Breakthrough in Japanese Railways 4

Electric Trains and Japanese Technology

Asahi Mochizuki

Overview

1872 marked the start of commercial railway operations in Japan, nearly half a century after railways had started in the UK. However, electric railways did not appear until 1890 at an exhibition held in Ueno, 10 years after the start in Europe but only 2 years after Frank J. Sprague (1857–1934) started running electric streetcars in Richmond, USA, in 1888, which triggered the rapid spread of electric rolling stocks.

Although the introduction of electric railways in Japan was not far behind Europe and America, Japan could not design or build electric rolling stock. Some of the locomotives imported in the early stages were still in the development phase, so Japan acquired basic technologies by overcoming challenges and making incremental improvements. Japanese engineers also studied overseas and entered into partnerships with European and American manufacturers to learn the new technologies. By the 1930s, Japanese engineers had become adept at designing and building electric rolling stock. However, since the two World Wars made import of material and technologies difficult, Japan was forced to design and manufacture on its own. By the 1950s, Japan reached a technology level equal to that of Europe and the USA but was still behind in terms of speed. However, while Europe and America remained at a standstill, Japan went on to develop the shinkansen, contributing to electric railway technology and rail redevelopment worldwide.

Shift to Domestic Production in Japan

Around 1870, Japan was eagerly importing new technologies from the West to make life easier, and the social climate of Japan was accepting of new technologies. However, people did more than just use them—Japanese engineers were strongly motivated to study and create their own advances.

Western engineers were hired to both operate the new technologies and to train Japanese engineers. At the time, the government sent students overseas to learn the new technologies. In many cases they were sent abroad in conjunction with placing orders for imported products. While the overall number was small, they replaced foreign engineers on return to Japan.

Figure 1 Historical Acquisition of Technologies

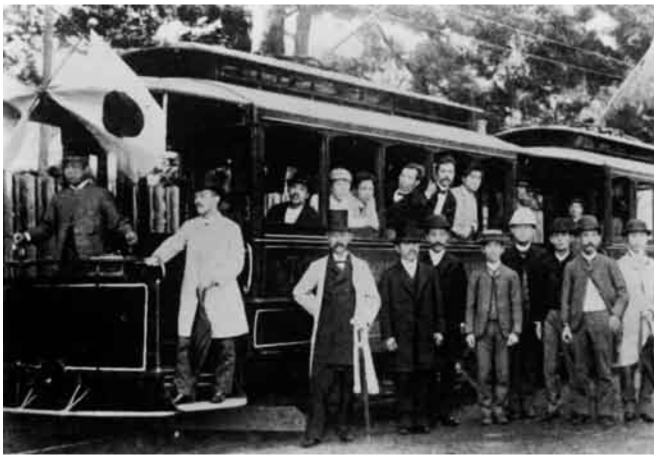
1870s	Buying and using products
1870s	Hiring Western specialists
From 1870s	Fostering engineers
1890s	Manufacturing by imitation
1900s	Manufacturing under license
1910s-1920s	Designing by imitation → Improvement on designs
1930s onward	Designing with own ideas

As Japanese started to educate the engineers, they also actively translated Western technical documents, spreading knowledge wider and producing an engineering cadre who naturally started making use of the knowledge and technologies they understood.

