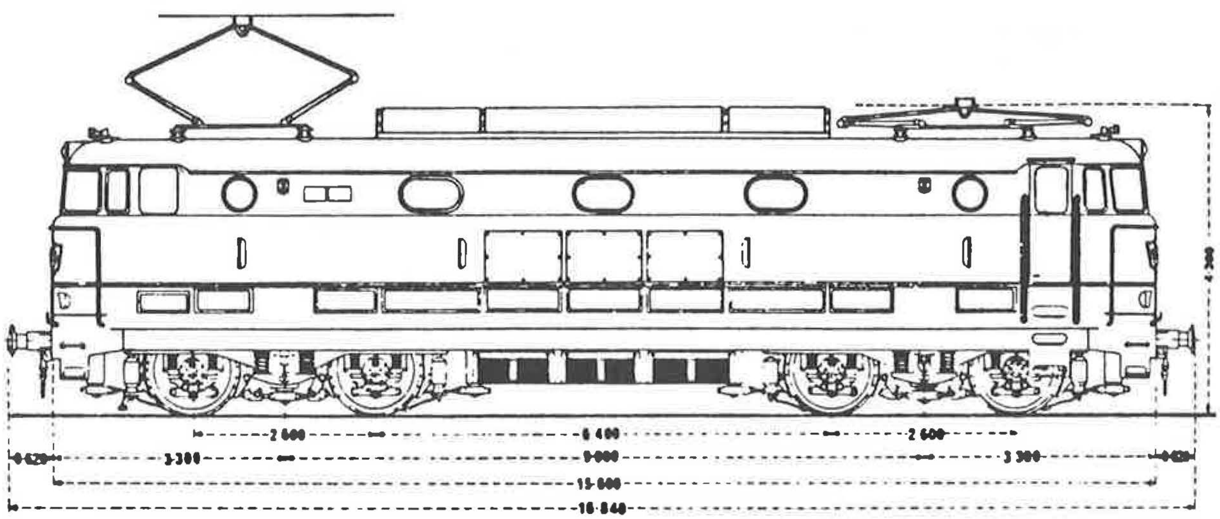

FIGURE 27 Electric locomotive Class E 444 (Italy).

mm. The principal dimensions of the consist are shown in Figure 28, and some details about it are given elsewhere (*131–133*).

Electric Locomotive Class 120 (Germany)

The first high-power electric locomotive with three-phase traction motors, Class 120, was delivered in May 1979 as one of five prototypes. After extensive testing of all five prototypes and some design modifications, the German Federal Railway placed, in November 1984, an order for 60 series-produced locomotives. Four of the prototypes were geared for 160 km/h and one for 200 km/h. Of the 60 locomotives now on order, 36 will be geared for 200 km/h and 24 for 250 km/h.

Class 120 is a BoBo locomotive with a continuous power at rail of 5600 kW. Power supply is from 15 kV at $16^2/_3$ Hz. The weight of the locomotive in working order is 84 tonnes, corresponding to an axle load of 21 tonnes. The transformer has a continuous rating of 5525 kVA. Power is monitored by a control system including rectifier and DC link and voltage source inverters, in which the DC link voltage is 2800 V. The four three-phase induction-type traction motors have a continuous rating of 1400 kW and weigh only 2380 kg. Their maximum rotational speed is 3600 r/min. The wheel diameter (new) is 1250 mm. Four of the prototype locomotives have a gear ratio of 22:106 = 1:4.82; one has a gear ratio of 25:103 = 1:4.12. With half-worn wheels (diameter = 1210 mm) and a maximum rotational speed of 3600 r/min for the traction motors, these gear ratios correspond to locomotive speeds of about 170 km/h and 200 km/h, respectively. The locomotive with the 25:103 gear ratio, in combination with a rotor designed for a maximum rotational speed of 4225 r/min, was tested at speeds of up to 265 km/h on October 17, 1984,

Maximum speed	200 km/h
Continuous power	8000 kW
Power supply	3000 volts dc
Weight of consist	152 tonnes
Track gauge	1524 mm

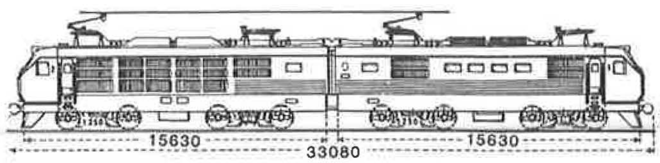

FIGURE 28 Electric locomotive consist Class ChS200 (USSR).

Maximum speed	200 km/h
Continuous power	5600 kW
Power supply	15 kV, 16 2/3 Hz

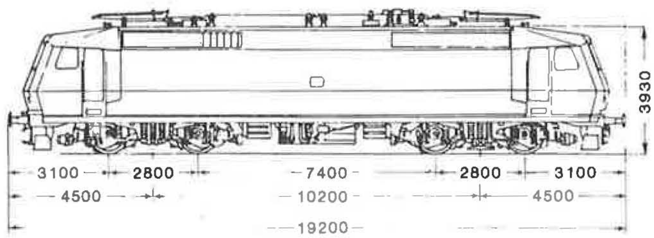

FIGURE 29 Electric locomotive Class 120 (Germany) with three-phase asynchronous traction motors.

and a maximum speed of 280 km/h should be possible. The principal dimensions of the Class 120 locomotive are shown in Figure 29, and descriptions of design and tests are given elsewhere (*134–138*).

Electric Locomotive Class AEM 7 (United States)

In 1975 and 1976 Amtrak decided to lease two European-built electric locomotives to be tried out in the Northeast Corridor. The choice fell on a modified Rc 4 locomotive from ASEA of Sweden and a modified CC 21000 locomotive from Alsthom-Atlantique and Francorail-MTE in France. The principal data on these modified locomotives are as follows:

Amtrak designation	X995	X996
Original designation	Rc 4	CC 21003
Axle arrangement	BoBo	CC
Weight (tonnes)	78	132
Axle load (tonnes)	19.5	22.0
Wheel diameter (mm)	1300	1140
Power at rail (kW)	4000	5760
Length (mm)	15 530	20 550
Truck wheel base (mm)	2700	3216

After 3 months of testing the X996 in 1977, Amtrak concluded that a fair test of the locomotive's capabilities could not be made over the poor track that then existed in much of the Northeast Corridor. Accordingly, the lease for testing this "monomoteur" locomotive was terminated. The X995 successfully completed an extended testing period.

Early in 1978, Amtrak placed an order for the first eight new electric locomotives for the Northeast Corridor, now designated AEM 7. This order was later followed by orders for 39 additional locomotives, bringing the total for Amtrak to 47. The first locomotive was delivered in December 1979. Because of Amtrak's request that the locomotive be able to run on three different catenary systems, 11 kV at 25 Hz, 12.5 kV at 60 Hz, and 25 kV at 60 Hz, a number of modifications were necessary relative to the X995. The principal parameters of the AEM 7 are as follows:

Maximum speed	200 km/h
Continuous power	4320 kW at rail
Weight	91 tonnes
Axle load	22.8 tonnes

The traction motors of ASEA's type LJH 108-5 are separately excited compensated direct-current motors. The wheel diameter (new) is 1300 mm and the gear ratio is 36:85 = 1:2.36. The principal dimensions of the AEM 7 locomotive are shown in Figure 30 and descriptions of the locomotive are given elsewhere (*139–142*).

Electric Locomotive Class 89 (Britain)

In 1983 British Rail ordered a prototype Class 89 electric locomotive from Brush. It was originally intended as a standard passenger locomotive for the East Coast main line in Britain and was specified to be able to run at a maximum speed of 200 km/h. Later developments—especially the request for even higher speeds on many main routes in Britain and on the European continent—have made it less and less likely that the prototype locomotive (which was completed in 1986) will be followed by a series production.

The Class 89 locomotive is geared for a maximum speed of 200 km/h and has a CoCo axle arrangement and a continuous power at rail of 4350 kW. Power supply is from 25 kV at 50 Hz. The weight of the locomotive in working order is 105 tonnes, corresponding to an axle load of 17.5 tonnes. The main transformer is rated at 6368 kVA. Four secondary transformer windings feed banks of thyristors with phase-angle control that, in turn, supply the direct-current traction motors. The principal dimensions of Class 89 are shown in Figure 31 and brief descriptions are given elsewhere (*143, 144*).

Electric "Sybic" Locomotive Class 26000 (France)

Three-phase traction drives can be either asynchronous (induction type) or synchronous. To enable a direct comparison to be made, in 1979 the French National Railways (SNCF) asked two groups of electrical engineering manufacturers to equip each locomotive with their preference of three-phase drive.

In February 1982 tests were begun on the first locomotive (originally BB 15055 but renamed BB 10004), now fitted with two synchronous traction motors of the monomoteur type by Jeumont-Schneider and MTE. The second locomotive, formerly BB 7003 but renamed BB 10003, was placed on a pair of new trucks, thus becoming a BoBo, and was fitted with four induction-type traction motors by Alsthom-Atlantique. Because of several problems, no road tests were begun of the BB 10003 until January 1985. In the meantime, successful

Maximum speed	**200 km/h**
Continuous power	**4320 kW**
Power supply	**11 kV, 25 Hz: 12.5 or 25 kV, 60 Hz**
Weight of locomotive	**91 tonnes**

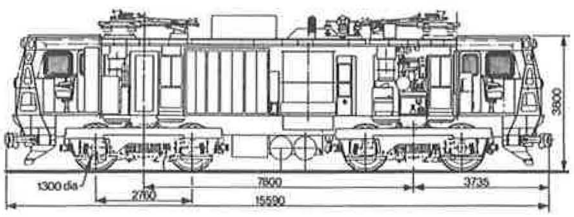

FIGURE 30 Electric locomotive Class AEM 7 (United States).

Maximum speed	**200 km/h**
Continuous power	**4350 kW**
Power supply	**25 kV, 50 Hz**
Weight of locomotive	**105 tonnes**

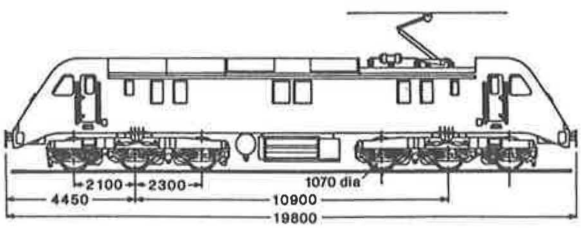

FIGURE 31 Electric locomotive Class 89 (Britain).

tests with the BB 10004 caused the SNCF to favor synchronous motor propulsion at least for the near future. Based on the electrical equipment of the BB 10004 but further developed to enable the locomotive to operate on both 25-kV, 50-Hz, and 1500-V DC catenaries, two prototype locomotives, BB 20011 and BB 20012, were built and handed over to SNCF for tests early in 1985. These locomotives have been called Sybic locomotives (from synchrone and bicourant). On July 23, 1984, SNCF ordered from Alsthom and Francorail a first batch of 44 Sybic locomotives, officially designated Class 26000.

Class 26000 is a BB locomotive geared for a maximum speed of 200 km/h. The continuous power at rail is 5600 kW and power supply can be 25-kV, 50-Hz, or 1500-V DC. The weight of the locomotive in working order is 90 tonnes, corresponding to an axle load of 22.5 tonnes. The body-mounted synchronous traction motors each have eight poles and two displaced three-phase stator windings. Their maximum rotational speed is 1980 r/min, and the continuous rating per motor of 2800 kW can be attained over a speed range of from 40 to 100 percent of maximum speed. The wheel diameter is 1250 mm and the gear ratio 33:73 = 1:2.21.

The principal layout of the prototype Sybic locomotives and a drawing of a series-produced locomotive are shown in Figures 32 and 33, respectively. Descriptions of the locomotives that led up to the Sybic are given elsewhere (*30, 31, 145–150*).

Electric Locomotive Class E 402 (Italy)

All main-line railroad electrification in Italy (except the island of Sardinia) is currently operating from 3000-V DC, and traditionally the traction motors have been conventional direct-current motors with 1500 V per armature, permanently connected two in series. With increasing demand for higher speeds and more powerful traction vehicles for speeds exceeding 200 km/h on the soon-to-be-completed Direttissima line between Rome and Florence, it has been found necessary to introduce three-phase propulsion.

Maximum speed	**200 km/h**
Continuous power	**5600 kW**
Power supply	**25 kV,50 Hz or 1500 volts dc**

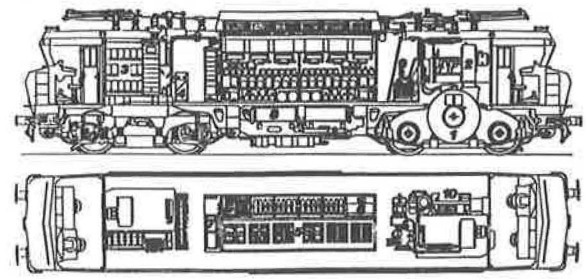

FIGURE 32 Prototype BB 10004 locomotive (France).

Maximum speed	200 km/h
Continuous power	5600 kW
Power supply	25 kV, 50 Hz, or 1500 volts dc
Weight of locomotive	90 tonnes
Tractive effort at start	320 kN

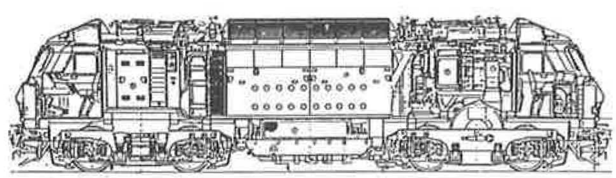

FIGURE 33 Electric dual-system Sybic locomotive Class 26000 (France) with three-phase synchronous motors.

