Japan's Rail Technology Development from 1945 to the Future

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Introduction

This article focuses on the development of rail technology in Japan although it puts it in the context of world developments. One could write a book on railway technology and the challenges facing rail transport but space limitations mean that some details are covered in the further reading list.

Japan's Rail Development from 1945

Rather than discuss each development separately, this first section separates railway developments in Japan into six time periods from 1945 to the present.

1945–57: Postwar reconstruction

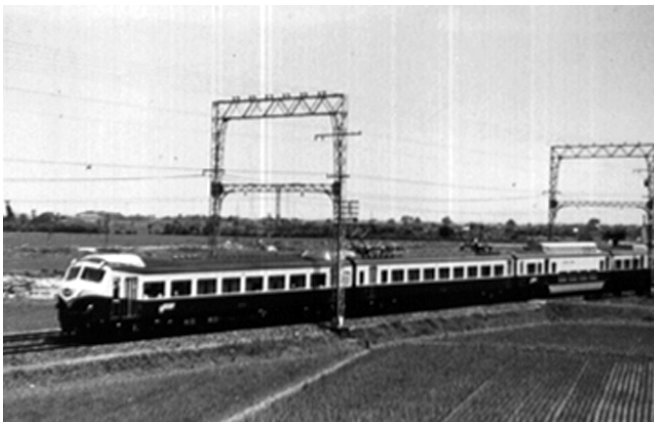
Although WWII ended with many Japanese cities in ruin, some trains were still moving in most parts of the country on the day hostilities ceased. Peace quickly brought rapidly increasing demand for transport, forcing trains to continue running even though many facilities were dilapidated or destroyed and serviceable carriages and wagons were few and far between. As a stopgap to increase capacity, rudimentary repairs were made to damaged rolling stock, and inoperable multiple units were used as passenger carriages hauled by locomotives. New carriages and wagons were in urgent demand and the few remaining works were manufacturing rolling stock to low wartime standards. The new stock was put into service wherever it could be used on government or private lines based on track gauge, carriage size, and loading gauge, etc.
Around 1949, the railways were gradually regaining the ability to design their own rolling stock, and the private railways pooled their management resources when developing new electric trains as described later in this article. At the same time, the newly formed Japanese National Railways (JNR) was making a name for itself by modernizing its motive power from steam to diesel and electric traction. In 1945, Japan was suffering from a shortage of coal and a surplus of electricity. As a result, the government railways began electrifying track (to 1.5 kV DC) that had not been electrified before or during the war (for strategic reasons) and in mountainous areas where more capacity was required. The work was difficult because electrification materials and food for construction workers were scarce. JNR took over the government railways' work and also developed new AC technology while electrifying to 1.5 kV DC.
On some rural lines, some steam loco-hauled passenger trains were replaced with diesel multiple units (DMUs). Hydraulic transmissions were chosen because trials showed they were lighter than electric transmissions. Hydraulic transmissions were soon being installed throughout Japan and JNR became one of the few railways in the world alongside British Rail with large numbers of DMUs. DMUs have since become less important in Japan but the technology still ranks among the best in the world as demonstrated by JR Shikoku's tilting Series 2000 DMU that entered revenue service in 1989.

1958–63: Revitalized railways

Many private railway companies in Japan began introducing high-performance electric multiple units (EMUs) around 1954 and JNR was following their example by 1957. Some of the best known are:

- *Romance Car* Super Express
  This high-speed EMU was introduced in 1957 by Odakyu Electric Railway Company on its main line between Shinjuku and Hakone. It was light with a low centre of gravity and a schedule speed of 80.1 km/h.
- *Vista Car* Limited Express
  Kinki Nippon Railway Company (Kintetsu) introduced this partly double-decked EMU in 1958.

Lightweight SE *Romance Car* standing at Shinjuku Terminal in 1957
(Odakyu Electric Railway)



Vista Car Express introduced in 1958 had Japan's first double-deck car
(Kinki Nippon Railway)

JNR's Series 151 for limited express services on DC-electrified lines (S. Kubo)

Special first-class lounge of Series 151 *Tsubame* on Tokyo–Osaka limited express services (Hoshi Collection)

Nagoya Railroad's Series 7000 EMU with 'Panorama Car' in 1961 (S. Kubo)

Series Kiha 82 *Kamome* on Kyoto–Hakata limited express services (A. Hoshi)

- *Kodama* Limited Express
  This long-distance limited express EMU was also introduced in 1958 by JNR for business travellers on the Tokaido main line.

With improved running performance and carriages designed with fixed windows and full air conditioning, which became the standard for future express trains on both JNR and private lines, these trains proved that EMU technology was the best answer for rail passenger services. At the time, a few long-distance EMUs like Italy's *Settebello* and Switzerland's *Trans Europ Express* (TEE) were carrying passengers in Europe too. However, the main technical difference between these European EMUs and JNR's Series 20 (and later Series 151) was that JNR's EMUs followed the trend to lightweight design first set by Odakyu's *Romance Car.*
An important advantage of JNR's *Kodama* was that the train did not need to be turned around at the termini unlike previous loco-hauled expresses. The fast turnaround and higher scheduled speed made it possible to operate one return run daily. This was another first for the line with added financial benefits.
In 1962, Nagoya Railroad Company (Meitetsu) began operating special express services with so-called 'Panorama Cars.' The driver's cab was over the seating area, so passengers could sit at the very front of the train. This was very popular and there was no express surcharge for these services. The high scheduled speed and improved ride comfort were a great success and boosted profits.
JNR was also making notable technical advances, especially in the field of motive power and AC electrification, which was being installed on main lines in north and west Japan even while the older DC system was being installed elsewhere. As a result, AC/DC dual-current EMUs were soon developed due to heavy demand for through connections from DC track on AC track. To meet this need, JNR successfully developed silicon rectifiers and soon put them to practical use. Mass production of dual-current EMUs started in the 1960s. Once JNR had developed a hydraulic transmission system for DMUs, it began using many of them on its non-electrified intercity and cross-country lines. Schedules were revamped frequently and the October 1961 timetable offered superior limited express DMU trains linking major cities throughout Japan.