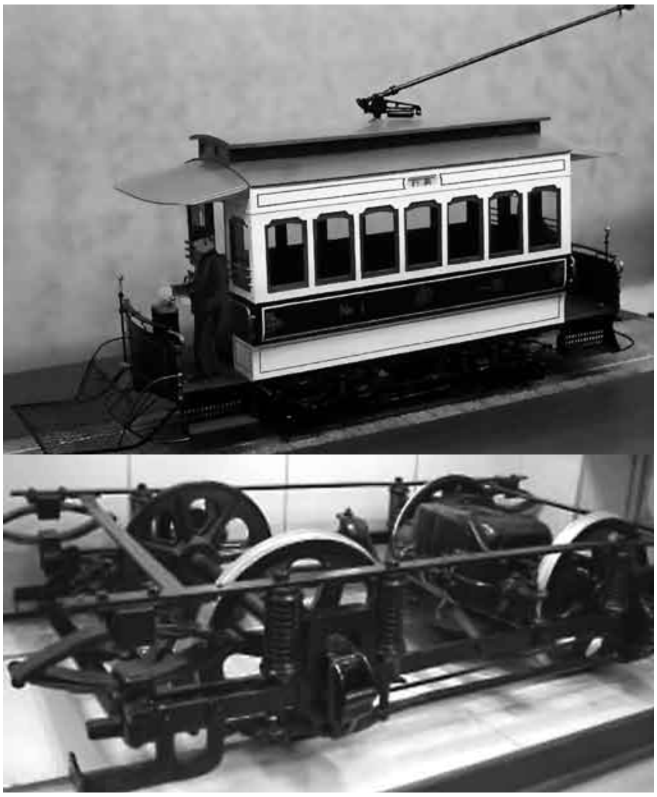
At that time, even imported passenger carriages and freight wagons had wooden bodies. Thus, it was only natural that Japanese, with a history of woodworking, were able to imitate these carriages from an early stage. However, locomotives, bogies, and wheel-sets continued to be imported.

It was 1893—about 20 years after the introduction of railways—when the first steam locomotives could be built by complete imitation at the Kobe Works. Full-scale manufacturing was launched in 1901. Production of steel—the main material of locomotives—started with the opening of the Yahata Steel Works.

About another 20 years would pass before Japanese designed and manufactured their own steam locomotives in 1914. By that time, more than 40 years had passed since the introduction of railways in Japan. The developments in Japanese railways can be expressed as shown in figure 1. While there are some slight differences, technologies for fields such as shipbuilding, civil engineering, and architecture were gained in a similar manner.



Sprague tram at industrial exhibition in Ueno, Tokyo (The Railway Museum)



Scale model (top) of tram and actual bogie and traction motor at The Railway Museum in Saitama Prefecture (The Railway Museum)

Introduction of Electric Rolling Stock Technologies

Electric traction started in Europe and the USA as tramcars and subway locomotives in the 1880s powered by 500/600 V DC.

However, the low-voltage DC feed made it difficult to develop electric locomotives with sufficiently high output to replace steam locomotives for hauling heavy passenger and freight trains, and to introduce electric traction on lines with steep grades and long tunnels where steam operation was difficult. Trials were made with high-voltage DC-motor, but commutation of DC motor did not go well, so AC feeds were developed but caused problems with control of speed and traction effort of AC motors. In addition, supply of three-phase AC through overhead lines and pantographs was complex and finally AC commutator motors (very similar to DC motors) were used at lower frequency. AC supply only became reliable and problem-free much later in the 20th century.

Many attempts were made using different current collection and power transmission methods for electric trams which started operation in 1881. However, Sprague found commercial success with a nose-suspension drive reduction gear method and a pole-pushed current collection method in 1888. The so-called Sprague system spread rapidly in the USA, followed by practical application for electric multiple units (EMUs) in 1897, leading to EMUs taking the railway world by storm.

Ichisuke Fujioka (1857–1918) studied electric engineering under professor William E. Ayrton (1847–1908) at the Imperial College of Engineering (predecessor of today's University of Tokyo Faculty of Engineering). He travelled to the USA in 1884 where he met Thomas Edison (1847–1931) and received advice on domestic manufacturing of electrical equipment.

Fujioka, who was Chief Engineer at Tokyo Electric Light (now Tokyo Electric Power Co., Inc), imported a Sprague tram in 1890, which he ran at an industrial exhibition in Ueno, Tokyo. Power was supplied from Tokyo Electric Light's power station.