Early in 1984, the Italian State Railways (FS) ordered trucks and three-phase traction motors from Ansaldo Trasporti for its prototype Class E 402 locomotive, and later an order was placed for five complete locomotives of this class. A prototype was completed in 1986 and is undergoing tests. Little information about the E 402 is available yet, but it is designed for a maximum speed of 220 km/h and has already been tested up to 230 km/h. It has a BoBo axle arrangement and the power at rail is specified to be 6000 kW for at least 20 min. The weight in working order is not to exceed 80 tonnes, corresponding to an axle load of 20 tonnes. The four traction motors are of the asynchronous type. A principal layout of the E 402 is shown in Figure 34.

Electric Locomotive Class 91 (Britain)

In 1984 locomotive manufacturers in several countries were invited by British Rail to submit outline proposals for an electric locomotive intended to haul BR's next generation of intercity trains at speeds of up to 225 km/h. The power at rail had to be in excess of 4000 kW and the traction motors were specified to be body mounted. Axle load was maximized to 20

Maximum speed	220 km/h
Power at rail	5600 kW cont.; 6000 kW, 20 minutes
Power supply	3000 volts dc
Weight of locomotive	82 tonnes

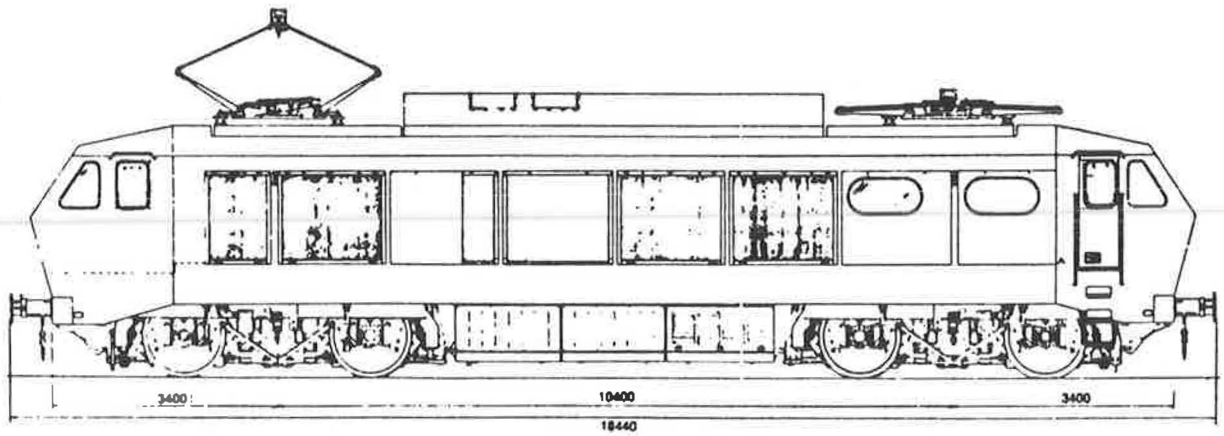

FIGURE 34 Electric locomotive Class E 402 (Italy) with three-phase asynchronous traction motors.

tonnes. The locomotives were not to tilt, but the final decision about whether the coaches should be provided with facilities for tilting was postponed. This locomotive may be considered a successor to the ill-fated Advanced Passenger Train.

Preliminarily designated as IC 225 or Electra, the locomotive finally has been named Class 91. Formal contracts for 31 locomotives to be purchased from the British GEC were signed on October 1, 1986. From the rather scant information presently available about the details of this locomotive, the following may be gleaned: The maximum speed will be 225 km/h. The peak power at rail is supposed to be 4700 kW and the power supply is 25 kV at 50 Hz. The axle load will still be limited to 20 tonnes.

Figure 35 shows a principal layout of the Class 91 locomotive and Figure 36 its drive system of "crossed drive shafts" as envisaged by British Rail. Brief descriptions of the locomotive are given elsewhere (*151, 152*).

Czechoslovakian Electric Locomotive Project

In addition to the previously mentioned eight-axle locomotive consists Class ChS200 that Skoda has delivered to the USSR,

Maximum speed	225 km/h
Continuous power at rail	4530 kW at 153 km/h 3750 kW at 225 km/h
Power supply	25 kV, 50 Hz
Weight of locomotive	82 tonnes
Axle load	20.5 tonnes
Tractive effort at start	193 kN

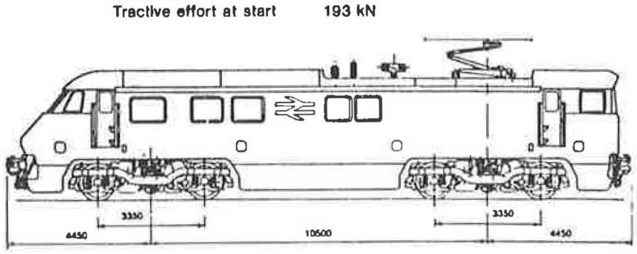

FIGURE 35 British electric locomotive Class 91 (Electra) with separately excited direct-current traction motors.

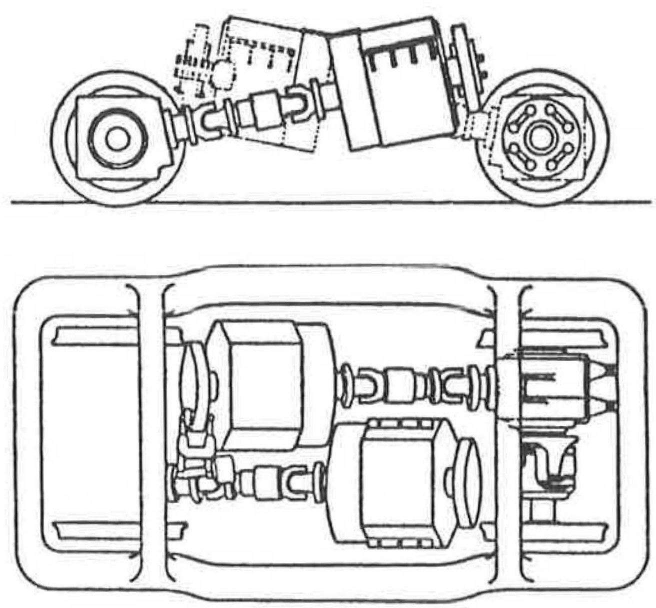

FIGURE 36 Drive system of Class 91 locomotive.

this locomotive manufacturer had, in 1984, a CoCo version on the drawing board rated at 6000 kW and suitable for 200 km/h (Figure 37). The power supply would be 3000-V DC and the total weight 114 tonnes, corresponding to an axle load of 19 tonnes (*131*). Conventional direct-current traction motors were to be used.

During the last few years, Skoda has devoted a lot of effort to developing three-phase asynchronous traction motors (*153*). Two main motor options have been studied: a single 3200-kW body-mounted motor on each truck (a monomoteur) driving both axles of the truck (assuming a BB locomotive) through longitudinal cardan shafts, or the more conventional arrangement of individual 800- to 1000-kW motors mounted in the truck parallel to each axle. The possibility of a fully suspended gearless motor in which the axle passes through the hollow center of the rotor is also under consideration. So far, Skoda's

TABLE 2 SHINKANSEN NETWORK EXPANSION

Date	Distance (km)	Between	Line	Power
March 1972	161	Osaka and Okayama	Sanyo	25 kV, 60 Hz
March 1975	393	Okayama and Hakata	Sanyo	25 kV, 60 Hz
June 1982	496	Ueno and Morioka	Tohoku	25 kV, 50 Hz
November 1982	270	Omiya and Nigata	Joetsu	25 kV, 50 Hz

Maximum speed	200 km/h
Continuous power	6000 kW
Power supply	3000 volts dc
Weight of locomotive	114 tonnes
Wheel diameter	1250 mm

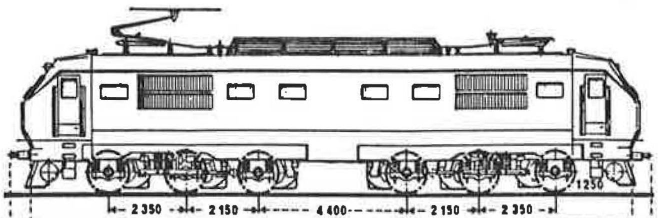

FIGURE 37 Czechoslovakian locomotive project.

efforts have been aimed at locomotives with maximum speeds of 160 km/h. Using three-phase traction motors instead of conventional DC motors is said to reduce, in one particular case, the total length of the locomotive by some 9 percent.

Some high-speed electric multiple-unit cars and power cars are described in the next sections.

Shinkansen Multiple-Unit Train (Japan)

The Japanese Shinkansen trains were the first in the world to run at speeds exceeding 200 km/h on a regular schedule. The main passenger trunk line in Japan is between Tokyo and Osaka. Around 1956 it became clear that the capacity of this line (which was narrow gauge, 1067 mm, and supplied with 1500-V DC) had to be greatly increased to cope with ever-increasing traffic. The construction of a new standard-gauge, 1435-mm, high-speed route about 515 km long was approved in 1959. This was the first railroad in Japan to use standard gauge. Orders for two-car and four-car trainsets were placed in November 1961. The first train was delivered in June 1962 and tried out on a test section of the new line. A speed of 257 km/h was attained in March 1963, and then an order was placed for 180 two-car trainsets (now called the O series). All of these were delivered in time for the opening of the new line, called the New Tokaido Line, on October 1, 1964. It is electrified with 25 kV at 60 Hz. The Shinkansen network has since been expanded (Table 2).

Shinkansen trains use, as a matter of principle, vehicles in which all axles are driven. So far, all of these vehicles have used conventional direct-current traction motors connected in series. This may at least partly explain why the JNR relies on only 3 to 5 percent adhesion at high speeds. The trains are formed entirely from two-car units (coach pairs) one coach of which carries a pantograph, a main circuit breaker, transformer, and rectifier; the other coach carries control gear and braking resistors. Thus the traction equipment is self-contained for each coach pair. The motors are frame mounted and driven through a hollow cardan shaft containing the axle. The motor yoke is partly laminated.

In addition to the production model trains of the O series (for the Tokaido and Sanyo lines) and the 200 series (for the Tohoku and Joetsu lines), experimental cars of type 951 and type 961 have been built. Some of the parameters for these vehicles are given in Table 3.

Figure 38 shows the general arrangement and some principal dimensions of a leading car in a Shinkansen O series train. Descriptions of various Shinkansen cars and their development are given elsewhere (*154–166*). The goal is to increase the maximum speed of new cars with smaller cross sections to 300 km/h in the 1990s. The new series 300 trains will be powered by three-phase asynchronous motors.

Intercity Multiple-Unit Train ET 403 (Germany)

This four-unit train consists of two identical end coaches with passenger compartments, one passenger coach, and one dining car. The first train was delivered in 1973. Each train is powered by 16 traction motors supplied with pulsating direct current (i.e., all axles in the train are powered).

The maximum speed is 200 km/h. Total power at rail is $16 \times 240 = 3840$ kW continuously, and power supply is from 15 kV at $16^2/_3$ Hz. The weight of the train in working order is 236 tonnes, corresponding to an axle load of 14.8 tonnes. The core-type transformer in each unit is rated 1020 kVA for traction. The control system is based on thyristor phase-angle control with two unsymmetrically semicontrolled rectifier bridges in sequential control. The four-pole compensated traction motors are each rated continuously 240 kW, 750 V, 350 A at 2000 r/min. The mechanical transmission uses a Siemens rubber-ring cardan drive and a gear ratio of 1:3.03. The wheel diameter is 1050 mm.

Figure 39 shows some principal dimensions of an end coach of the ET 403. Descriptions of the train are given elsewhere (*28, 29, 167, 168*).

TABLE 3 PARAMETERS OF SHINKANSEN TRAINS

Parameter	0 Series	200 Series	Type 951	Type 961
Maximum design speed (km/h)	210	210	260	260
Continuous power (kW)	740	920	1000	1100
Wheel diameter (mm)	910	910	1000	980
Gear ratio	29:63	29:63	27:56	25:60
Axle load (tonnes)	16	17	17	16
Transformer rating for traction (kVA)	1500		2260	2450

Maximum speed	km/h	210	(240)
Continuous power per car	kW	740	920
Maximum axle load	tonnes	16	17
Power supply		25 kV, 60 Hz	

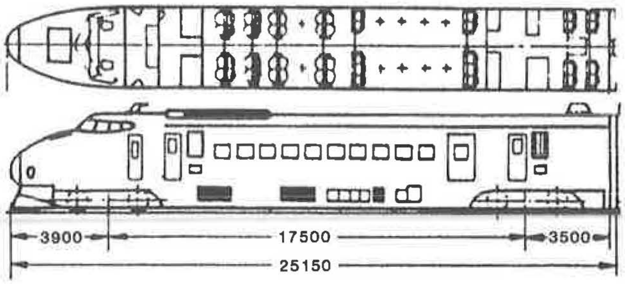

FIGURE 38 Leading power car of Shinkansen train O series (Japan).

Electric Multiple-Unit Train ER 200 (USSR)

The trunk line between Moscow and Leningrad is the most important for intercity passenger traffic in the USSR. Accordingly, it was the first railroad in the Soviet Union to be provided, in 1975, with trainsets designed for speeds of up to 200 km/h. The electric multiple-unit trainsets Class ER 200 have been designed and built by the Riga Carriage Works in Latvia.