1964–75: Focus on speed and safety

As soon as the Tokaido main line was electrified, it was in even heavier use by both EMUs and freight trains hauled by 8-axle electric locomotives. The booming Japanese economy soon overwhelmed the line capacity and the obvious solution was to build another double-tracked line. There were many different proposals, but the chosen option resulted in the now world-famous shinkansen running on grade-separated standard-gauge track.

Although JNR's narrow-gauge trains could not run anywhere as fast as the shinkansen, services were being considerably improved. By 1961, JNR was raising schedule speeds and increasing the number of departures. These efforts soon paid off as was evident in the October 1968 timetable with more limited express trains serving many main lines at maximum speeds of 120 km/h, which is close to the limit for conventional line trains with a maximum braking distance restriction of 600 m.

Japanese railways were making strides in safety as well. In Japan today, the railway accident rate (number of people killed or injured per passenger-km) is less than 0.1% that of road traffic. But the situation was much bleaker in the 1950s and 60s when some train accidents killed more than 100 people at a time. Each accident led to more stringent safety precautions but railway accidents causing more than 10 deaths continued to occur all too frequently until 1972. Since 1972, there has been only one very serious accident on the Shigaraki Kogen Railway in which 42 people were killed in a head-on collision.

The 1964–75 period should mostly be remembered as the time when Japan established the foundation for safe, high-speed rail transport. Railways in other countries have used many of the safety-related innovations developed in Japan during that time.

1976–86: JNR losing out to private motor transport

The Tokaido Shinkansen entered service in 1964 the same year that JNR first fell into the red. This was only a coincidence, because the shinkansen construction did not impact negatively on JNR's bottom line. In fact, the opposite was true—the profits from the Tokaido Shinkansen were so large that JNR could quickly pay back the construction and World Bank loans. The Tokaido Shinkansen was always a cash cow for JNR and it still is for the successor JRs.

The growing JNR deficit was caused particularly by the growing popularity of motor vehicles, political interference in JNR's business forcing it to build and operate loss-making lines in rural areas and labour-management disputes that dragged down productivity.

Higher train speeds damaged the rails faster than the maintenance crews could keep up with and the labour unions refused to accept new working procedures that would have kept trains running on time. As a result, JNR was forced to issue a new national timetable in October 1978 with its best trains running slower than before (a backward step only seen during the war) and fewer additional peak-hour trains.

In an effort to reduce its mounting deficit, JNR introduced successive fare increases so that its fares soon became higher than those of the major private railways. As a result, the private railways suddenly found themselves offering lower fares and better services, thereby attracting more passengers without even really trying. This led many to lose their entrepreneurial zeal.

The end result was that Japanese railway technology stopped advancing. This is obvious if we compare the French TGV with the Tohoku Shinkansen, both of which were introduced at about the same time. The Tohoku Shinkansen began operations in 1982, 18 years after the Tokaido Shinkansen but as far as passengers could see these 18 years had brought few technical advances. The 210 km/h maximum speed was the same as that of the older shinkansen and getting a seat during peak periods was just as difficult. France's TGV was designed with a conscious effort to avoid the inadequacies of Japan's Tokaido Shinkansen.

The technical decisions made by JNR at this time were often coloured by the worsening labour-management relations. Capital investment was focused on facilities that the workforce could repair and maintain with little effort, leading to an inferior railway with heavier equipment and uniformity promoted in the guise of standardization.

A good example is that of the Tohoku and Joetsu shinkansen constructed at this time. Most of the older Tokaido Shinkansen tracks were on embankments while the new Tohoku and Joetsu tracks ran on elevated concrete structures. The new lines used hot water to melt snow and had concrete slabs instead of ballasted beds. Heavy trolley wires with a large cross-section were used to reduce snapping. Although the cars were made of aluminium, the axle load for the new Series 200 rolling stock was 17 tonnes, 1 tonne more than that of the older Tokaido Shinkansen. The effective floor area of the rolling stock was reduced to permit installation of more equipment to facilitate inspection and snow-related procedures.

There was one exception to this overall technological inertia. Research and development at JNR's Miyazaki Test Track brought rail technology to a new height in 1979 when a superconducting magnetically levitated train reached a world record speed of 517 km/h.

1987–97: Re-energized by privatization

Clearly JNR was on the brink of bankruptcy and would have to be broken up and privatized. This awareness led to a rapid improvement in labour-management relations with both sides realizing the importance of cost-effectiveness and passenger-friendly services. JNR began picking up hints from the major private railways and even before it was privatized as six passenger companies (the JRs) and one freight company (JR Freight) plus a number of smaller specialist businesses, it had improved service by running shorter trains more frequently. It shook off the lethargy of the last 10 years, finally understanding what railway companies the world over know—better service starts with higher speed.

The last JNR rolling stock before privatization shows the former eagerness to provide quality service based on cost-effective principles. The Series 100 unveiled for shinkansen services included two comfortable double-decker carriages per train set with private rooms and other amenities. Passengers enjoyed the greater comfort and JNR enjoyed the financial advantages of cheaper construction costs, lighter rolling stock, and greater seating capacity.

For narrow-gauge lines, JNR unveiled the Series 213—comfortable, cost-effective rolling stock with the electric regenerative braking commonly used by private railways. This lineup of new rolling stock gave JNR a competitive edge.

After 1987, the six new JRs and JR Freight wasted no time launching a belated campaign to increase speed. JR Central inherited the technology that JNR had developed for the proposed Hokuriku Shinkansen, putting it in a good position to develop the Series 300 that would boost speeds on the Tokaido Shinkansen to 270 km/h when introduced in 1992. The new Tokyo–Hakata (Fukuoka) train entered service in 1993 with one return run each hour.