Meanwhile, Imperial College of Engineering graduate Sakuro Tanabe (1861–1944), who had led the work on the Lake Biwa Canal, visited the USA in 1888 with Kyoto entrepreneur Bunpei Takagi just before completion of the canal. During their stay in the USA, they visited a hydroelectric power plant which was under development after an introduction by Sprague. On returning to Japan in 1891, Tanabe built the Keage Hydroelectric Power Plant using the Lake Biwa Canal. Takagi and others ran power from the plant to trams in Kyoto in 1895. He was president of the tram company and Fujioka oversaw technical areas, later becoming a technical instructor for electric railways throughout Japan.

Japan's first electric tramcars were 6-m long and 2-m wide with one bogie powered with one traction motor (550 V, 25 hp). The motor was by GE of the USA and the bogie was also American. The body was built in Japan. A traction motor and bogie are preserved at The Railway Museum in Saitama Prefecture.

Development and Domestic Production of Electric Rolling Stock

Trams also began running in Nagoya in 1898, followed by the Keihin Kyuko Daishi Line in 1899 and Tokyo and Osaka in 1903. Kobu Railway started running EMU trains in Tokyo in 1904 as the first multiple-unit-control operation. Kobu's EMUs became the predecessors of the government railways' EMUs, as the company was nationalized in 1906. Most of the electrical equipment and bogies were imported.

The EMUs on the Paris Metro opened in 1900 were also Sprague type, and the first were very similar to the EMUs in Japan at the time. In other words, trains running in the West and in Japan were at about the same technical level.

During these developments, Tanaka Engineering Works (predecessor of Toshiba) examined the imported technologies and started manufacture of traction motors, controllers, and bogies in 1899 for use on the Daishi Line electric railcars in 1901. Although domestic manufacture had started, most items were still imported perhaps because of production quality and capacity problems. Even so, domestic production started soon after trams started running in Japan.

As trams came into widespread use across Japan, suburban EMUs like those of Kobu Railway also became common in urban areas; Hanshin Electric Railway was electrified in 1905; Nankai Railway in 1907; Keihan Electric Railway, Hankyu Railway and others in 1910. The bogies and major electrical equipment were imported from General Electric (GE), Westinghouse, Siemens-Schuckert, and English Electric.

The electric locomotives had already been used in mines and in other excavations, but they were first used in main line operations in 1912 with Abt rack-and-pinion electric locomotives crossing the steeply graded Usui Pass. They were built by Allgemeine Elektrizitäts-Gesellschaft (AEG) of Germany, but lacked power and were prone to trouble because sufficiently reliable electric locomotive technology was not yet established in Europe. In conjunction with this order for electric locomotives, the government railways engineers studying in Germany conducted research into electric locomotives in 1909 along with overseeing production. In this way, many engineering graduates of the Imperial College of Engineering often studied abroad, moving between newly established electric railway companies and making technical selection of imports.

Meanwhile, Toshiba entered into a technical partnership with GE in 1909; Toyo Electric with English Electric in 1916; and Mitsubishi Electric with Westinghouse sometime before 1925, marking the start of domestic design of electric locomotives and EMUs.

The outbreak of WWI cut off imports from Europe and later from the USA too. However, rail passenger levels were rising and more trams and EMUs were needed, driving the start of domestic production.

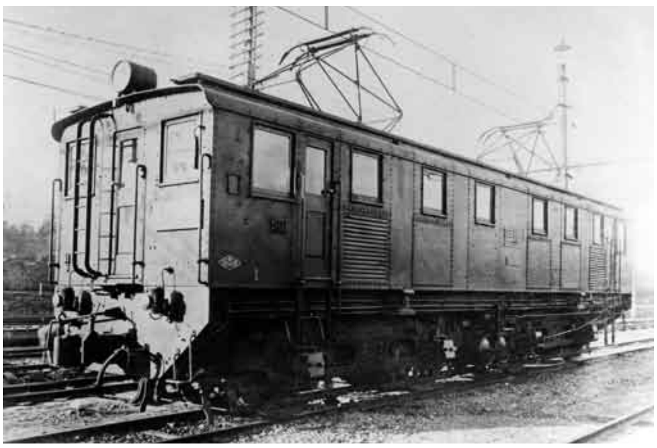
Manufacturing of traction motors started at the government railways Oi Works in 1916 by disassembling English Electric traction motors, making detailed drawings, and manufacturing exact copies. Engineers had previously acquired good technical skills through service repairs, so they reached the quality level of imports right from the start. In 6 years, 296 motors were built and most of the government railway's traction motors were ordered from Toshiba, Hitachi, and Toyo Electric by 1920.