The ER 200 is a 14-unit train with a maximum speed of 200 km/h. It has a rather unusual makeup: the end cars have driver's cabs and buffet areas but no driving axles, and the intermediate 12 cars are permanently formed into six identical two-car groups in which all axles are driven. The continuous power at rail is no less than 10 320 kW and the power supply is from 3-kV DC. The track gauge is 1524 mm, and the total weight of the train is 830 tonnes of which 720 tonnes can be used for adhesion. Maximum axle load is 15 tonnes for an empty train and 17 tonnes for a loaded one. The fully suspended conventional direct-current traction motors are each rated 215 kW continuously. The wheel diameter is 950 mm.

Figure 40 shows a picture of and some data on the ER 200. The general arrangement of an end car is shown in Figure 41. Descriptions of the train are given elsewhere (*169–171*).

Maximum speed	200 km/h
Continuous power	840 kW per car
Power supply	15 kV, 16 2/3 Hz
Wheel diameter (new)	1000 mm
Wheel base in truck	2600 mm

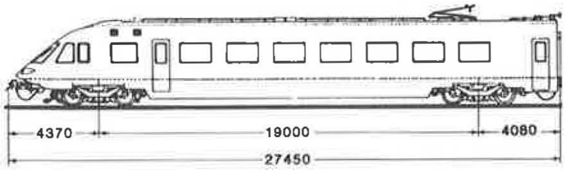

FIGURE 39 Power car (end coach) of train ET 403 (Germany).

Maximum speed	200 km/h	
Power at rail	48 x 215 kW	10320 kW for complete train
Power supply	3000 volts DC	
Weight of powered car	60 tonnes	
Maximum axle load	17 tonnes fully loaded	
Wheel diameter (new)	950 mm	
Gear ratio	1 : 2.35	
Wheel base in powered truck	2500 mm	

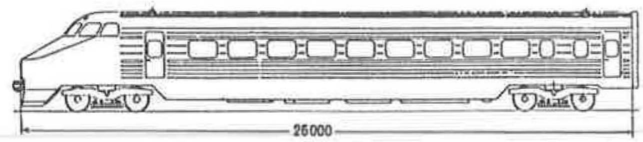

FIGURE 40 Trailer with driver's cab for train Class ER 200 (1 trailer + 12 powered cars + 1 trailer) with direct-current traction motors (USSR).

Maximum speed	200 km/h
Power supply	3000 volts dc
Total propulsion power	10320 kW
Maximum axle load	17 tonnes

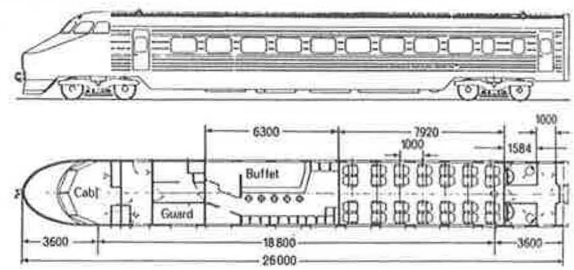

FIGURE 41 Soviet electric high-speed train ER 200 (2 trailers with driver's cab + 12 coaches).

Electric Semiarticulated High-Speed Train—TGV Sud-Est (France)

The straight electric version of the TGV was ordered by the SNCF on February 12, 1976, and the first trainset was handed over to the railroad on July 28, 1978.

Less than a month later, on August 23, it reached a maximum speed of 260 km/h during trials in Alsace. It reached 280 km/h on September 24 the same year. On February 26, 1981, the TGV trainset No. 16 set a world record for wheel-on-rail transportation by attaining a speed of 380 km/h.

The maximum speed of the TGV Sud-Est trains is now 270 km/h in scheduled service. The continuous power at rail is 6300 kW. The power supply is normally from 25 kV at 50 Hz, but all trains can also operate from a 1500-V DC catenary and some are also able to make use of 15 kV at $16^2/_3$ Hz in Switzerland or Germany. The TGV Sud-Est consists of one power car at each end with all four axles powered and, in between, a total of eight intermediate passenger cars that form an indivisible articulated set. The outer nonarticulated two-axle trucks at each end of the eight-car set are also powered. This means that 12 axles of a total of 26 axles in a complete ten-unit train are powered. The total tare weight of a train is 382 tonnes and the adhesion weight 194 tonnes. The maximum axle load is 16.3 tonnes and the wheel diameter (new) 920 mm. The self-ventilated direct-current four-pole traction motors are Alsthom's model TAB 676 and have a continuous rating of 525 kW at 2770 r/min. Rated voltage is 1050 V and rated current 525 A. The motors are frame mounted and drive the wheels through tripod cardan transmissions and reduction gearings. The rotational speed of the motor is 3115 r/min when the train speed is 270 km/h. An important feature of the TAB 676 motor is that its stator is fully laminated.

The principal dimensions of a power car for the TGV Sud-Est are shown in Figure 42. Figures 43 and 44 show, respectively, an unwound traction motor stator and the motor laminations used. A total of 109 trainsets have been ordered and all are already in regular service.

SNCF received approval from the French government in November 1983 to build 346 km of new track to the southwest of Paris, the TGV Atlantique, to be electrified with 25 kV at 50 Hz. The trains to run on this line (95 sets have been ordered) will be different from the TGV Sud-Est in several important respects. The TGV Atlantique train will consist of 12 units—one power car at each end and 10 nonpowered intermediate passenger cars. The traction circuitry will be quite different because of SNCF's decision to use three-phase synchronous traction motors for propulsion. Because these traction motors, within the same space restraints, can be rated 1100 kW continuously instead of 525 kW for the direct-current traction motors used for the TGV Sud-Est, only eight motors per train are needed (instead of 12), and the maximum speed in service can be increased to 300 km/h. Each synchronous motor weighs 1450 kg. A prototype TGV-A train made its first trip on February 3, 1986. In the first week of trials it attained a speed of 290 km/h. On September 23, 1986, the train reached 356 km/h.

Maximum speed	270 km/h
Continuous power	6300 kW (total for train)
Power supply	25 kV, 50 Hz or 1500 volts dc
Wheel diameter (new)	920 mm
Maximum axle load	16.3 tonnes

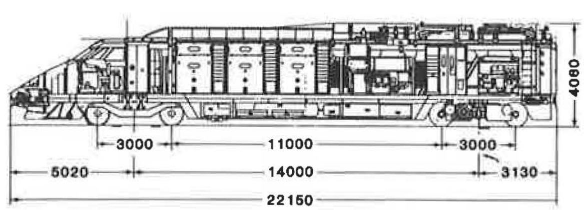

FIGURE 42 Power car for TGV Sud-Est train.

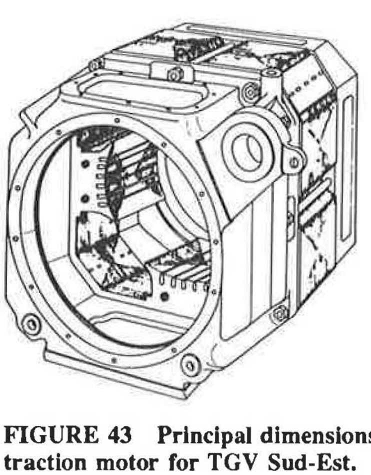

FIGURE 43 Principal dimensions of direct-current traction motor for TGV Sud-Est.

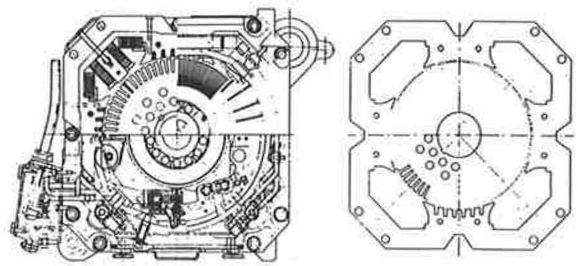

FIGURE 44 Cross section and laminations for direct-current traction motor for TGV Sud-Est.

Information about the TGV Sud-Est trains in general is available elsewhere (*172–179*). Its traction motor is described by Jouy (*180*), and brief information about the TGV Atlantique trains is also available (*30–32, 149, 181, 182*).

Electric Intercity Experimental Train (Germany)

In September 1982, a decision was taken by the Federal Ministry of Research and Technology (BMFT) in Germany to help fund the first stage of a research program aimed at developing a high-speed nonlevitated four-unit trainset consisting of a power car at each end and two intermediate coaches, one of which was to be used as an instrumentation car. The total estimated cost of DM 72 million was to be shared by BMFT (61 percent), the Federal Railway (17 percent), and the manufacturing industry (22 percent).

One of the three diesel-electric locomotives Class DE 2500 with three-phase traction motors built speculatively by Thyssen-Henschel and Brown Boveri in the early 1970s was modified to include a special mechanical transmission, Um-An (*183*). The principle is that the mass of the traction motor is transferred from the truck to the locomotive for high-speed running, thereby reducing the dynamic forces exerted on the track at high speeds. At low speeds the motor rests in the frame in the normal way, but at higher speeds pneumatic cylinders attached to the body lift the motor so that its weight is carried by the secondary suspension.

A series of trials with Um-An proved that it was not indispensable to adopt this principle in toto for the InterCity Experimental (ICE) train. A simpler design was developed. The traction motor and its gearcase are positioned alongside the axle between the side frames of the truck, but the bulk of the mass is supported by the car body in such a way as to permit truck rotation. The outer end of the motor-and-gearcase block is supported by vertical links from the truck frame, and horizontal links and dampers ensure that displacement between gearcase and axle does not exceed limits imposed by the hollow quill drive. To keep the mass of the wheelset down to 1500 kg, three brake discs are mounted on the hollow shaft carrying the gearwheel and not on the axle itself. Figures 45 and 46 show in principle the drive systems for the Um-An and the ICE, respectively.

The electrical equipment is modeled on that used in the Class 120 electric locomotives with three-phase motors, but, of course, it has somewhat different parameters. The first ICE

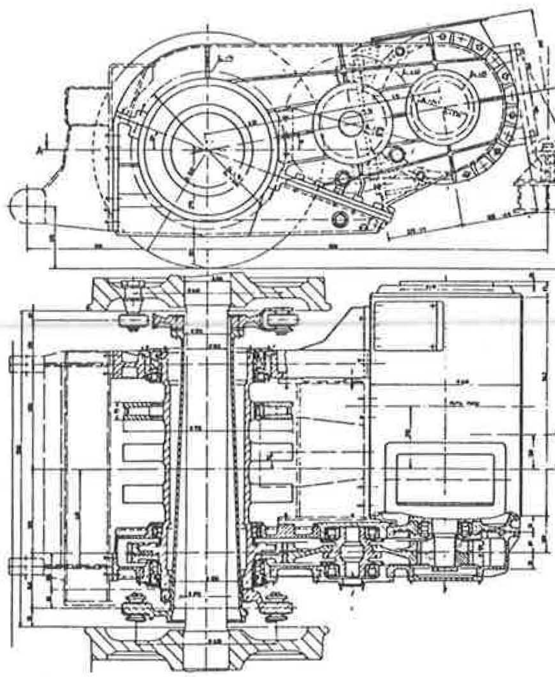

FIGURE 45 Um-An high-speed drive system.

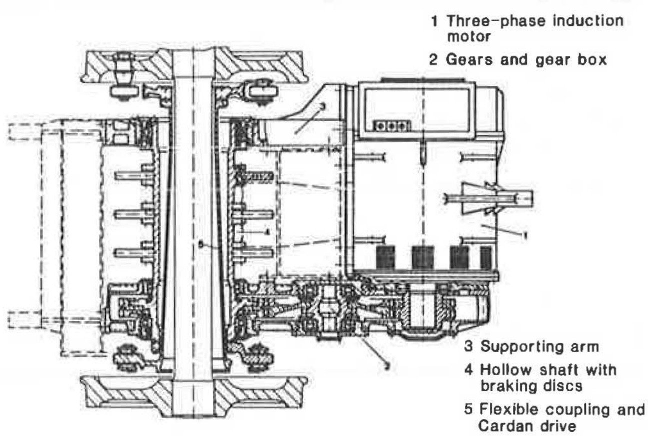

FIGURE 46 ICE drive system.

power car was demonstrated for the press for the first time on February 21, 1985. The whole train was shown to the general public on November 26, 1985, and on the same day attained a maximum speed of 317 km/h. In the middle of 1986, a power car was tested on a roller rig in Munich at a simulated speed of 385 km/h.

The ICE is designed for a maximum speed of 350 km/h. The continuous power at rail is, according to UIC rules, 2800 kW per power car. Power supply is from 15 kV at $16^2/_3$ Hz. The total weight of a five-unit train is about 304 tonnes, of which about 156 tonnes (78·tonnes per power car) can be used for adhesion. This corresponds to a maximum axle load of 19.5 tonnes. The transformer in each power car has a continuous rating of 3200 kVA. The control system consists of a four-quadrant controller (1430-V input voltage and 1050-A rated current), a direct-current link with a voltage of 2800 V, and a voltage source inverter with an output rating of 1900 kVA, 2200 V, 600 A, at a maximum frequency of 130 Hz. The separately cooled four-pole three-phase asynchronous traction motors have a stator core length of 475 mm, and the inside diameter of the stator laminations is 380 mm. Each motor has a continuous rating of 700 kW, 2050 V, 232 A, 2077 r/min, and the maximum speed is 3670 r/min. The wheel diameter (new) is 1000 mm.

Figure 47 is a picture of the ICE train, and Figure 48 shows some principal dimensions of an ICE power car. The outside dimensions of a traction motor for this train are indicated in Figure 49, and Figures 45 and 46 show the two mechanical drive systems contemplated. Development of the ICE is discussed elsewhere (*13, 183–192*).