JR West developed the Series 500 and began operating it on the San'yo Shinkansen at 300 km/h in 1997 thereby returning the honor of operating the world's fastest train to Japan. The TGV and Series 500 both have a maximum speed of 300 km/h but the actual maximum allowable speed is 305 km/h for the San'yo Shinkansen and 320 km/h for the TGV. However, a train's true speed is its schedule speed, making the San'yo Shinkansen the world's fastest train.


Series 2000 tilting DMU introduced in 1989 for rural limited express services (JR Shikoku)

The JRs were soon offering higher speeds on their narrow-gauge networks too. In 1968, the maximum speed was set at 120 km/h where it remained for some time but many trains now run faster. Japanese train regulations place a high premium on safety and still enforce a maximum braking distance of 600 m on track with level crossings. But many trains travelling at 130 km/h can now meet this 600 m maximum and some even travel at 150 km/h on track with no level crossings.

Because large sections of Japan's narrow-gauge rail network are in mountainous regions, there are many tight curves. In these regions, any attempt to increase speed is focused not so much on raising maximum speed but more on raising speed on curves. With this in mind, JNR developed and introduced pendulum passive tilting carriages in 1973. This type of rolling stock was not popular because the passive tilting was slightly delayed after the carriage entered the curve, resulting in poor ride comfort. The problem was finally solved by developing a unique active tilt control mechanism that controlled tilting based on track data stored in onboard memory and accurate information on the train's position provided by land-based transponders. The new system was first used by JR Shikoku in March 1989 and soon spread to operations throughout the JRs' narrow-gauge network. As one example, JR Hokkaido's fastest train can now travel the 318.7 km between Sapporo and Hakodate in 3 hours with 5 stops along the way. This translates into a schedule speed of 106.2 km/h.

Thanks to the private railways' development of inverter controls, Japan continues to lead the world in the area of AC traction motors. Inverter controls were first put to practical use in 1982, around the time that the gate turn-off (GTO) thyristor was introduced and today Insulated Gate Bipolar Transistor (IGBT) or Intelligent Power Module (IPM) facilitating GTO use are increasingly common. Railways worldwide are showing interest in Japan's ability to reduce the number of switching devices by increasing IGBT capacity, and to develop new devices and their circuits such as Injection Enhanced Gate Transistor (IEGT) and Gate Commutated Turn-off Thyristor (GCT).

Since 1998: Abandoning business principles again

Although the JNR privatization is generally seen as a success, do Japanese railways offer the high level of service demanded by the public? More and more people are saying they do not.

Table 1 Comparison of Standard Carriages built to Guidelines of Private Railways Management Association and Previous Carriages (standard car length 17 m, width 2.7 m, 2-car train set)

	Train set	Weight (tonnes)	Motive power (kW)	Brakes	Maximum speed (km/h)	Acceleration (m/s^2)	Transmission system
Older cars	Mc + Tc	40 + 30	4 x 100	Auto	90	0.5	Nose-suspended type
New standard cars	Mc - Mc	29 + 29	8 x 75	HSC-D*	100	0.9	Cardan-drive type

* Rapid-response air brake used jointly with dynamic brake

It is clear that Japanese railways invest less money, in relative terms, than their European counterparts. They lag behind in their use of information technologies, confidence in trains is dwindling, and passengers are not given enough information when the timetable is disrupted. While rail is increasingly seen as *the* environmentally friendly way to travel, Japanese railways have been slow to catch this wave while appearing once again to be ignoring the desire for faster speed.

Here I will restrict my remarks to the railways' sluggish introduction of information technologies. In many other countries of the world an ordinary credit card can be used to buy a ticket for intercity rail travel, but the custom is rare in Japan. In many large cities outside Japan, passengers are increasingly using IC or magnetic cards to transfer from one transit mode to another, but this is rarely the case in the greater Tokyo and Osaka areas. Switzerland has begun work on the EasyR!de system, hoping to eliminate the need for tickets on all public transportation modes by 2005. Japan lags far behind in areas like this.

Major Advances in Rail Technology

Private railways' development of high-performance EMUs

At the end of WWII, the private railways were the first to launch efforts to improve rail transport in Japan. They started by developing and manufacturing lightweight, high-performance EMUs, realizing that this was the most effective way to quickly boost carrying capacity and speed, and to break the cycle of continually maintaining rolling stock that kept breaking down. In 1951, the companies began reducing carriage weight by about 25% by using high-tensile steel with a shell (monocoque) structure. They also developed a light, fast drive system that rarely failed. The old nose-suspended motor was replaced with a Cardan-drive type motor mounted on the bogie frame and configured to drive the axle via a flexible coupling. Braking was also improved by adding electrical braking to reduce the dependence on inferior friction brakes.

As a follow up to these efforts, in 1954, the Private Railways Management Association established specification for EMUs. Thereafter, most carriages produced by the private railways conformed to this standard as did those of JNR after 1957.

Table 1 shows some ways in which the new carriages differed from their predecessors. In order to achieve high performance, each car of the private railways' early EMUs was motorized. To make this configuration as economic as possible, the railways developed a standard system in which eight motors for two cars were controlled from a single controller. The same configuration was adopted by JNR but there was an evolution to non-standard train sets with some non-motorized cars. This caused performance drops in some cases, but the configuration was accepted because of limited substation capacity. In other cases, it was accepted as a cost-effective measure and performance was also maintained. The technology prompting this evolution was used for Odakyu's *Romance Car* and then for JNR's shinkansen.

Development of AC systems

In 1952, Japan heard tantalizing tidbits from France about practical use of commercial-frequency single-phase AC systems for electric trains that had been tested in Germany in 1936 and were almost ready for application studies. In August 1953, JNR established the AC Electrification Research Committee charged with developing an AC supply system for rail transport. Conferences on practical use of AC rail systems were held in London in 1954 and Lille in 1955. Japan hoped to move forward on two fronts by buying several electric locomotives from France in order to gain experience and knowledge of the system and by developing its own AC locomotives at the same time. However, negotiations with France broke down because the minimum locomotive purchase was 100 units.