The shift to domestic production of electric equipment for public trams was going forward at the time, but these were simply exact copies. Electric equipment of private-railway high-speed EMUs was comprised mostly of imports. The main reason was quality, but imports also cost less. While the government railways shifted to domestic equipment as part of national policy, the same logic did not always apply to private railways.

Domestic Production of Electric Locomotives

As mentioned, AEG electric locomotives were imported in 1912 to electrify the section of continuous steep grades between Yokokawa and Karuizawa. However, major design changes at manufacture resulted in many failures after the start of operations because electric locomotive technology was still not well established even in the West.

Locomotives were already equipped with electric brakes using either dynamic or regenerative braking, but neither was reliable. The frequent breakdowns resulted in many retrofits. From 1919 to 1922, four-axle electric locomotives, including traction motors, were designed by the government



Hitachi's Class ED15 was the first domestically built electric locomotive completed in 1924 and delivered to government railways in 1926
(The Railway Museum)

railways and manufactured at the Omiya Works by imitating imported three-axle locomotives, but stable operations were achieved through original modifications.

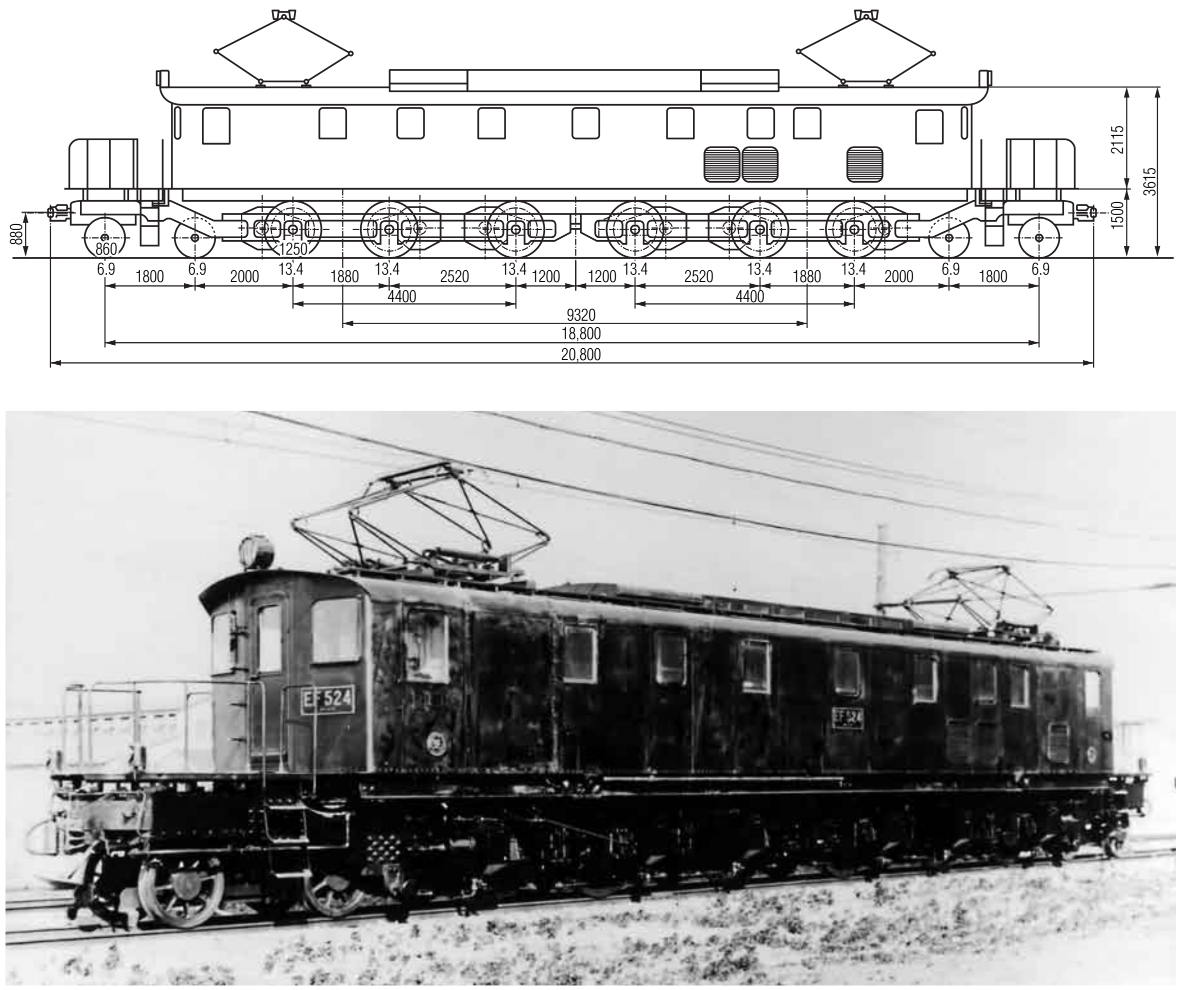
Operation of electric locomotives started on the Yokosuka and Tokaido main lines in 1925 with electrification of the Tokyo to Kozu section, but the locomotives were all imports mostly from English Electric but with some from GE, Westinghouse, and Brown Boveri. Early electric locomotives broke down so often that they had to be coupled with steam locomotives as a backup. To drive and maintain them, the Japanese railway engineers were forced to work painstakingly, and they said in later years, they were able to 'gain good knowledge of the technologies as a consequence'. If the imports had not broken down, engineers would simply have driven them and not looked closely at the detailed parts. When troubles occurred, the engineers from import agents could not satisfactorily deal with them and railway engineers conducted repairs and made modifications so that failures would not reoccur. In this way they naturally came to be intimate with the technologies.