Electric High-Speed Train X 2 (Sweden)

In 1973 Swedish State Railways (SJ) and ASEA signed an agreement to develop a train that, with the help of active body tilting, could run at speeds exceeding 200 km/h even through existing curves with radii down to 1000 m. An existing three-car electric trainset Class X 5 was to be modified and used for tests. After years of experiments SJ requested bids for a number of high-speed trains to meet very tough specifications including a maximum axle load of 15 tonnes. It was only after SJ relaxed this requirement to 17.5 tonnes that it was possible for a bidder to meet the other parts of the specification—and then only by applying three-phase traction instead of direct-current traction motors.

In August 1986, ASEA Traction received an order from SJ for a fleet of 20 high-speed trainsets with an option for 32 additional sets. The first 20 sets will operate on the trunk line between Stockholm and Gothenburg, which in 1986 had an

FIGURE 47 ICE train (Germany).

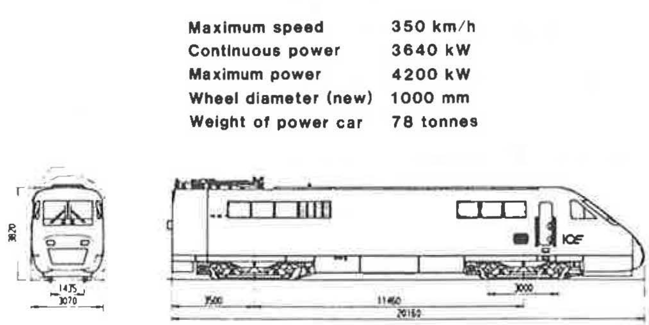

FIGURE 48 ICE power car.

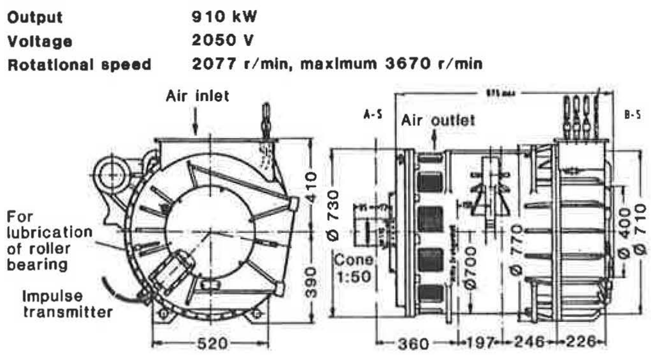

FIGURE 49 ICE three-phase traction motor.

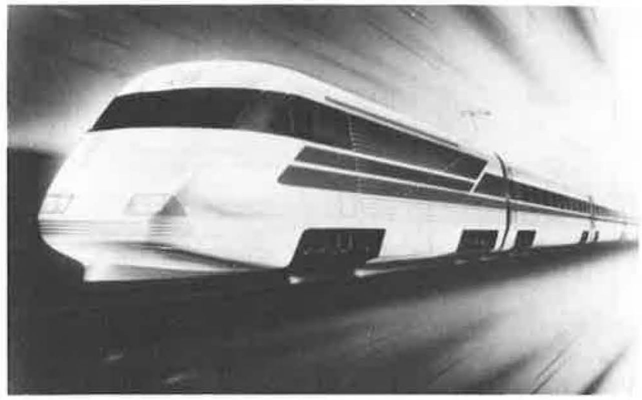

FIGURE 50 High-speed train Class X 2 (Sweden) with maximum speed of 200 km/h and three-phase traction motors.

annual ridership of about 2.7 million passengers. The new high-speed train, X 2, embodies three technical characteristics of importance for use on existing curved track:

1. Trucks with radial steering axles: These are based on experience since 1976 with the electric trainset X 15 (which is a modified X 5) and since 1982 with series-produced X 10 multiple-unit trainsets.
2. Active tilting system: Tests with an experimental train for about 15 years have shown that full compensation for lateral acceleration on curves is not necessary and, indeed, not even desirable. The system selected for the X 2 will reduce lateral acceleration experienced by passengers to 30 percent of what it would have been without tilting. Active hydraulic tilting, maximized to a 6.5-degree effective tilting angle, will be used.
3. Propulsion system with three-phase asynchronous traction motors: This means lighter motors and lower unsprung mass for the trucks. The control system will make use of gate-turn-off (GTO) thyristors.

The X 2 train will, in principle, consist of one power car and five coaches. The coach at the end of the train will be provided with a driver's cab from which the train can be monitored. The maximum train speed in scheduled service will be 200 km/h. The continuous power at rail is 3260 kW, and the power supply is 15 kV at 16⅔ Hz. The total weight of a five-unit train fully loaded is 343 tonnes, of which 70 tonnes can be used for adhesion, corresponding to an axle load of 17.5 tonnes. The main transformer is oil cooled and mounted under the carbody. It has four separate secondary windings supplying the four line-side converters that use self-commutated GTO thyristors. There are two DC links that consist of capacitor banks and are normally connected in parallel. The power car has two independently operating inverters, each supplying two traction motors in the same truck. All converters and inverters are liquid cooled. The asynchronous traction motors are fully suspended and force ventilated and have form-wound stator windings. Rotor resistance is optimized between the opposing requirements of low losses and maximum allowable difference between diameters of wheels in the same truck. The wheel diameter (new) is 1100 mm in the power car and 880 mm in the coaches.

Figure 50 shows an artist's conception of the X 2 train, and Figure 51 indicates some of the principal dimensions of its

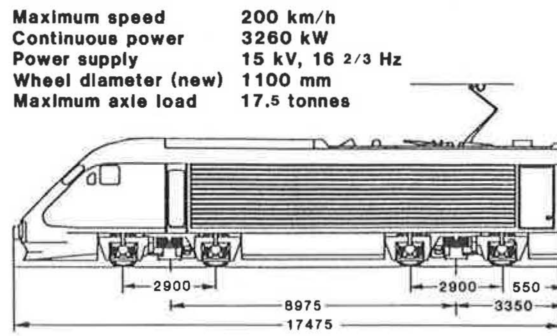

FIGURE 51 Power car for train X 2 (Sweden).

power car. Brief information about the train is given elsewhere (*193, 194*).

GEARLESS TRACTION MOTOR DRIVES

In the mid-1970s British Rail developed a gearless three-phase asynchronous traction motor drive of a special kind. The motor has been turned inside out in that a wound "stator" is inserted within a hollow tube connecting the vehicle wheels, and a squirrel cage "rotor" winding is fixed to the inside of that hollow tube. The whole arrangement was called a tubular axial induction motor (*195, 196*). The idea appears to have been later abandoned.

As already mentioned, the Skoda locomotive manufacturer in Czechoslovakia is considering the possibility of using a fully suspended gearless traction motor in which the locomotive axle passes through the hollow center of the rotor (*153*).

Similar ideas are also being discussed in the USSR (Figure 52) (*197*). The rotor is pressed onto a hollow shaft surrounding the locomotive axle. If necessary for easy assembly and disassembly, the stator can without too much difficulty be designed and built in two halves. The transmission of torque from the hollow shaft of the rotor to the locomotive wheel can be achieved in many different ways. Figure 52 shows one example.

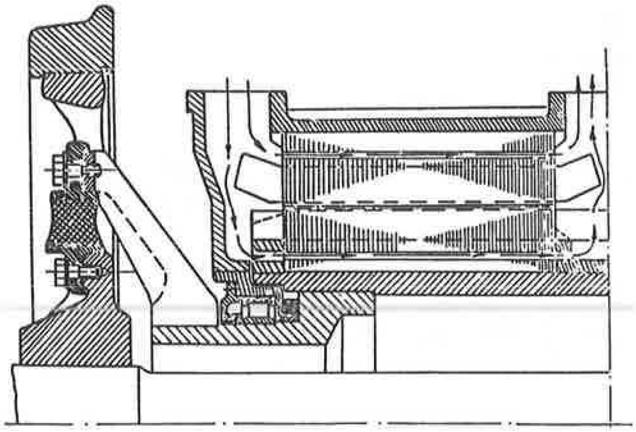

FIGURE 52 Gearless drive for electric locomotive—proposal with three-phase traction motor (USSR).

The elimination of gear and gearbox (and, in comparison with a direct-current motor, the commutator as well) enables the core length to be correspondingly increased thereby enhancing the motor torque for an unchanged diameter. However, because the power output is proportional to the rotational speed and a gearless motor is unable to take any advantage of gear ratio, the increased core length is unlikely to compensate for loss of power output because of a much lower motor speed for a given locomotive speed. Advantages of a gearless motor may be lower iron losses in the motor and eliminated gear losses. The rotor bearing design may also have some advantages. The wheel base of the truck may be reduced if desired.

LEVITATED TRANSPORTATION

The last part of this survey will deal with levitated transportation. Levitation means raising and keeping a heavy body in the air with no visible support. Levitation can be achieved either by an air cushion or by some type of magnetic "cushion" between the vehicle and the track. To accomplish the intended movement along the track, the vehicle has to be guided laterally in order to follow the track, and thrust must be provided to move the vehicle longitudinally.

There was considerable interest in air-cushioned vehicles in the late 1960s and early 1970s, primarily in France, Britain, and the United States. A Frenchman, Jean Bertin, built several vehicles of this type, the first a small jet-propelled prototype, Aerotrain 01, that ran on a test track in December 1965. The next, Aerotrain 02, achieved 425 km/h on January 22, 1969, propelled by a jet engine with a thrust of 12.3 kN temporarily increased with the help of a rocket with 4.9-kN thrust. Bertin also designed and built a full-scale vehicle, Orleans 180 (*198*). It was driven by a propeller developing a thrust of 39 kN at 1800 r/min. The propeller itself was driven by two gas turbines with a combined power of about 1800 kW. The vehicle was supported by six air cushions and guided by six additional air cushions acting against the central vertical member of the inverted-T concrete guideway. However, plans to build a tracked air-cushion vehicle (TACV) line from Cergy to Paris were canceled by the French government on July 17, 1974.

In Britain, a company called Tracked Hovercraft Limited developed air-cushioned research vehicles to run on a 5-km test track in Cambridgeshire. The first vehicle, RTV 31, was delivered on August 2, 1971. It ran at a maximum speed of 167 km/h on February 7, 1973, but a week later the British government announced that work on this project would be discontinued. The vehicles designed by Tracked Hovercraft used linear induction motors for thrust (*199, 200*).

Before its demise, Tracked Hovercraft received a contract from the U.S. Department of Transportation (DOT) to advise on the choice of air-cushion systems in the United States. The DOT awarded, in 1971, a contract to Grumman Aerospace Corporation to design and build a tracked air-cushioned research vehicle to be driven by a linear motor and to be tested at the Pueblo test center. This vehicle was originally powered by three JT 15D turbofan engines designed to give it a maximum speed of 200 km/h. These engines provided power for lift and guidance as well as propulsion. The Rohr Corporation received a grant from the Urban Mass Transportation Administration (UMTA) to build a prototype based on Aerotrain techniques. This vehicle was designed for a maximum speed of 270 km/h and propelled by a linear induction motor (LIM) developing about 1850 kW and a maximum thrust of 44 kN. Power was collected from three conductor rails holding the collector shoe captive and guiding it independently from the vehicle. The guideway was of the inverted-T configuration; the upright center member was formed by the LIM reaction rail. Lift and guidance power for the vehicle was provided by two electrically powered fans, each rated 260 kW. In May 1974, this research vehicle reached 383 km/h at Pueblo. Jet engines had been mounted at the rear of the vehicle to provide direct thrust.

At this time, because of less than satisfactory experience in Britain and France with air-cushioned vehicles, the Grumman test vehicle was rebuilt to be used for magnetic levitation and renamed the Tracked Levitated Research Vehicle (TLRV). A linear induction motor providing a continuous thrust of 22.2 kN and built by Garrett was fitted to the vehicle. Rectifier and inverter were also supplied by Garrett. In its final form, the vehicle was intended to be propelled by both a linear motor and a gas turbine.

In addition to the vehicles already mentioned, there was a linear induction motor research vehicle (LIMRV) intended solely to develop and test LIM technology. The LIMRV was designed and built by AiResearch and started operations in 1971. The primary propulsion system was an on-board gas-turbine-driven alternator rated 3000 kVA supplying a variable-voltage variable-frequency linear induction motor. Two external jet thrust boosters were installed to attain a designed maximum speed of 400 km/h.

On January 3, 1975, the U.S. DOT canceled all of the programs related to levitated vehicles. The vehicles mentioned here are described elsewhere (*201–204*).

Germany and Japan decided rather early in favor of magnetic levitation instead of air cushions. A number of magnetically levitated vehicles have been built and tested in these two countries. Some of them are listed in the Table 4. They are all driven by linear motors. Levitation is achieved magnetically but can be of either of two types depending on the relative position between linear motor components located on the vehicle and those located in the track. Repulsion-type levitation, as the name indicates, is based on the components on both sides of the air gap repelling one another. In attraction-type levitation they attract each other. The relative position of the interacting surfaces must, of course, in both cases be such as to actually lift the vehicles above the track.

At the end of 1977, the German Federal Ministry for Research and Development decided that all magnetic levitation efforts in Germany should be concentrated on the attraction system. Previously, both systems had been built and tested. In Japan, Japan Air Lines has favored an attraction system for its research vehicles of the High-Speed Surface Transport (HSST) type; the Japanese National Railways so far has aimed development toward a repulsion system.