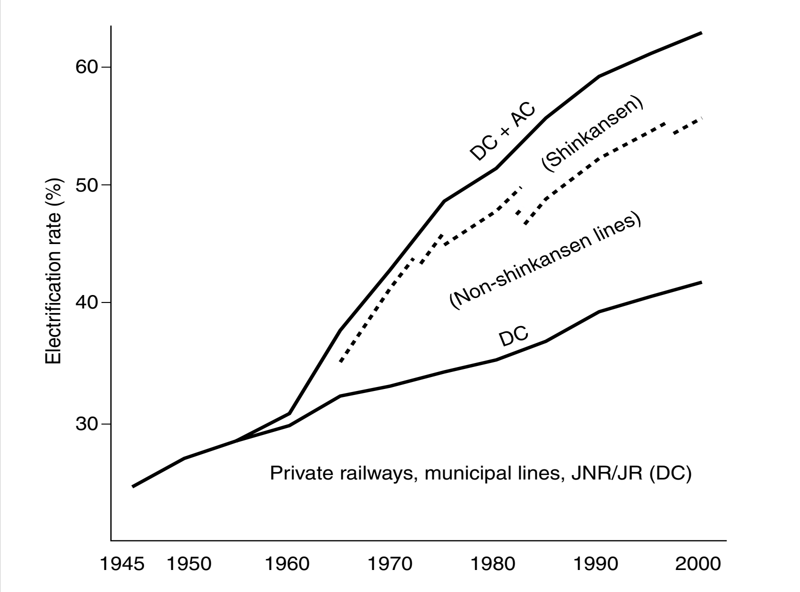
Luckily, the results of the German experiments were revealed in detail the following year and partial news reports arrived from France giving Japan a general idea of developments in Europe. At the time, JNR was pushing forward with its own development, bringing together electrical equipment manufacturers from different parts of Japan. In June 1955, just 1 month after the Lille Conference, Hitachi, Toshiba and Fuji Electric each produced two AC-commutator motors for direct-type locomotives, and Hitachi also produced an ED44-1 locomotive main unit. For its part, Mitsubishi Electric produced another rectifier-type locomotive, the ED45-1, in July 1955. This latter unit incorporated mercury rectifiers (ignitrons) and low-tension tap changers. Induction interference tests were begun in September 1954, 1 year prior to completion of the locomotives, which were submitted to test runs on the Senzan Line in August 1955.

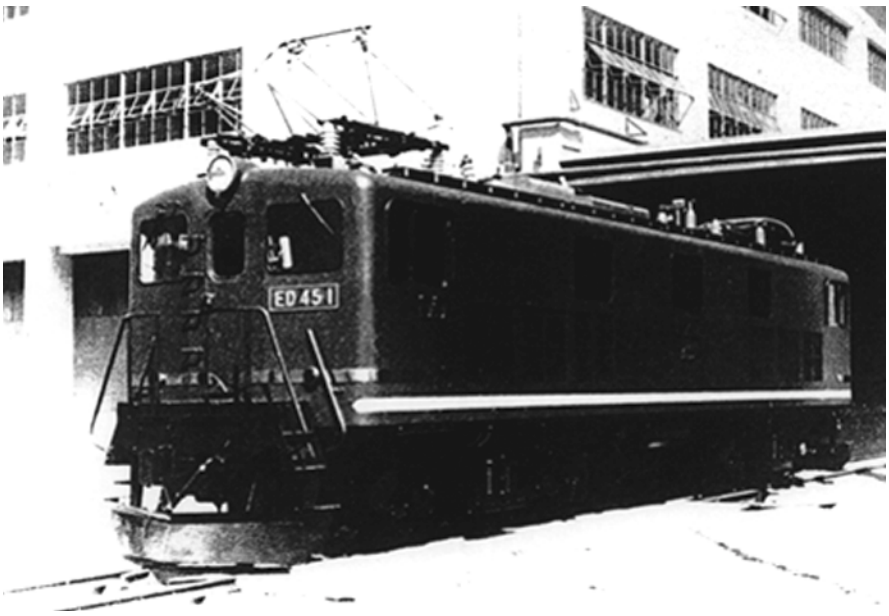
The direct-type locomotive had been considered the best choice and tests showed that it was almost as good as expected. However, the rectifier-type locomotive performed far better than expected so the decision was made to use rectifier-type locomotives and development was soon completed. JNR then asked Toshiba and Hitachi to each produce one additional rectifier-type locomotive for commercial use on the Senzan Line, which had been fully electrified with AC technology. The idea was to give several electrical equipment manufacturers experience in manufacturing AC locomotives in preparation for future full-scale AC electrification of main lines. The ED45-11 was very similar to the ED45-1 although the motive power was slightly superior. The ED45-21 used high-tension tap control and an excitron as a mercury-arc rectifier; its motive power was 50% greater than that of the ED45-1. The locomotives were completed in February and March 1957 and commercial AC operations using the four locomotives began on the Senzan Line in September 1957.

Success in developing AC technology enabled JNR to promote both conventional DC and the new AC electrification, considerably boosting the progress of railway electrification.

Figure 1 shows route electrification rates in Japan since WWII. During the 55 years since the war, there have been increases in total route length mainly through construction of new lines (including shinkansen and urban lines) and decreases through closure of some local lines and tram lines. The lengthenings and shortenings occurred within the narrow range of 27,070 to 28,450 km, largely cancelling each other out.