The GE locomotives were the most reliable but were the most expensive. Hitachi engineers had been closely observing locomotives made by American manufacturers and completed the company's own Class ED15 electric locomotive in 1924. It replaced American electric locomotives in 1926 and was more reliable.

With this opportunity, Japanese builders started working on their own designs but the government railways was worried about the diverse range of designs. They met with the Japanese manufacturers and took the lead in promoting a standardized design of electric locomotives. Following this policy, Hitachi, Toshiba (which had a technical partnership with GE) and Mitsubishi Electric (which had technical partnership with Westinghouse) and others conducted joint design. Their first Class EF52 electric locomotive was completed in 1928 under the leadership of government railway's Kiichi Asakura (1883–1978).

Asakura was a famous designer of Japanese steam

Figure 2 First Domestically Produced Jointly Designed Standardized Class EF52 Electric Locomotive



EF52 Electric Locomotive (The Railway Museum)

locomotives, but he observed electric locomotives for 2 years in Europe and America. He oversaw building of Japanese electric locomotives, realizing that the nose-suspension drive and leading bogies had advantages over other systems. Hitachi's Seiji Mitsuida, a production engineer participating in the joint design, observed American railway companies and manufacturers in 1926 on referral from Asakura. Observation at European and American manufacturers was limited but those manufacturers accepting government railway's engineers treated him favourably. Since Mitsuida laboured over designing and building an original electric locomotive before going to the USA, he was able to learn the essence of design. Mitsubishi Electric's Saneyoshi Hirota was another participant in the joint development who also visited the USA in 1928 where he made observations mainly at Westinghouse.

Full-scale Production and Standardization of Electric Equipment for Electric Rolling Stock

As previously mentioned, imports of products such as electric equipment were cut off as a result of World War I while demand for EMUs increased, creating a need for full-scale domestic production, as was happening for trams. After the war, imported EMUs were often used by private railways for intercity and suburban trains due to their high speed and reliability.