The principles applied to linear motors and a comparison between such motors and conventional "rotating" motors are indicated in Figures 53 and 54. Selected papers on linear motors of different types applied to transportation can be found elsewhere (*205–220*).

The fastest Maglev vehicle so far, the Japanese ML 500, is shown in Figures 55–57. The Japanese Ministry of Transport announced in 1970 an extensive program to develop guided ground transport using magnetic levitation of the repulsion type and linear motors for propulsion. Two research vehicles, ML 100 with a short-stator linear induction motor drive, and ML 100A with a long-stator linear synchronous motor drive, were built and tested (*211, 221–223*); they were followed by a bigger vehicle, the ML 500, also with a long-stator linear synchronous motor drive. The ML 500 attained a maximum

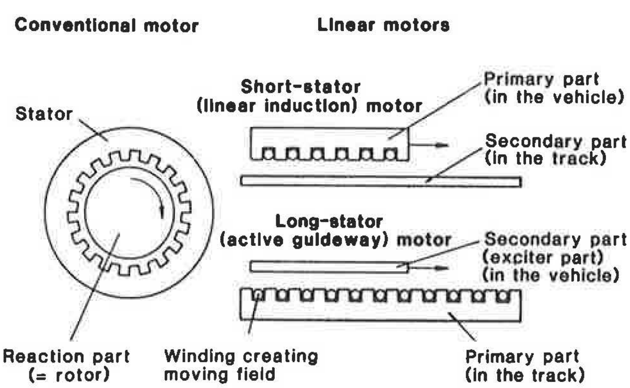

FIGURE 53 Comparison of conventional rotating motors and short-stator or long-stator linear motors.

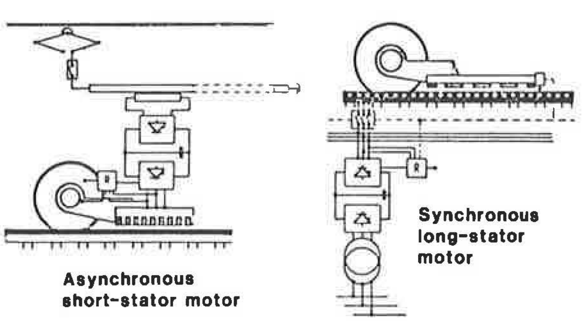

FIGURE 54 Principles of linear motors.

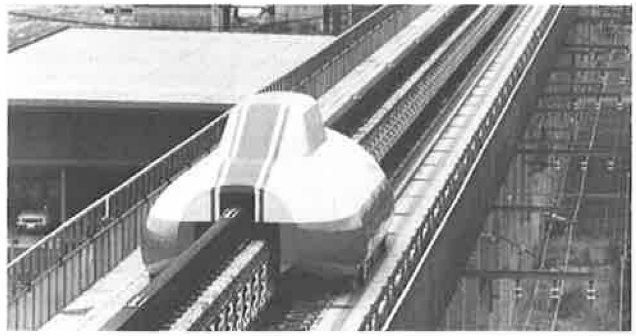

FIGURE 55 Maglev experimental vehicle ML 500 (Japan).

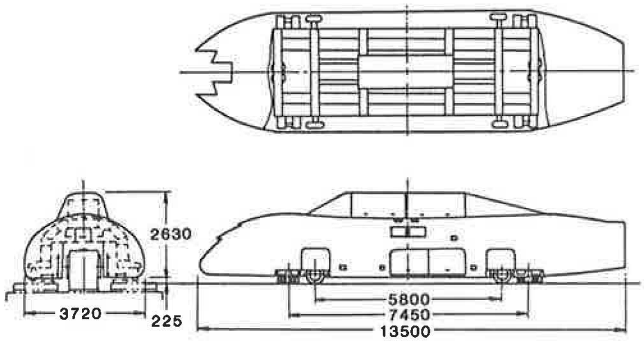

FIGURE 56 Maglev experimental vehicle ML 500 (achieved 517 km/h on December 21, 1979).

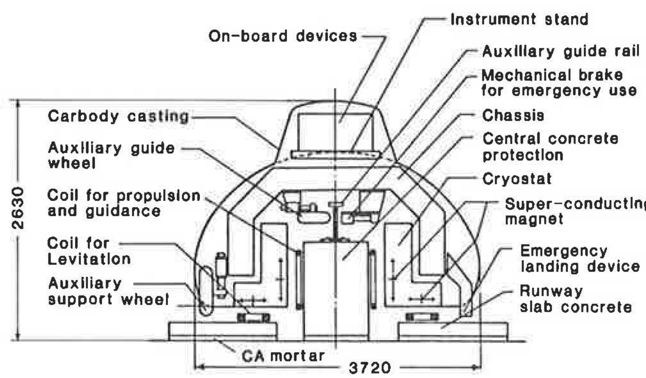

FIGURE 57 Cross section of Maglev vehicle ML 500 on inverted-T guideway.

FIGURE 58 Maglev experimental vehicle MLU 001 (Japan).

TABLE 4 SOME MAGLEV VEHICLES

	Vehicle parameters				Levitation mm	Levitation principle	Type of motor	Attained speed km/h
	Length mm	Width mm	Height mm	Tare weight tonnes				
TR 02	11000			12.0		Attraction	SSIM	164
TR 04	15000	3400		18.5	12	Attraction	SSIM	253
TR 05	26240	3100	3430	30.8	13	Attraction	LSSM	75
TR 06	54200	3700	4200	102.4	10	Attraction	LSSM	413
ML 500	13500	3720	2630	9.9	100	Repulsion	LSSM	517
MLU 001	13000	3000	3300	10.0		Repulsion	LSSM	400

speed of 517 km/h on December 21, 1979 (*224*). The track at the Miyazaki test center was then reconstructed from an inverted-T-type to a U-type version, and three units of a new Maglev experimental train, MLU 001, were built one at a time. Figures 58 and 59 show the first MLU 001 unit and Figure 60 a complete train of this type. Short descriptions of the MLU 001 are given elsewhere (*225–227*). Unmanned tests with the complete MLU 001 three-unit set started on November 1, 1981, and manned tests began in September 1982.

In Germany, where the first patent on the magnetic levitation principle was granted on August 11, 1934, to Hermann Kemper, a number of Maglev test vehicles have been built (*210*). A special circular test track 280 m in diameter was built in Erlangen, and an experimental vehicle, EET 01, ran for the first time on this track in 1976 at speeds of up to 180 km/h

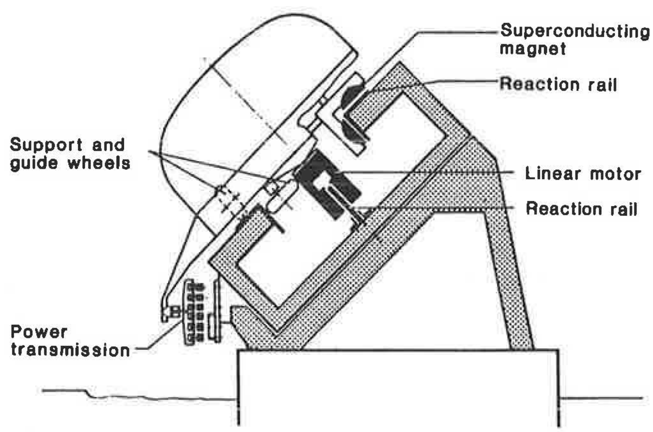

FIGURE 61 Maglev test track in Erlangen, Germany.

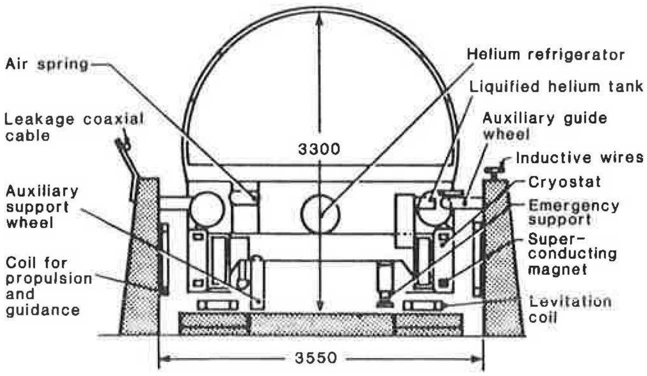

FIGURE 59 Cross section of Maglev experimental vehicle MLU 001.

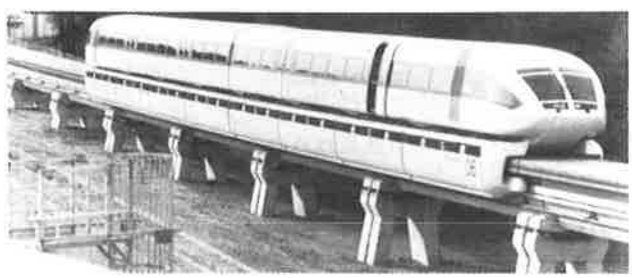

FIGURE 62 Maglev vehicle Transrapid 06 designed for 400 km/h (Germany).

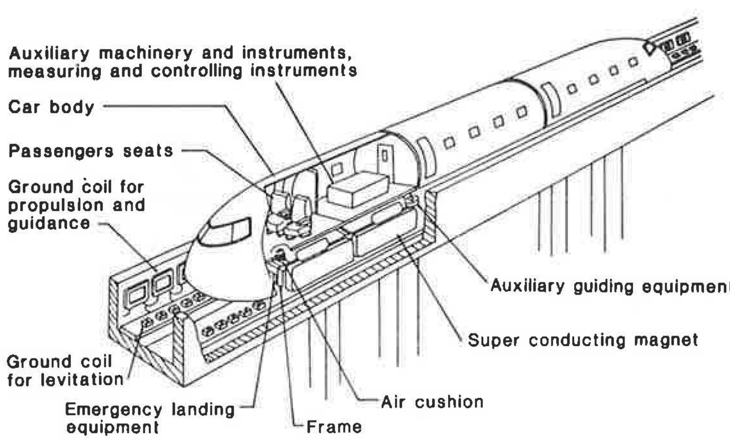

FIGURE 60 Three-car Maglev train Class MLU 001 (Japan).

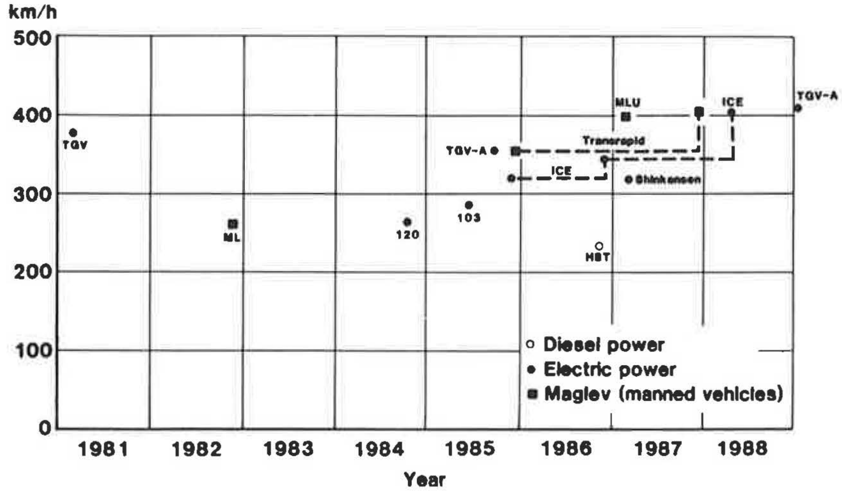

FIGURE 63 Recent speed records.

using an air gap of about 100 mm. This vehicle made first use of a short-stator linear induction motor drive and later a long-stator synchronous motor drive (Figure 61) (*228*).

It would appear that, at least in Germany, the choice of magnetic levitation and propulsion system is clear: the Transrapid system based on attraction-type levitation and using a long-stator linear synchronous motor drive is technically very promising and may become economically acceptable for certain routes between heavily populated areas (*210, 214, 217, 219, 229–233*). On December 12, 1985, the TR 06 attained a speed of 355 km/h and, after the full 31-km-long test track in Emsland had been completed, a maximum speed of 412.6 km/h was attained on January 22, 1988. Figure 62 is a picture of the Transrapid 06 vehicle.

CONCLUSIONS

It is always risky to try to predict the future, but some conclusions may be drawn from recent speed records (Figure 63) and the advancement of technologies described in this paper.

The conventional adhesion-dependent wheel-on-rail technology is likely to be used for maximum speeds up to 300 km/h (as is done with the TGV Atlantique) and possibly 350 km/h. Because of the high power requirements, it will be necessary to use, for speeds like these, straight-electric power in locomotives, power cars, or multiple-unit trains. Gas-turbine-powered vehicles with electric transmissions may be used for some nonelectrified routes. For maximum speeds above 350 km/h, use of an adhesion-independent Maglev system appears inevitable, and, assuming economic feasibility, the most probable choice is a long-stator linear synchronous motor system.

To minimize power requirements, the high-speed train of the future has to make use of a well-developed aerodynamic shape including underbody streamlining and radial steering trucks to achieve the lowest possible train resistance. The power required will, nevertheless, be of such a magnitude that a three-phase propulsion system with either asynchronous or synchronous motors, rotating or linear, must be adopted.

In cases in which a high-speed ground transportation system is deemed necessary, but constructing new track would be economically prohibitive, powered tilting of passenger cars may be a practical solution.

Recently developed materials that superconduct at much higher temperatures than was previously possible may find an important and interesting application in propulsion systems for high-speed trains.