Figure 1 Railway Electrification in Japan 1945–2000





Mitsubishi Electric's Series ED45-1—one of Japan's first test AC locomotives (Transport Museum)

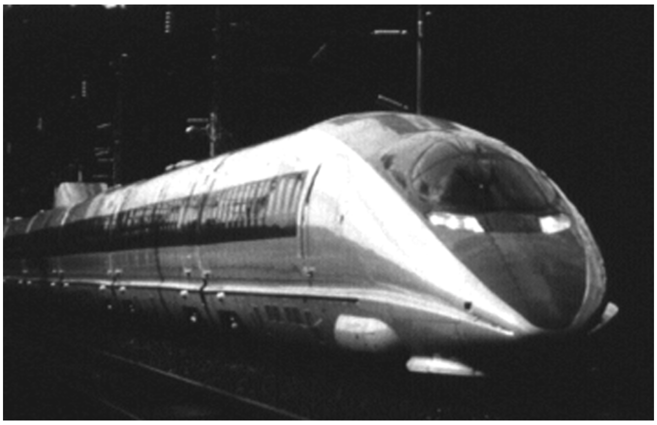
The Shinkansen

The shinkansen was constructed not so much to create the world's fastest high-speed train, but more to increase capacity on the saturated Tokyo–Osaka rail corridor. Common sense dictated quadrupling the existing Tokaido main line but it was too difficult to purchase more land alongside the existing line.

There had been a plan to construct an entirely new standard-gauge line between Tokyo and Shimonoseki (western Honshu) from as early as 1939 and some land had already been purchased for the project. However, construction was halted by the war and never restarted. A somewhat similar plan for a shorter high-speed railway was announced at an event to commemorate the 50th anniversary of JNR's RTRI in 1957.

Many of the people (notably Hideo Shima (1901–98), the son of the government railways Chief Engineer Yasujiro Shima and architect of the prewar plan) were anxious to see a standard-gauge high-speed line come to fruition. Somewhat

Series 0, 100, 300 standing side by side at JR Central depot. Series 100 has two or four intermediate double-deckers (S. Kubo)



JR West's Series 500 developed for Japan's first 300-km/h operation on San'yo Shinkansen (JR West)

JR East's Series E2 for *Asama* services on Nagano Shinkansen. (JR East)

High-speed (150 km/h) Series 681 in Niigata (Hokuetsu Express)

unexpectedly, a public lecture entitled 'Tokyo to Osaka in Three Hours—Can It Be Done?' was announced in 1957, arousing much public interest.

The entire Tokaido main line had just been electrified but JNR had not yet launched its *Kodama* limited express to reduce the time between Tokyo and Osaka to 6 hours and 30 minutes. It is no surprise that a train linking the two cities in just 3 hours was regarded as a 'futuristic super express.'

Many JNR executives still believed that quadrupling the existing Tokaido main line was the most realistic approach but JNR President, Shinji Sogo (1884–1981), respected the initiative of RTRI and invited Hideo Shima to return as Vice President for Engineering. These two men exerted strong leadership and promoted the concept of a new standard-gauge line.

Obviously, the shinkansen concept could not have become reality without incorporating prior technological developments. Of central importance was the high-performance EMUs being developed by the private railways, JNR's AC electrification projects, and the growth of systems technology.

Systems technology takes a comprehensive, all-inclusive approach to problems. In the case of the shinkansen, it made maximum use of the positive effect obtained by building a new railway from scratch—a railway that had no through operations with conventional lines.

Since the track would be grade-separated through its entire length, allowable braking distance could be increased by several magnitudes. Fast trains could run frequently due to the adoption of onboard Automatic Train Control (ATC) and the world's first Centralized Traffic Control (CTC) on double track. In addition, the world's first nationwide rail seat reservation system was developed to permit smooth reservation services for the vast number of passengers.

The planned maximum speed of 210 km/h was achieved from the first day of commercial operations and as soon as the ballasted track bed was judged to have stabilized sufficiently, the Tokaido Shinkansen began making the 515.3-km run between Tokyo and Osaka in 3 hours and 10 minutes on 1 November 1965. It kept its top position in terms of maximum operating speed and schedule speed, until the French TGV began partial operations in September 1981.

Not only was the shinkansen fast, but it also broke records in carrying capacity, safety, and punctuality. It even showed that rail operations could be profitable. Public policy in Europe and elsewhere, which now favours a modal shift to high-speed railways, is based on the success of the shinkansen and current environmental and safety concerns.

For some time after the Tokaido Shinkansen first appeared, speeds remained virtually unchanged in Japan.

Then the TGV arrived and Japan took up the challenge to boost speed further. JR Central was the first to succeed in this endeavour—developing the lighter Series 300 by doing everything possible to reduce weight in order to increase speeds to 270 km/h on the Tokaido Shinkansen, which is not as conducive to high speeds as other shinkansen lines.

Prior to the Series 300, the lightest axle load for high-speed trains was 16 tonnes for the Series 0 shinkansen, and 17 tonnes for Britain's HST and France's TGV. Sweden had aimed at 15 tonnes for its X2000 but no manufacturer had been able to meet the target. However, Japan's use of electric regenerative braking, almost unknown in fast trains at the time, helped reduce axle load to under 12 tonnes. This development made it possible to operate at the aimed-for speed of 270 km/h in 1993.

Concurrent with development of the Series 300, JR West was developing its WIN350 with the aim of operations at 350 km/h on the San'yo Shinkansen. JR East began developing the test star 21 that it hopes will evolve into a superlative high-speed train for the 21st century and JR Central began using the 300X test car for R&D of an ideal carriage to be used in addition to the Series 300. These JRs helped Japan return to the top position in high-speed rail technology, a position that had been taken temporarily by the TGV.

The test vehicles were submitted to many high-speed runs, focusing on important environmental factors such as external running noise and conditions when a train rushes through a tunnel. The results are being used for further development. Table 2 shows the highest speeds attained during these tests, although the tests were not conducted as speed tests *per se*. Since 1997, the test results have helped the JRs increase operating speeds to 300 km/h for the Series 500 on the San'yo Shinkansen and to 275 km/h for Series E2 and E3 on the Tohoku Shinkansen.