The 1920s saw the production of many Japanese-designed traction motors and controllers but most were Western-designed or derived from Western-designed products. The basic design for EMU multiple unit control, automatic traction control, electromagnetic switch control, and other areas was American.

As an example, a private railway engineer who had returned from studying abroad intended to use GE products for EMUs on a trunk line with continuous steep grades constructed between Osaka and Ise around 1930. However, Mitsubishi Electric brought the full influence of the Mitsubishi Group to bear, demanding domestic production and use of Mitsubishi Electric products. Hirota, a designer of traction motors for Mitsubishi Electric was a member of the government railways' joint design team and succeeded in designing the Mitsubishi traction motor for the Osaka-Ise high-speed EMUs without any problems. However, he did not succeed in designing the controller. Since it used electric braking, the design had to be implemented using technology from Westinghouse who had a partnership with Mitsubishi Electric. Many problems after the start of operations forced repeated improvements, giving Hirota and Kintetsu's (the railway company) engineers intimate knowledge of the technology.

Meanwhile, the government railways raised the feed voltage from 600 to 1200 V in 1914. The trains' electrical layouts were made in the USA, and the breakers on these circuits were connected in series using two devices. This seemed like a stopgap measure, and was not a technology to be admired.

American electric railway track using trams or EMU even today totals more than 300 km at 1500 V DC. Japan, on the other hand, has more than 10,000 km of such track. In the USA, direct current is mainly for urban transport, and is mostly 600 to 750 V. American railways using 1500 V DC today still struggle to handle the high voltage, so high-voltage direct current technology with a sufficient record for EMUs probably did not exist in the USA at the time.

With 1500 V adoption in Japan in 1923, local modifications were added. Japanese original designs were also developed.

The different timing of equipment introductions and different manufacturing methods made handling and maintenance complex, so standardization by joint design started around 1925. The first target of standardization was EMU traction motors. Toshiba, Hitachi, and Toyo Electric started building traction motors for government railways in 1920 but differences between makers caused problems with coupling rolling stocks with traction motors with different characteristics. Moreover, the different designs, lack of detailed drawings, different parts, etc., caused headaches at inspection and repair.

To solve these problems, government railways took the lead in standardization by manufacturing companies, which included some companies such as Toshiba, Hitachi, Toyo Electric, and Mitsubishi Electric, that were involved in the joint designing of traction motors. There were some companies which had partnerships with GE, Westinghouse, and English Electric, while some others were using their own unique designs. This made provision of detailed structural diagrams difficult. Moreover, all electrical manufacturers tended to be more secretive about their designs than manufacturers of steam locomotives, so they would not provide detailed structural diagrams. As a consequence, the government railways had problems determining the best design and none of the Japanese companies wanted to be subject to a determination about which company was superior. In the end, government railways decided only one joint design would be built jointly by four companies including Mitsubishi. The individual companies all showed reservations about carrying out joint design. Government railways, however, insisted on unified design, and it went full out in pushing the project forward as it would benefit domestic production. The first product was the 100-kW class MT15 traction motor. Design was based on technologies of developed nations, but it proved to be a Japanese-original design achieved by sifting through the technologies of the individual companies.

EMU controller technology is unique, and unlike traction motors, it requires usage experience even when just copying other designs. As a result, no unique Japanese designs were built for many years and reliance on imports lasted a long time. However, licensed production did lead to original design and manufacturing in 1923 and became standardized in 1931 when the CS5 standard controller was built by Toshiba, Hitachi, Toyo Electric, Mitsubishi Electric, and Kawasaki Heavy Industries based on technologies from GE, Westinghouse, and English Electric. This controller remained in production for 20 years, indicating the success of the design.

At this time, private railways were often using imports. However, once they started using domestically manufactured products, private railways tended to continuously order from specific companies, which held back standardization.