REFERENCES

1. T. Ohyama and S. Shirai. Adhesion at Higher Speeds and Its Control. *RTRI* (Japan) *Quarterly Reports*, Vol. 23, No. 3, 1982, pp. 97–104.
2. F. Nouvion. The French High Speed Motor Units. *French Railway Techniques*, Vol. 11, No. 2, 1968, pp. 79–95.
3. E. W. Curtius and A. Kniffler. Neue Erkenntnisse über die Haftung zwischen Treibrad und Schiene. *Elektrische Bahnen*, Vol. 21, No. 9, 1950, pp. 201–210.
4. M. Tessier and C. Mignot. Programme for Technical Research into Very High Speeds. *French Railway Techniques*, Vol. 13, No. 1, 1970, pp. 1–13.
5. R. G. Gawthorpe. Aerodynamics of Trains in the Open Air. *Railway Engineer International*, Vol. 3, No. 3, 1978, pp. 7–12.
6. E. Kuhla. Der Advanced Passenger Train: Programm und Innovation. *ZEV Glasers Annalen*, Vol. 102, No. 5, 1978, pp. 137–142.
7. T. Maeda et al. Aerodynamic Drag of Series 200 Shinkansen Train. *RTRI* (Japan) *Quarterly Reports*, Vol. 25, 1984, pp. 140–143.
8. T. Hara et al. Aerodynamic Drag of Trains. *RTRI* (Japan) *Quarterly Reports*, Vol. 8, No. 4, 1967, pp. 226–229.
9. M. Bernard. New Knowledge About Train Resistance at Very High Speed. *French Railway Techniques*, Vol. 18, No. 2, 1975, pp. 31–36.
10. W. Hillmann et al. Aerodynamische Untersuchungen zur Entwicklung der DB-Lokomotive 103 für hohe Fahrgeschwindigkeiten. *Glasers Annalen*, Vol. 92, Nos. 9, 11, 1968, pp. 269–276, 352–360.
11. C. J. Baker. Fact and Friction. *Modern Railways*, Vol. 41, No 425, 1984, pp. 86–88.
12. W. Rappenglück. Fahrzeugtechnik für den Hochgeschwindigkeits-Personenverkehr. *Eisenbahntechnische Rundschau*, Vol. 29, No. 7/8, 1980, pp. 525–534, 536.
13. H. R. Kurz. Der Hochgeschwindigkeits-Versuchszug Intercity-Experimental. *Eisenbahntechnische Rundschau*, Vol. 32, No. 12, 1983, pp. 807–812, 815–817.
14. D. Lübke. Intercity-Experimental. *ZEV Glasers Annalen*, Vol. 108, No. 9, 1984, pp. 255–261.
15. Underbody Streamlining Cuts Energy Costs. *International Railway Journal*, Vol. 26, No. 8, 1986, p. 42.

16. Aerodynamic Drag Measurements. *Modern Railways*, Vol. 43, No. 455, 1986, p. 439.
17. W. J. Davis, Jr. The Tractive Resistance of Electric Locomotives and Cars. *General Electric Review*, Vol. 29, No. 10, 1926, pp. 685–707.
18. J.-L. Peters. Optimising Aerodynamics To Raise IC Performance. *Railway Gazette International*, Vol. 138, No. 10, 1982, pp. 817–819.
19. M. Bernard. The Aerodynamic Properties of Trains. *French Railway Techniques*, Vol. 14, No. 3, 1971, pp. 61–76.
20. M. Oishi. Running Resistance of Shinkansen Electric Cars. *RTRI* (Japan) *Quarterly Reports*, Vol. 15, No. 3, 1974, p. 172.
21. S. Jones. The Advanced Passenger Train: An Economic Alternative to the Construction of New Track for High Speed. *Rail International*, Vol. 7, No. 7, 1975, pp. 605–614.
22. M. Bernard and C. Guiheu. Mesures récentes de la résistance à l'avancement de matériels roulants. *Revue Générale des Chemins de Fer*, Vol. 95, No. 4, 1976, 243–255.
23. H. Hochbruck and J. Körber. Traktion mit Drehstromlokomotiven—Bedeutung für die Zukunft. *Eisenbahntechnische Rundschau*, Vol. 26, No. 1/2, 1977, pp. 13–14, 16–18, 20–22, 24.
24. J.-C. Boutonnet. L'aluminium dans la construction du matériel ferroviaire. *Revue Générale des Chemins de Fer*, Vol. 99, No. 4, 1980, pp. 241–256.
25. R. G. Gawthorpe. Train Drag Reduction from Simple Design Changes. *International Journal of Vehicle Design*, Vol. 3, No. 3, 1982, pp. 263–274.
26. S. Ozava et al. Wind Tunnel Investigation of Aerodynamic Drag of Future Shinkansen Train with Modified Nose Configuration. *RTRI* (Japan) *Quarterly Reports*, Vol. 23, No. 4, 1982, pp. 189–190.
27. H. Neppert. Komponenten-Widerstände im Einfluss der Grenzschicht an Zugen variabler Länge. *ZEV Glasers Annalen*, Vol. 108, No. 9, 1984, pp. 239–247.
28. Prototype EMU Sets for DB's High-Speed Intercity Routes. *Railway Gazette International*, Vol. 128, No. 8, 1972, pp. 293–295.
29. Ultra-Modern Light-Weight Constructional Features Applied to DB 200 km/h Electric Train Sets. *Rail Engineering International*, Vol. 3, No. 7, 1973, pp. 314–316.
30. D. Brun. Why the French Chose Synchronous Motors. *Railway Gazette International*, Vol. 141, No. 2, 1985, pp. 130–134.
31. Y. Machefert-Tassin and A. Gache. La traction électrique par moteurs sans collecteurs. *Revue Générale des Chemins de Fer*, Vol. 104, No. 10. 1985, pp. 511–528.
32. SNCF Orders 300 km/h Trains. *Railway Gazette International*, Vol. 141, No. 12, 1985, p. 897.
33. G. Manz. Traktionstechnische Massnahmen und Planungen der DB für den Schnellverkehr mit elektrischen Triebfahrzeugen. *Glasers Annalen*, Vol. 95, No. 7/8, 1971, pp. 181–190.
34. R. Ford. UK Ltd Bids for Channel Tunnel Through Trains. *Modern Railways*, Vol. 43, No. 452, 1986, pp. 263–264.
35. J. Kuhlow. Bahnantriebe mit Drehstrommotoren. *ZEV Glasers Annalen*, Vol. 98, No. 7/8, 1974, pp. 245–251.
36. M. Mauzin et al. Une nouvelle voiture dite "pendulaire" destinée aux très grandes vitesses. *Revue Générale des Chemins de Fer*, Vol. 76, No. 11, 1957, pp. 581–593.
37. R. Terrasse and R. Joly. Running of Tilting Railway Vehicles over Curved Track. *French Railway Techniques*, Vol. 13, No. 3, 1970, pp. 89–103.
38. F. Hegenbarth. Dieseltriebwagenzug Baureihe 624/924 für Bezirks- und Nahverkehr mit gleisbogenabhängiger Luftfedersteuerung. *Glasers Annalen*, Vol. 93, No. 1, 1969, pp. 22–26.
39. DB Experiments with Powered Tilting of Coach Bodies. *Railway Gazette*, Vol. 125, No. 2, 1969, pp. 57–58.
40. S. Sakai. Increase of Train Speeds on Curves. *Japanese Railway Engineering*, Vol. 10, No. 3, 1969, pp. 33–35.
41. T. Shima. Running Tests of the Pendulum Electric Railcar (Ku-Mo-Ha 591 Series). *Japanese Railway Engineering*, Vol. 11, No. 2, 1970, pp. 20–21.
42. Tilting Coaches To Raise Speeds on Curves. *Railway Gazette*, Vol. 126, No. 17, 1970, pp. 655–659.
43. Higher Speeds on the Narrow Gauge. *Railway Gazette International*, Vol. 127, No. 8, 1971, pp. 310–312.
44. Unique Suspension Tilts JNR Gas-Turbine Prototype. *Railway Gazette International*, Vol. 127, No. 11, 1971, pp. 430–432.
45. S. F. Smith. The Advanced Passenger Train. *Railway Gazette*, Vol. 124, No. 11, 1968, pp. 409–412, 416.
46. N. J. Granger. Remote Electrical Readout Spirit-Level Technique Applied to BR APT Body-Tilt Control. *Rail Engineering International*, Vol. 4, No. 3, 1974, pp. 124–127.
47. Prototype APTs Take Shape at Derby. *Railway Gazette International*, Vol. 133, No. 1, 1977, pp. 27, 29, 31.
48. FS Orders Prototype Tilting Train. *Railway Gazette*, Vol. 126, No. 13, 1970, p. 485.
49. High Speed Motive Power Development Moves Ahead in Italy. *Railway Gazette International*, Vol. 129, No. 5, 1973, pp. 190–191, 193.
50. O. Santanera. FS and RENFE Try Out Tilt-Body Prototype Trains. *Railway Gazette International*, Vol. 130, No. 3, 1974, pp. 101–104.
51. W. Messerschmidt. Ein italienischer Triebzug mit gleisbogenabhängiger Wagenkastensteuerung. *ZEV Glasers Annalen*, Vol. 99, No. 9, 1975, pp. 261–263.
52. J. L. S. Gonzales. Passengers Will Sample Tilting Train This Spring. *Railway Gazette International*, Vol. 133, No. 2, 1977, pp. 56–57, 59.
53. Una svolta per l'alta velocità in Italia. *Ingegneria Ferroviaria*, Vol. 40, No. 7, 1985, pp. 415–417.
54. N. Nilstam. Swedish Body-Tilting Electric Set for Very High Speed on Severely-Curved Main Lines. *Rail Engineering International*, Vol. 11, No. 2, 1982, pp. 58–62.
55. R. Ford. Sweden—First with Practical Tilting Trains? *Modern Railways*, Vol. 41, No. 424, 1984, pp. 21–23.
56. SJ Orders Tilting Trains. *International Railway Journal*, Vol. 26, No. 10, 1986, pp. 44, 46.
57. D. J. C. Lumpie. Experimental Talgo Features Pendular Body-Tilting. *Railway Gazette International*, Vol. 133, No. 2, 1977, pp. 58–59.
58. Tilting Talgos Will Cut RENFE Schedules from May. *Railway Gazette International*, Vol. 136, No. 2, 1980, pp. 143–144.
59. L. M. de Oriol y Lopez Montenegro. Der Talgo Pendular. *Elektrische Bahnen*, Vol. 83, Nos. 5, 6, 1985, pp. 156–158, 160–162, 192–194, 196–197.
60. British Railways High Speed Passenger Train Takes Shape. *Rail Engineering International*, Vol. 1, No. 1, 1971, pp. 21–23.
61. S. Janota and H. M. Dannatt. British Railways Prototype High Speed Train for 200 km/h. *Rail Engineering International*, Vol. 2, No. 4, 1972, pp. 156–165.
62. W. M. Stanier. The High Speed Train. *Railway Engineering Journal*, Vol. 2, No. 4, 1973, pp. 4–11.
63. B. G. Sephton. The High Speed Train. *Railway Engineering Journal*, Vol. 3, No. 5, 1974, pp. 22–41.
64. How HST Kept Rolling at 200 km/h. *Railway Gazette International*, Vol. 135, No. 2, 1979, pp. 144–145.
65. S. F. Smith. The Advanced Passenger Train. *Railway Gazette*, Vol. 124, No. 11, 1968, pp. 409–412, 416.
66. APT Enters Three-Year Development Phase. *Railway Gazette International*, Vol. 126, No. 21, 1970, pp. 827–828.
67. BR APT . . . Initial Trials. *Rail Engineering International*, Vol. 1, No. 5, 1971, pp. 212–217.
68. A. H. Wickens. APT-E Takes to the Rails. *Railway Gazette International*, Vol. 128, No. 5, 1972, pp. 185–189.
69. BR APT Experimental Train for 250 km/h Trials. *Rail Engineering International*, Vol. 2, No. 6, 1972, pp. 274–280.
70. B. Gunston. The Aerospace Train. *Flight International*, Vol. 102, No. 3319, 1972, pp. 536–540.
71. APT Programme Moves Ahead After Searching Reappraisal. *Railway Gazette International*, Vol. 129, No. 12, 1973, pp. 469–471.
72. The Advanced Passenger Train. *Modern Railways*, Vol. 34, No. 341, 1977, pp. 56–62.
73. D. Boocock and M. Newman. The Advanced Passenger Train. *Railway Engineer*, Vol. 2, No. 2, 1977, pp. 20–27, 38.
74. R. T. Ribbons. Basic Design Philosophy of the Advanced Passenger Train. *Rail Engineering International*, Vol. 9, No. 2, 1980, pp. 42–45.