Table 2 JNR/JR Shinkansen Speed Records

Date	Railway	Type	Highest speed (km/h)	Remarks
7 Dec 1979	JNR	Series 961	319.0	Tohoku Shinkansen test cars
28 Feb 1991	JR Central	Series 300	325.7	Advance mass-produced cars
8 Aug 1992	JR West	WIN350	350.4	Dedicated test cars
21 Dec 1993	JR East	star21	425.0	Dedicated test cars
23 Jul 1996	JR Central	300X	443.0	Dedicated test cars

Any company running frequent trains at high speed must reduce external noise and track wear and tear, and must ensure sufficiently high reliability for supply of electric power and maintenance. Lighter cars with electrical braking help attain these objectives. The Series E2 is 15 tonnes lighter than the Series 200 per car in average.

Superconducting Maglev train

The concept for a superconducting magnetically levitated (Maglev) train was proposed in the 1960s, and Maglev R&D began in Japan on a large scale in 1972—the 100th anniversary of railways in Japan. In 1979, an experimental Maglev achieved a record speed of 517 km/h on the JNR Miyazaki Test Track. The track shape was then changed from an inverted-T to a U-shape, to more closely match actual operating conditions. Subsequent tests used connected railcars.

Maglevs attracted attention in many countries in the 1970s, and about 10 nations conducted experiments in air and magnetic levitation. Research quickly divided into two areas—low-speed vehicles for short distances, and super-high-speed vehicles for longer distances. Air levitation was seen as unsuitable for super-high-speed vehicles, leaving Japan's superconducting inductive repulsion technology and Germany's normal-conducting attractive control technology as possible options. Germany took the lead in practical application, building a circular test line with a length of more than 30 km in Emsland. The new technology was exhibited at the Transport Expo in Hamburg and carried thousands of passengers.

After the 1987 privatization, Maglev development was taken over by RTRI and JR Central, which also assumed responsibility for most rail operations in the regions located roughly between Tokyo and Osaka. Concurrent with ongoing Miyazaki tests, a government project was launched to select another location for a test line to conduct further development and feasibility studies. This led to the decision to construct a test line of more than 40 km in Yamanashi Prefecture, where topographical and weather conditions are similar to actual operating conditions, and where local collaboration was assured. The test line was also located to become part of the first commercial track.

The design specifications were a maximum speed of 500 km/h carrying 10,000 seated passengers per hour each way on steepest gradients of 4% with a minimum curve radius of 8,000 m. The equipment was designed to permit trains to pass each other in opposite directions at high speed.

Other research focused on other factors that are essential to commercial operations: electric power supply; design, manufacture and installation of levitation and propulsion coils; tunnel cross-section area and distance between tracks; braking systems; structure of stations and turnouts;

electric supply for car interiors; onboard equipment such as cryogenic devices; and emergency measures.

Various tests were conducted on the first 18.4-km Yamanashi Test Line, and the planned maximum test speed of 550 km/h (commercial maximum speed + 10% to determine resonance levels and other factors) was achieved in December 1997, 8 month after test runs began in April. By March 2000, tests were being conducted by trains closing in opposite directions at a relative speed of over 1000 km/h. Hypothetical failures were tested and various braking systems, such as aerodynamic brakes, were examined.

The results prompted the Maglev Evaluation Committee of the then Ministry of Transport (MOT) to conclude that the Maglev 'shows basic potential for commercial operations.' Issues being tackled today include optimum design and better cost-effectiveness. In the meantime, durability tests are continuing. It is anticipated that future design changes will bring the Maglev's passenger-km energy consumption to about three times that of the shinkansen with fares comparable to air and schedule speeds of around 400 km/h, giving the Maglev the advantage over air travel in the 500–1000 km range from the viewpoints of energy conservation, environmental protection, safety, travel time between city centres, and land use efficiency.

Important role of railways in power electronics

Electric power semiconductor devices assist in practical use of electric power but were not available in Japan in 1957 when AC rail electrification was being promoted. With the development of silicon rectifiers, AC/DC EMUs were being mass-produced by 1960, and silicon rectifiers were quickly installed in ground-based substations, too. By 1962, silicon diodes were being installed on AC locomotives, which had been upgraded to phase control with mercury-arc rectifiers. Prototypes created by introducing thyristors to diode-type locomotives, which were phase-controlled with magnetic amplifiers, were being produced in 1966. The world's first thyristor-type AC regenerative locomotives were being produced on a trial basis the following year.

For DC circuits, tests aiming at use of chopper controls were conducted simultaneously with the start of thyristor application. The private railways began mass-producing and introducing thyristor-controlled EMUs in 1970, and thyristor-controlled cars with the world's first regenerative brakes in 1971.

Starting in the 1980s, the DC drive system abandoned choppers with DC motors, changing to inverters and induction motors. GTO thyristors capable of withstanding 4500 V were adapted to the standard voltage of 1.5 kV for DC electrification. For a considerable period, only Japanese electrical equipment manufacturers were able to produce GTO thyristors suitable for rolling stock.

Although it is easy to make GTO thyristors that can withstand high voltages, it is hard to ensure high operating frequency. Various new integrated devices were made later and their application to railways is important, even in the case of devices not developed specifically for trains. European railways are also very interested in the potential offered by these devices.

EMU Trains

As far back as the 1930s, private railways were mainly operating electric railcars in cities and urban areas.

As previously mentioned, JNR introduced EMUs for long distance express services in the late 1950s. As a result, the shinkansen in EMUs was born... However, in Europe, trams and subway trains were seen as having little in common with main-line railways so when main lines in Europe were electrified, steam and diesel locomotives were replaced by electric locomotives with almost no consideration given to distributed power.