Joint-design System

Joint design had big benefits for government railways but there were worries that it would not produce the best designs and might impede competition and creativity. While described as 'joint design' there was competition at the basic design stage when the manufacturer with the best proposal was selected. Competition was thus fierce, and optimal proposals were created. Manufacturers were able to make proposals that were to their benefit even if they were not chosen for the base design. Every now and then, such proposals were adopted by the JNR leader. Also, sometimes manufacturers were able to access technologies of other participating companies, thereby benefiting from increased quality while securing some assured level of orders instead of dominant market share. So none of the manufacturers avoided participation. Many of the engineers from manufacturers felt that, by participating in joint design meetings and competing with each other, their technical levels were improved. Since new designs were needed periodically, standardization was not a major hindrance to technical progress.

This joint design system had benefits for both the operator and manufacturers. So, while there was some indecision at the change from JNR to JR with privatization, the system is followed even today, contributing greatly to technical progress. Private railways are often used as the test venue for manufacturers, but they benefit by gaining access to government railways' high-quality standard equipment.

However, the success of the joint design system is greatly affected by the qualifications of the project leader. The design leader determines the merits of the individual companies' proposals and requires a sense of balance to pick and choose the advantages of companies. Thus, design engineers are fostered from those with maintenance worksite experience and experience in design improvement, such as pursuing causes of and dealing with factors such as breakdowns.

Development of Original Japanese Technologies

World War II and the immediate pre and postwar years were blanks in terms of technical development, which restarted again around 1950 based on Western technology.

The Series 151 DC EMU running 556 km between Tokyo and Osaka in 6.5 hours from 1958 was the culmination of new technologies developed by private railways and manufacturers from around 1950 (The Railway Museum)

First mass-produced Class ED70 AC locomotive in 1957
(A Hundred Years of Progress in JNR Rolling Stock)

However, the rebirth was not in the form of imports; rather, original designs created by using select information gained from the West through technical partnerships progressed rapidly. As one example, JNR Chief Engineer Hideo Shima (1901–98) took the lead in ongoing research into high-speed bogies, leading to rapid development of EMUs for mass transport of commuters as well as long-distance high-speed intercity travel.

The main technologies were two motorized cars making up one unit for high acceleration and deceleration, use of electric brakes from high speed to full stop, and long train sets giving comfortable rides thanks to bogie-mounted traction motors and air springs. Such base technologies supported Japan's unique railway system form where EMUs are the main force of passenger transport, forming the foundation for development in a country that has one of the largest numbers of EMUs in the world.

The West had been using AC electrification from the early 1900s, but it was mainly low-frequency AC. When commercial frequency AC electrification was put to practical use in 1951, rolling stock with AC traction came into practical use. Japan started research into AC traction in 1953 and considered importing European technologies but failed negotiations forced domestic development. A prototype AC electric locomotive with mercury rectifiers was built in 1955, and full-scale commercial operation of AC electric locomotives began in 1957.

Electric locomotives with mercury rectifiers were mainstream at first but silicon diodes developed in 1958 were soon in use in EMUs. Dual AC/DC EMUs were being manufactured in 1960 and came into commercial service in 1961. AC-DC dual system EMUs were deployed rapidly across Japan. The development of technologies for power semiconductors was achieved at almost the same time as in Europe. However, Japanese advances in semiconductor thyristor later outstripped the West. With development of semiconductor thyristor, chopper control for DC EMUs was quickly developed, and electric dynamic braking switched to regenerative braking. Practical use started with subways that could handle stop braking with relatively small-capacity choppers.

Concurrently, JNR engineer Yuji Kawazoe (1933–) worked as leader in replacing AC electric locomotive tap changers with thyristor phase control to achieve contactless continuous control in 1965. Furthermore, an AC electric locomotive with external commutating converters that could be used for AC regenerative braking on sharp grades was put into commercial service in 1968.