75. Canada's LRC Prototype Coach on Trial. *Railway Gazette International*, Vol. 127, No. 11, 1971, pp. 438–439.
76. LRC: Canada's High Speed Contender. *Railway Gazette International*, Vol. 128, No. 8, 1972, pp. 310–311.
77. MLW Delivers Power for Canada's LRC. *Railway Age*, Vol. 174, No. 1, 1973, p. 9.
78. J. Z. Tomaka. The LRC—A Canadian High-Speed Diesel Train. *Rail Engineering International*, Vol. 4, No. 2, 1974, pp. 88–96.
79. Canadian Run by LRC at 205 km/h. *Railway Engineer*, Vol. 1, No. 2, 1976, pp. 45–46.
80. Uprated LRC Clinches Foothold in High-Speed Passenger Market. *Railway Gazette International*, Vol. 133, No. 9, 1977, pp. 351–353.
81. B. Fahrenwald. Canada's LRC: Low Cost, High Speed Add up to a Winner. *Railway Age*, Vol. 183, No. 15, 1982, pp. 34–35, 38–39.
82. The Gas Turbine Makes Progress. *Modern Railroads*, Vol. 2, No. 4, 1947, pp. 20–23.
83. E. C. Poultney. British Build Gas-Turbine Locomotive. *Railway Age*, Vol. 129, No. 13, 1950, pp. 22–25.
84. E. C. Poultney. British Railways Acquire a Gas-Turbine Locomotive. *Railway Age*, Vol. 132, No. 16, 1952, pp. 65–68.
85. BR Project for 150 mile/h Gas Turbine Train. *Railway Gazette*, Vol. 123, No. 8, 1967, pp. 300–301.
86. Powerful Diesel-Turbine Unit for German Federal Railway. *Railway Gazette*, Vol. 121, No. 13, 1965, pp. 523–526.
87. K. Friedrich. Gesamt-Entwurf und -Konstruktion einschliesslich der Bauvarianten V 162 und V 169. *Glasers Annalen*, Vol. 90, No. 2, 1966, pp. 57–64.
88. K. Friedrich. Vom Dieseltriebwagen und der Diesellokomotive zum Turbo-Triebfahrzeug. *Glasers Annalen*, Vol. 93, No. 7, 1969, pp. 203–210, 225.
89. B. Schmücker. Die V 210, eine Diesellokomotive mit Gasturbine. *Glasers Annalen*, Vol. 94, No. 11, 1970, pp. 344–353.
90. D. Zboralski and W. Furst. Gasturbinen treiben Triebzüge der Deutschen Bundesbahn. *Glasers Annalen*, Vol. 94, Nos. 11, 12, 1970, pp. 354–361, 397–406.
91. Gas Turbine Conversion Doubles Power Car Rating. *Railway Gazette International*, Vol. 127, No. 6, 1971, pp. 240–241.
92. G. Brauer. Gasturbinen als Hauptantrieb in Triebzügen. *Eisenbahntechnische Rundschau*, Vol. 20, No. 11, 1971, pp. 472–475.
93. D. Zboralski. Conversion to Gas-Turbine Traction of DB TEE Train Sets. *Rail Engineering International*, Vol. 2, No. 2, 1972, pp. 70–77.
94. A. Feulner. Anwendung und Bewährung von Gasturbinen in Triebfahrzeugen der Deutschen Bundesbahn. *ZEV Glasers Annalen*, Vol. 98, No. 7/8, 1974, pp. 199–209.
95. High-Speed Gas Turbine Train by United Aircraft. *Modern Railways*, Vol. 22, No. 209, 1966, pp. 100–101.
96. Lightweight Turbine Motor Trains. *Railway Gazette*, Vol. 122, No. 13, 1966, pp. 515–519.
97. A. R. Cripe. Developing the United Aircraft Turbotrain. *Railway Gazette*, Vol. 126, No. 3, 1970, pp. 105–110.
98. F. N. Houser. Amtrak's French Connection. *Railway Age*, Vol. 174, No. 3, 1973, pp. 16–17, 27.
99. W. D. Middleton. Americanizing the Turboliner. *Railway Age*, Vol. 176, No. 7, 1975, pp. 20–21, 26–27.
100. Japan Looks at Gas Turbines. *Railway Gazette*, Vol. 126, No. 4, 1970, p. 149.
101. Y. Ishii. Development of Gas Turbine Car in Japan. *Japanese Railway Engineering*, Vol. 11, No. 3, 1970, pp. 11–13.
102. T. Nagakura. Outline of KIHA 391 Prototype Gas Turbine Railcar. *Japanese Railway Engineering*, Vol. 13, No. 3, 1972, pp. 8–12.
103. J. P. Bernard. Gas-Turbine Trains: SNCF Experience and Plans. *Rail Engineering International*, Vol. 1, No. 1, 1971, pp. 11–15.
104. J. P. Bernard. Gas Turbine Trains for the SNCF. *Railway Gazette*, Vol. 125, No. 4, 1969, pp. 129–132.
105. High-Speed Trains with Gas Turbine Traction. *Railway Gazette*, Vol. 125, No. 24, 1969, pp. 933–935.
106. J. P. Bernard. SNCF Turbos on the Move. *Railway Gazette*, Vol, 126, No. 11, 1970, pp. 412–414.
107. F. Duflot. Turbinengetriebene Züge der Französischen Staatsbahnen (SNCF). *Glasers Annalen*, Vol. 95, No. 7/8, 1971, pp. 263–270.
108. P. Gauthier and F. Barret. A Year's Operation of the Turbotrains. *French Railway Techniques*, Vol. 15, No. 4, 1972, pp. 121–130.
109. J. P. Bernard. The RTG Turbine Trains. *French Railway Techniques*, Vol. 15, No. 4, 1972, pp. 131–145.
110. J. P. Bernard. SNCF Introduces the 200 km/h RTG Turbotrain with a Set for Very High Speed Trials. *Rail Engineering International*, Vol. 3, No. 2, 1973, pp. 58–62.
111. G. Senac. Tests with Turbine Train RTG 01. *French Railway Techniques*, Vol. 17, No. 4, 1974, pp. 123–140.
112. F. Nouvion. Experimental Gas Turbine Trains. *French Railway Techniques*, Vol. 13, No. 1, 1970, pp. 14–41.
113. France Builds Experimental 300 km/h Train for Paris–Lyon. *Railway Gazette International*, Vol. 128, No. 5, 1972, pp. 172–175.
114. J. P. Bernard. TGV 001: The Precursor of the 300 km/h SNCF Programme Is Introduced. *Rail Engineering International*, Vol. 2, No. 4, 1972, pp. 166–172.
115. G. Petit. Light-Weight High-Speed Electrical Machines Developed for SNCF 300 km/h Experimental Turbo Train. *Rail Engineering International*, Vol. 2, No. 6, 1972, pp. 252–259.
116. J. P. Bernard. The Experimental Turbine Train TGV 001. *French Railway Techniques*, Vol. 16, No. 1, 1973, pp. 1–24.
117. M. Gaudichon. Der Turbotrain TGV 001 der SNCF. *ZEV Glasers Annalen*, Vol. 98, No. 6, 1974, pp. 159–170, 173.
118. W. Bode. Turbozüge. *Glasers Annalen*, Vol. 93, No. 5, 1969, pp. 133–140.
119. J. Vogts. Die Gasturbine als Antrieb in Schienenfahrzeugen. *Glasers Annalen*, Vol. 93, No. 5, 1969, pp. 141–149, 163.
120. G. Senac. 10 Years of Development Work on the Gas Turbine for Traction. *French Railway Techniques*, Vol. 22, No. 4, 1979, pp. 184–206.
121. F. Nouvion. Description des installations de traction et du matériel moteur de la SNCF aptes à la grande vitesse. *Revue Générale des Chemins de Fer*, Vol. 85, No. 3, 1966, pp. 141–159.
122. E. Gierth and K. W. Seibert. Die elektrische Co′Co′-Schnellzuglokomotive Baureihe E 03 der Deutschen Bundesbahn. *Elektrische Bahnen*, Vol. 36, No. 10, 1965, pp. 230–251.
123. E. Gierth. Die Serienlokomotive der Baureihe 103—ein weiterer Schritt zu höhen Leistungen elektrischer Lokomotiven der Deutschen Bundesbahn. *Elektrische Bahnen*, Vol. 41, No. 6, 1970, pp. 124–132.
124. H. Gluck. Die Leistungsfähigkeit der neuen Schnellfahrlokomotiven Baureihe 103 der Deutschen Bundesbahn. *Glasers Annalen*, Vol. 94, No. 7, 1970, pp. 227–232.
125. M. Manzo. Stabilità di marcia alle alte velocità: La nuova locomotiva E 444. *Ingegneria Ferroviaria*, Vol. 23, No. 7/8, 1968, pp. 541–554.
126. C. Bologmin. Italian Railways BoBo of 4000 kW for 200 km/h. *Rail Engineering International*, Vol. 1, No. 5, 1971, pp. 202–208.
127. W. Messerschmidt. Die Nachbau-Serie der italienischen Schnellfahrlokomotive E 444 (Bo′Bo′) und ihre Weiterentwicklung zur E 666 (Co′Co′). *Glasers Annalen*, Vol. 95, No. 11, 1971, pp. 368–370.
128. D. Piscaglia and M. Cavagnaro. La locomotiva elettrica a chopper E 444.005 delle FS. *Ingegneria Ferroviaria*, Vol. 31, No. 1, 1976, pp. 5–14.
129. M. Cavagnaro and D. Piscaglia. FS Powerful Prototype with Choppers. *Railway Engineer*, Vol. 1, No. 5, 1976, pp. 33–37.
130. A. Cogliati et al. The Experimental 3000 V D.C. Locomotive of the Italian State Railways with Chopper Control. *Brown Boveri Review*, Vol. 63, No. 12, 1976, pp. 737–743.
131. Skoda Develops a Second Generation of Electric Locomotives. *Railway Gazette International*, Vol. 130, No. 6, 1974, pp. 221–223.
132. Skoda Builds Exports on Vigorous Home Market. *Railway Gazette International*, Vol. 136, No. 3, 1980, pp. 201–203.
133. Soviet Designers Strive To Combine Power with Reliability. *Railway Gazette International*, Vol. 138, No. 7, 1982, pp. 555–557, 559.
134. E. Becker. Electrical Equipment of the Three-Phase DB Class E 120 Universal Mainline Electric. *Rail Engineering International*, Vol. 8, No. 3, 1979, pp. 70–73.