In the days when all electric trains were driven by DC motors, European and Japanese engineers would sometimes engage in discussions on which drive was more effective. The Europeans favoured trains hauled by locomotives. The Japanese favoured multiple units but were unable to show any great advantage of distributed power except for lower axle loads. In Europe, distributed power was believed to make little economic sense even in the case of the all-powered three-car Swiss ABDe12/12 used for suburban transport and the all-powered four-car ET-403 high-speed railcars produced in Germany for comparison purposes. In the absence of a compelling economic reason, no other models were built in Europe. And since it was a fact that Britain's locomotive-hauled HST exhibited stable operation—something that had been considered impossible in Japan from the adhesion viewpoint—Japanese arguments lacked persuasiveness.

But with the introduction of AC motors, the disadvantage of having many traction motors has been reduced in terms of weight and maintenance. The advantage of regenerative braking, which converts the high kinetic energy of moving trains to electric power, has even increased. Finally, the Japanese argument appears to have won the day and EMUs are now appearing in increasing numbers in Europe, where locomotive-hauled trains have long remained in favour. Distributed power is superior, especially in fast trains where kinetic energy levels are high, and using electric regenerative braking to absorb kinetic energy reduces car weight and brake heat generation better than any other braking method.

In addition, since the inverters on EMUs are true four quadrant controllers, it is possible to use electrical braking to a complete stop. This eliminates the various problems that occur when mixing electrical and friction braking. The technologies for integrated systems are currently available only in Japan.

Safety precautions

Little thought is given in Japan to the passenger's responsibility to ensure his or her own safety while riding on public transportation. Even if an accident occurs due to a passenger's carelessness, the transport company is often held to blame. Within this social context, exhaustive safety measures were taken in the wake of three serious JNR accidents—each involving the death of more then 100 people—leading to much higher safety levels.

Soon after a disastrous fire at Sakuragi-cho near Yokohama in 1951, all railcars were improved by provision of a through passage to adjoining cars for evacuation; signs indicating how to open doors in an emergency; window structures to permit evacuation; fire-resistant cars, and mechanisms permitting rapid power shutdown to reduce the possiblity of fire in the first place.

After a driver ignored a stop signal and caused a dual collision at Mikawashima in Tokyo in 1962, the old Automatic Warning System (AWS) used on some track sections was changed to an on-board Automatic Train Protection (ATP) system, called Automatic Train Stop (ATS) in Japan.

Another dual collision at Tsurumi in Yokohama in 1963 was due mainly to the derailment of a four-wheel freight wagon. Since this was a multi-factor derailment, it was investigated exhaustively with much testing on the abandoned Karikachi Line in Hokkaido. Following the tests, tens of thousands of four-wheel freight wagons were modified to double-link suspension and a safer maximum speed was specified for each wagon type.

The ATS system had been installed on all 20,000 km of JNR lines and in all drivers' cabs by 1966. This greatly reduced the number of accidents caused by ignoring signals but did not eradicate them completely, because ATS was configured in such a way that the driver could release the stop function by pressing a check button after an alarm. Therefore, the MOT instructed the major private railways, who had followed JNR's footsteps and adopted ATS, to install a more sophisticated ATS with a speed-checking function not released by a check operation. This also helped prevent accidents caused by overspeeding. JNR (and then the JRs) upgraded their ATS, installing functions equivalent to those of the private railways or replacing ATS with Automatic Train Control (ATC) on trunk lines. These measures have prevented almost all accidents caused by violating signals.


Aftermath of 1962 collision at Mikawashima Station in north Tokyo (*Transportation News*)

Another train fire caused by flames spreading from a coal cooking stove while a train was passing through the Hokuriku Tunnel in 1972 led to strengthened fire regulations for cars used in long tunnels. Train operations were also modified by requiring the train to move out of the tunnel rather than stop immediately after a fire breaks out in a long tunnel.

A system that reduces train speed before an earthquake wave hits the track has been installed on the shinkansen lines. Seismometers on the coast detect early earthquake waves and send signals that immediately command trains to stop.

After another multi-factor derailment on the Hibiya Line in Tokyo in March 2000, measures have been taken recently to control unbalanced loads on left and right wheels.

Current Problems and Possible Solutions

Instant and transparent information to recover public trust

Japanese railways are admired throughout the world for their safety and reliability. But various incidents have recently caused the Japanese public to question the reliability of rail travel. Passengers are especially dissatisfied with the lack of information provided after a mishap, and the railways' attempts to sometimes conceal information. In today's information age, where mobile terminals can provide all kinds of data, passengers are questioning the companies' practice of releasing only 100% accurate information where it is needed. On the other hand, if the railways were to take the opposite approach, releasing all information to anyone and keeping nothing back, they would satisfy the desire to base decisions on plenty of instant information, but could be criticized for releasing information irresponsibly, or releasing wrong information or stirring up inflammatory rumours. One issue that requires careful thought is how information can be given so that passengers feel once again that they can completely trust transportation companies.

Information technologies for passenger convenience

The world's most advanced fare payment system is undoubtedly the Swiss EasyR!de system already being used on a trial basis in some areas. The advantages offered by this system include cash-free fare payment and automatic collection of detailed transport demand information by the transit company. In addition to these two functions, a next-generation system with individual real-time guidance functions was proposed in Japan in 1995 and is under development.

In a country like Switzerland, where transport density is relatively low, there is perhaps no need for an information system for individual users. But there is high demand for individual real-time information in large cities in east Asia, including Japan, with very dense public transportation networks where it is difficult for users to choose the best route.

Such a system was given a jump-start by the keynote speaker at a 1989 seminar in Japan organized by RTRI entitled, *The Use of IC Cards for Public Transportation*. Even when first proposed, the system concept included the idea of providing guidance to the travelling public. Later, the system was called **I**ntelligent **P**assenger **AS**sistance **S**ystem (IPASS). In addition to the IC Cards proposed first, PHS phones, mobile phones and wristwatches like the Swiss EasyR!de system could be effective mobile information terminals.

IPASS opens the door to many improvements in service. For example, if an incident disrupts traffic on one line and passengers need to use another line or another transit mode, they can base their decisions on the latest information via IPASS. For their part, railway companies could add more trains to lines still in operation after an accident, increasing capacity as indicated by congestion projections.

The information could direct some passengers from crowded cars to other cars with empty seats. It could direct them to a station where they could transfer without using stairs. Being able to give passengers the information they ask for would be a tremendous improvement in service. And for the railway company, having more information on passenger demand would help them offer a greater variety of services for individual passengers, making it possible for public transit to satisfy personal needs, much like the private automobile does.

True high speed

It is widely accepted that the company that can carry passengers faster than other companies is the most competitive. But it is not as well understood that travel speed is not the same as origin-to-destination speed. Making a train run faster shortens travel time but if passengers must wait longer for train connections, their origin-to-destination speed might not decrease at all. And faster origin-to-destination speed is not necessarily always better. Many passengers would find a 7-hour overnight train trip better than a 4-hour trip during the day. And if the only option is a 4-hour trip during the day, on-board services that let them use that time constructively would make travel time seem shorter.

The search for faster travel speed should of course continue, but in tandem with two other endeavours: discovering what passengers consider to be unconstructive use of time, taking into consideration the time required for access, egress, train connections, etc., and improving the technology used to schedule public transport services over the entire network. In this regard, Switzerland has had considerable success with equal-interval scheduling since 1982. The scheduling is nearly perfect in cases where there are only one or two trains each hour, but the system has not yet been upgraded for a truly fast network in large cities with high service frequencies and many difficult problems remain to be solved. Some of these problems have been resolved in the Kansai region by JR West which has earned praise for its urban network schedule that lets passengers transfer smoothly between local and express trains with almost no waiting.

Japan's rail standards for world?

Railways are safe and environmentally friendly, so the whole world could benefit from development of public transport systems centred around rail networks offering excellent services at reasonable prices. Needless to say, the railway industry would benefit too. As countries work towards such systems, pressure will increase to establish international standards for train systems, software, etc., as well as parts, equipment.

Some rail technologies developed in Japan offer advantages that would benefit railways elsewhere. Here I would like to discuss several areas where Japanese technology could be used to establish new world standards.

EMUs with regenerative braking

Japan has developed EMU passenger trains to a level higher than anywhere else in the world when measured by almost any yardstick such as years of experience, quality of transport, number of trains, etc., and have reached the stage where they could form the basis for a world standard. European railways have recently introduced EMUs such as the ICE-3, but it appears that the introduction was primarily to reduce axle load by dispersing the motive power as much as possible.

Yet the EMU offers many other advantages. For example, electric service braking practically eliminates the need for brake maintenance and the train can be stopped quickly and precisely with a minimum of ride discomfort. People who do not fully understand electric regenerative braking tend to doubt its reliability but use in Japan and Switzerland has fully demonstrated complete reliability and economy. The EMU also makes it possible to reduce the threshold strength needed to withstand buffer loads in turn reducing rolling stock mass, while ensuring sufficient stiffness to maintain ride comfort. This mass reduction makes it possible to use less powerful motors which in turn reduces rolling stock mass further.

Safety

Weak ground, earthquakes, typhoons, and heavy precipitation (both snow and rain) are some of the natural phenomena that make railway operations difficult in Japan. The mountainous terrain requires steeper gradients and sharper curves than in most parts of Europe. Yet despite these adversities, since 1972 Japanese railways enjoy a safety record that is the envy of the world. This is due to the numerous safety measures that have been taken. Over the last 20 or 30 years, European railways have introduced safety measures that were inspired by Japan, including fire-resistant cars, locked doors on moving trains, and back-up safety devices such as ATP. Since Japanese railways have reached the level where we can almost completely prevent the three major causes of railway accident (derailment, collision, and fire), Japanese rolling stock manufacturers have stopped developing crashworthy designs for head-on collision. However, train-automobile collisions at level crossings still occur too frequently so this possibility has always been considered in train design.

Tilting rolling stock

Full-bore tunnelling techniques are a recent technical innovation that have facilitated the number of high-speed lines by reducing the need for curves and grades. On older lines with many sharp curves, advanced train design can help support faster services. In this regard, the main approach taken by railways in Japan and Europe has been to install tilt control mechanisms on rolling stock. Many experts agree that recent tilting controls provide acceptable ride comfort, but some passengers still say they do not like the experience and never want to ride a tilting train again.

The tilting mechanism used in Europe involves an accelerometer to measure lateral acceleration and then compensate for lateral movement by applying a tilting force. On the other hand, the Japanese system involves computing the ideal tilt angle based on track data stored in onboard memory and data on the train's actual speed and location. The two systems are based on different principles and each has advantages and disadvantages.

The European system of tilting the carriage with an applied force offers considerable freedom on where to locate the centre of swing. Tilting the carriage on high-speed curves allows passengers walk along train corridors without staggering sideways, but because tilting is governed by accelerometer readings only after the curve has been entered, there is some time delay in the tilting effect. As a result, ride comfort drops considerably on short transition curves.

The Japanese system based on memorized track curve data, position and speed makes it possible to apply the tilting force just before the train enters a curve, thereby partly compensating for lateral forces on short transition curves. However, this system is so far based on pendulum principles so the centre of swing is relatively high, meaning that walking along train corridors can be hard. Another problem is that the train cannot be used on track for which there is no stored data unless the tilting mechanism is deactivated first.

Locating the centre of swing in a relatively high position also has a bearing on the lateral movement of the pantograph during tilting. In Japan, only some tilting cars have been designed to compensate for this lateral movement.

If the advantages of the two systems could be combined, ride comfort on curved track would be further improved. The answer is for Japanese and European railways to join forces to develop an almost perfect tilt mechanism. ■

Further Reading

The experimental train was reported in a special edition of *Elektrische Bahnen 8 Jahrgang, Heft3/4* (1937). It describes each of the four new locomotive types in detail and gives information on the test vehicle.

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