135. DB Starts Tests with Class 120 Three-Phase Locos. *Railway Gazette International*, Vol. 135, No. 7, 1979, pp. 655–657.
136. Elektrische Lokomotive in Drehstromtechnik: Baureihe 120 der Deutschen Bundesbahn. *ZEV Glasers Annalen*, Vol. 103, No. 7/8, 1979, pp. 312–313.
137. J. Körber. Die elektrische Ausrüstung der Hochleistungslokomotive Baureihe E 120 der Deutschen Bundesbahn mit Drehstromfahrmotoren. *ZEV Glasers Annalen*, Vol. 104, No. 8/9, 1980, pp. 299–308.
138. M. Niessen. Versuchsschnellfahrten mit der elektrischen Lokomotive 120001 der Deutschen Bundesbahn. *Elektrische Bahnen*, Vol. 83, Nos. 8, 12, 1985, pp. 260–262, 418–424.
139. Amtrak Orders First Batch of Northeast Corridor Thyristor Locos. *Railway Gazette International*, Vol. 134, No. 2, 1978, p. 55.
140. Amtrak bestellt acht Thyristorlokomotiven. *ZEV Glasers Annalen*, Vol. 102, No. 9, 1978, p. 274.
141. Amtrak's 200 km/h Locos Spearhead Revised Northeast Corridor Plans. *Railway Gazette International*, Vol. 135, No. 4, 1979, pp. 305–307.
142. G. Lundh. Amtrak—200 km/h in den Vereinigten Staaten mit ASEA-Thyristorlokomotiven. *ZEV Glasers Annalen*, Vol. 106, No. 2/3, 1982, pp. 85–92.
143. BR's Class 89 Takes Shape. *Railway Gazette International*, Vol. 140, No. 3, 1984, p. 185.
144. D. Boocock. Next Generation of Electric Trains Will Have 225 km/h Capability. *Railway Gazette International*, Vol. 141, No. 6, 1985, pp. 441–444.
145. Comparing Synchronous and Asynchronous Traction Motors. *Railway Gazette International*, Vol. 138, No. 6, 1982, pp. 458–459.
146. P. Hérissé. La BB 15055 à moteurs synchrones. *La Vie du Rail*, No. 1851, July 8, 1982, pp. 4–8.
147. A. Cossié. French Hail Synchronous Motor as Traction Panacea. *Railway Gazette International*, Vol. 139, No. 5, 1983, pp. 349, 351, 353.
148. P. Hérissé. Les moteurs triphasés plus que jamais d'actualité. *La Vie du Rail*, No. 1943, May 10, 1984, pp. 4–5, 7–10.
149. A. Cossié. Die Lokomotive BB 10004 mit selbstgefuhrten Synchronmotoren—Anwendung der Synchrontechnik bei der SNCF. *Elektrische Bahnen*, Vol. 82, No. 7, 1984, pp. 194–200.
150. G. Landgraf. Locomotives synchrone et asynchrone. *La Vie du Rail*, No. 1980, Feb. 7, 1985, p. 55.
151. Proposed Class 91 Locomotive. *Modern Railways*, Vol. 42, No. 443, 1985, p. 391.
152. Electra Heralds East Coast Speed-Up. *Railway Gazette International*, Vol. 142, No. 4, 1986, pp. 267, 269.
153. Skoda Designs Three-Phase Motored Prototypes. *Railway Gazette International*, Vol. 141, No. 6, 1985, pp. 446–447.
154. Electric Trains for the New Tokaido Line. *Railway Gazette*, Vol. 121, No. 3, 1963, pp. 100–104
155. M. Ishizawa. Electric Railcars for New Sanyo Line. *Japanese Railway Engineering*, Vol. 10, No. 2, 1969, pp. 14–15.
156. K. Kasai. Shinkansen Railcars in the Future. *Japanese Railway Engineering*, Vol. 13, No. 1/2, 1972, pp. 35–38.
157. M. Ishiyama. Nationwide Shinkansen Network and Prototype Electric Railcar Multiple Unit Train. *Japanese Railway Engineering*, Vol. 13, No. 4, 1972, pp. 15–18.
158. H. Inoue. Prototype Electric Railcar (Type 961) for the Nationwide Shinkansen Network. *Japanese Railway Engineering*, Vol. 15, No. 1, 1974, pp. 4–8.
159. Series 962 Prototypes Will Be Geared for 210 km/h. *Railway Gazette International*, Vol. 134, No. 5, 1978, p. 298.
160. T. Shima. The Second Generation of the Shinkansen Train Has Made Its Debut. *Japanese Railway Engineering*, Vol. 19, No. 1, 1979, pp. 19–23.
161. Y. Ishii. The Course of Development of Shinkansen Cars and Future Planning. *Japanese Railway Engineering*, Vol. 19, No. 2, 1979, pp. 11–15.
162. Shinkansen Prototype Cars Type 961 Reach the Maximum Speed of 319 km/h. *Japanese Railway Engineering*, Vol. 19, No, 4, 1980, p. 35.
163. The 200 Series Shinkansen Train for the Tohoku and Joetsu Shinkansen. *Japanese Railway Engineering*, Vol. 20, No. 4, 1981, pp. 23–24.
164. T. Haga. Progress of the Shinkansen Trains in 20 Years. *Japanese Railway Engineering*, Vol. 24, No. 4, 1985, pp. 16–20.
165. K. Watanabe. Review and Perspective of the Shinkansen. *Elektrische Bahnen*, Vol. 83, No. 5, 1985, pp. 145–152.
166. C. Suda. Air Competition Forces JNR Speed-Up. *Railway Gazette International*, Vol. 142, No. 9, 1986, pp. 636–639.
167. W. Rappengluck. Elektrischer Schnelltriebzug ET 403 der Deutschen Bundesbahn. *Elektrische Bahnen*, Vol. 44, No. 5, 1973, pp. 98–108.
168. W. Lossel et al. Die elektrische Ausrüstung des Schnelltriebzüges 403. *Elektrische Bahnen*, Vol. 44, Nos. 6, 7, 1973, pp. 118–130, 154–162.
169. Y. N. Dimant et al. Moscow–Leningrad Train Set Designed for 200 km/h. *Railway Gazette International*, Vol. 127, No. 4, 1971, pp. 145–148.
170. J. Dimant and V. Zhiva. Der elektrische Schnelltriebzug ER 200 für die Eisenbahnen der USSR. *ZEV Glasers Annalen*, Vol. 96, No. 11, 1972, pp. 343–350.
171. Y. Dimant and V. Zhiva. Riga's 200 km/h EMU Ready for Moscow–Leningrad Line. *Railway Gazette International*, Vol. 131, No. 6, 1975, pp. 220–222.
172. J.-M. Metzler. The Pre-production TGV Train Sets a Few Months Before Delivery. *French Railway Techniques*, Vol. 21, No. 3, 1978, pp. 187–192.
173. Electric TGVs Spotlight French Lead in High-Speed Technology. *Railway Gazette International*, Vol. 134, No. 12, 1978, pp. 967–970.
174. Les TGV rames automotrices électriques à grande vitesse de la SNCF. *La Vie du Rail*, No. 1682, Feb. 25, 1979, pp. 8–19, 62–63.
175. The TGV High Speed Train Sets for the New Paris-Southeast Line. *French Railway Techniques*, Vol. 22, No. 3, 1979, pp. 109–114.
176. J. C. Brimont. Les rames TGV pour la nouvelle ligne Paris—Sud-Est. *ZEV Glasers Annalen*, Vol. 104, No. 12, 1980, pp. 419–424.
177. TGV Hits 380 km/h in Record-Breaking Run. *Railway Gazette International*, Vol. 137, No. 4, 1981, p. 263.
178. A. Cossié. Conception générale et caractéristiques des parties électriques des rames TGV. *Elektrische Bahnen*, Vol. 79, No. 10, 1981, pp. 361–367.
179. L. Gauthier and J. Waleckx. Sistema di trasmissione dei treni francesi ad alta velocità. *Ingegneria Ferroviaria*, Vol. 40, No. 6, 1985, pp. 349–351.
180. B. Jouy. Conception et réalisation des moteurs du TGV. *Revue Générale de l'Électricité*, Vol. 65, No. 2, 1981, pp. 129–133.
181. France's Second High Speed Line at Crucial Stage. *Railway Gazette International*, Vol. 139, No. 9, 1983, pp. 683–684.
182. F. Lacote. Second Generation TGVs Raise Speed and Comfort Standards. *Railway Gazette International*, Vol. 142, No. 12, 1986, pp. 885–888.
183. H.-D. Eisbrecher et al. DE 2500 UmAn 202 003-0—Ein Erprobungsträger für Hochgeschwindigkeits-Triebdrehgestelle. *ZEV Glasers Annalen*, Vol. 107, No. 5, 1983, pp. 131–138.
184. Germans Revise Design of High Speed Test Train. *Railway Gazette International*, Vol. 139, No. 11, 1983, pp. 848–849.
185. H. R. Kurz. Der Hochgeschwindigkeits-Versuchszug Intercity-Experimental: Fortschritt bei Entwicklung und Fertigung. *Eisenbahntechnische Rundschau*, Vol. 33, No. 12, 1984, pp. 899–902, 905–906, 908.
186. D. Lübke. ICE Poised To Start Running Tests. *Railway Gazette International*, Vol. 141, No. 3, 1985, pp. 186–189.
187. ICE Unveiled by Thyssen Henschel. *Railway Gazette International*, Vol. 141, No. 4, 1985, p. 282.
188. H. Kurz. Die Konzeption für den Hochgeschwindigkeitszug Intercity-Experimental (ICE). *Elektrische Bahnen*, Vol. 83, No. 5, 1985, pp. 138–140, 142–144.
189. C. E. Krull and K.-H. Garre. Intercity-Express (ICE). *Elektrische Bahnen*, Vol. 83, No. 10, 1985, pp. 313–318.
190. P. Falk et al. Die elektrische Ausrüstung der ICE-Triebköpfe. *Elektrische Bahnen*, Vol. 83, No. 10, 1985, pp. 319–334.

191. U. Budde et al. Entwicklung des mechanischen Teils der ICE-Triebköpfe. *Elektrische Bahnen*, Vol. 83, No. 10, 1985, pp. 335–338, 340–344.
192. R. Schumann. Moderne Eisenbahnantriebe am Beispiel des ICE. *Antriebstechnik*, Vol. 25, No. 8, 1986, pp. 23–24, 26, 28–29.
193. ASEA To Build SJ Tilting Trainsets. *Railway Gazette International*, Vol. 142, No. 10, 1986, p. 691.
194. *The Swedish High Speed Train*. ASEA Traction brochure, undated.
195. Three-Phase Motor Built into Hollow Axle. *Railway Gazette International*, Vol. 131, No. 11, 1975, p. 433.
196. R. Stokes. Three-Phase Traction: Problems and Prospects. *Railway Gazette International*, Vol. 132, No. 11, 1976, pp. 418–422.
197. I. P. Isaew and A. S. Kurbassow. Die Entwicklung des Antriebes von elektrischen Triebfahrzeugen. *Elektrische Bahnen*, Vol. 84, No. 3, 1986, pp. 85–91.
198. Aerotrain Prototype Is Completed. *Railway Gazette*, Vol. 125, No. 19, 1969, pp. 747–748.
199. The Way Ahead for Tracked Hovercraft. *Railway Gazette International*, Vol. 127, No. 6, 1971, pp. 229–232.
200. T. G. Fellows. High Speed Surface Transport. *Railway Engineering Journal*, Vol. 3, No. 2, 1974, pp. 4–20.
201. K. D. E. Crawford. Electronic Control of Spin and Slide. *Railway Gazette International*, Vol. 127, No. 4, 1971, pp. 140–142.
202. Pueblo Paves the Way for Guided Transport. *Railway Gazette International*, Vol. 127, No. 10, 1971, pp. 399–400.
203. Air Cushions and Maglev. *Railway Gazette International*, Vol. 129, No. 9, 1973, pp. 340–343.
204. G. P. Kalman. Linear Motors To Power DOT's High-Speed Research Vehicles. *Railway Gazette International*, Vol. 130, No. 10, 1974, pp. 378–383.
205. D. S. Armstrong. Application of the Linear Motor to Transport. *Railway Gazette*, Vol. 123, No. 4, 1967, pp. 145–150.
206. H. Autruffe. Le moteur linéaire. *Revue Générale des Chemins de Fer*, Vol. 87, No. 4, 1968, pp. 209–218.
207. H. Autruffe. Le moteur linéaire. *Revue Générale des Chemins de Fer*, Vol. 90, No. 6, 1971, pp. 438–450.
208. H. Autruffe et al. Les études de sustentation magnétique à la SNCF. *Revue Générale des Chemins de Fer*, Vol. 94, No. 9, 1975, pp. 497–522.
209. H. Yamashita. Repulsive Levitation and Propulsion. *RTRI* (Japan) *Quarterly Reports*, Vol. 17, No. 4, 1976, pp. 157–165.
210. Motor lineal y sustentación magnética en la R.F. Alemana. *Revista AIT*, No. 30, Nov.–Dec. 1979, pp. 19–22.
211. Y. Kyotani et al. Motor lineal y sustentación magnética en Japón. *Revista AIT*, No. 30, Nov.–Dec. 1979, pp. 55–56.
212. J.-P. Pascal. Le moteur linéaire de Jean Guimbal. *Revue Générale des Chemins de Fer*, Vol. 99, No. 1, 1980, pp. 3–8.
213. D. Lancien and R. Moulin. Caractéristiques et développement des systémes de transport à sustentation magnétique en 1980. *Revue Générale des Chemins de Fer*, Vol. 99, No. 11, 1980, pp. 633–646.
214. C.-P. Parsch and H.-G. Raschbichler. Der eisenbehaftete synchrone Langstatormotor für die Transrapid Versuchsanlage Emsland (TVE). *ZEV Glasers Annalen*, Vol. 105, No. 7/8, 1981, pp. 225–232.
215. P.-J. Gaede. Magnetbahntechnik mit Kurzstatorantrieb. *ZEV Glasers Annalen*, Vol 105, No. 7/8, 1981, pp. 252–255.
216. L. Miller. Magnetfahrtechnik mit synchronem bzw. asynchronem Kurzstator-Linearantrieb. *ZEV Glasers Annalen*, Vol. 105, No. 7/8, 1981, pp. 256–260.
217. C. P. Parsch and G. Ciessow. Die Antriebsausrüstung des Transrapid 06 mit eisenbehafteten synchronen Langstatormotor. *Elektrische Bahnen*, Vol. 79, No. 8, 1981, pp. 290–295.
218. T. Azukizawa. Optimum Linear Synchronous Motor Design for High Speed Ground Transportation. *IEEE Transactions on Power Apparatus and Systems*, Vol. 102, No. 10, 1983, pp. 3306–3314.
219. E. Eitlhuber. Transrapid 06 und sein Antriebssystem. *Eisenbahntechnische Rundschau*, Vol. 33, No. 6, 1984, pp. 501–504, 506.
220. Internationale Magnetbahnkonferenz in Solihull. *Eisenbahntechnische Rundschau*, Vol. 33, Nos. 11, 12, 1984, pp. 875–876, 949–952.
221. Y. Usemi. Superconducting Magnet Levitation/Propulsion Test Vehicle. *RTRI* (Japan) *Quarterly Reports*, Vol. 15, No. 2, 1974, pp. 62–68.
222. S. Fujiwara. Characteristics of Propulsion System of the Magnetic Levitation Vehicle Named ML 100. *RTRI* (Japan) *Quarterly Reports*, Vol. 16, No. 2, 1975, pp. 77–78.
223. Year of Progress for Japan's Three Maglev Projects. *Railway Gazette International*, Vol. 133, No. 6, 1977, pp. 232–234.
224. S. Nishi and T. Iwahana. Test Results Concerning Vehicle and Devices. *Japanese Railway Engineering*, Vol. 19, No. 1, 1979, pp. 14–18.
225. K. Miyazaki. The Magnetic Levitation Railway. *Japanese Railway Engineering*, Vol. 20, No. 4, 1981, pp. 2–5.
226. Japon: le développement de la sustentation magnétique. *Revue Générale des Chemins de Fer*, Vol. 100, No. 6, 1981, p. 368.
227. H. Tanaka. Present Conditions of Maglev Test in JNR. *Japanese Railway Engineering*, No. 96, Dec. 1985, pp. 8–11.
228. K. Mandt. Measuring and Control System for Testing New Components for Guided Transportation Systems. *Siemens Review*, Vol. 41, No. 12, 1974, pp. 527–532.
229. H.-G. Raschbichler. Development Tendencies of the Electromagnetic Levitation Techniques for Application in High-Speed Traffic Systems. *Thyssen Technische Berichte*, No. 1, 1979, pp. 1–15.
230. Demonstrationsanlage für Magnetschwebetechnik zur Internationalen Verkehrsausstellung (IVA) 1979. *Eisenbahntechnische Rundschau*, Vol. 28, No. 4, 1979, pp. 281–292.
231. P. Schwarzler et al. Transrapid 06—Fahrzeugkonzept. *ZEV Glasers Annalen*, Vol. 105, No. 7/8, 1981, pp. 216–224.
232. Transrapid Halfway to Target Speed. *Railway Gazette International*, Vol. 140, No. 7, 1984, pp. 538–539.
233. C. de Paux-Courrouges and J.-M. Willigens. Le "Transrapid" en bout de piste. *La Vie du Rail*, No. 1957, Aug. 30, 1984, pp. 9–12.

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