Technologies to use these power semiconductors in electric rolling stock were developed completely through original Japanese technologies. However, semiconductor developments, in many aspects, were advanced by the needs of electric rolling stock. As gate turn off (GTO) thyristor was developed, variable voltage variable frequency (VVVF) inverters came into practical use for DC EMUs, three-phase asynchronous motors appeared, and EMU systems became mostly contactless, greatly reducing maintenance. Pulse width modulation (PWM) converters were developed for shinkansen and other AC EMUs, and AC regenerative braking could be used freely as self-excited converters, making shinkansen much lighter.

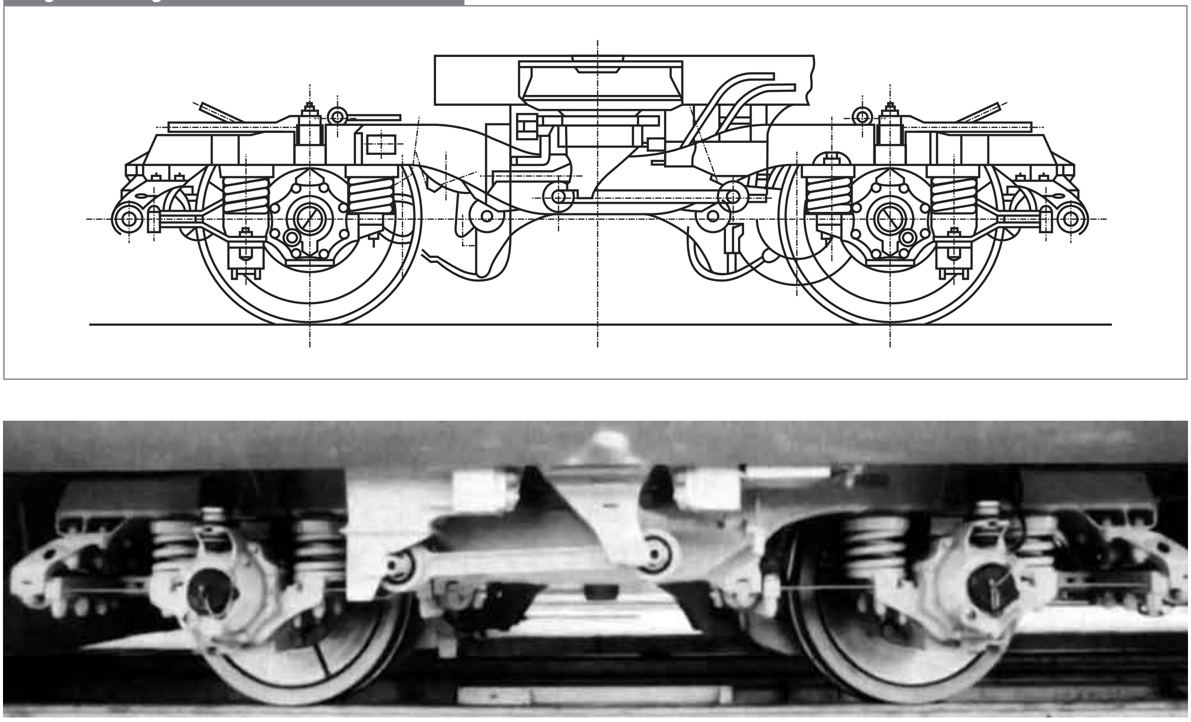
Synchronous motors and induction motors were used in Europe from the age of thyristor because commutation, such as with TVG-PSE DC motors, was not good and maintenance was a heavy chore. Also, Commutation was essentially difficult with German and other AC commutator motors. In Japan, the good quality of commutators and brushes enabled delays until GTO thyristor was developed; Germany put PWM converters into use with thyristor before Japan, but experienced many problems that were finally solved using Japanese GTO thyristor.

Development of Technologies for Higher Speeds

Main lines connecting Japan's major cities were mostly completed by the 1950s, but routing through the many mountainous areas, resulted in many steep grades and tight curves. Because of high population density, there were many level crossings. The many level crossings required a train emergency braking distance of 600 m.

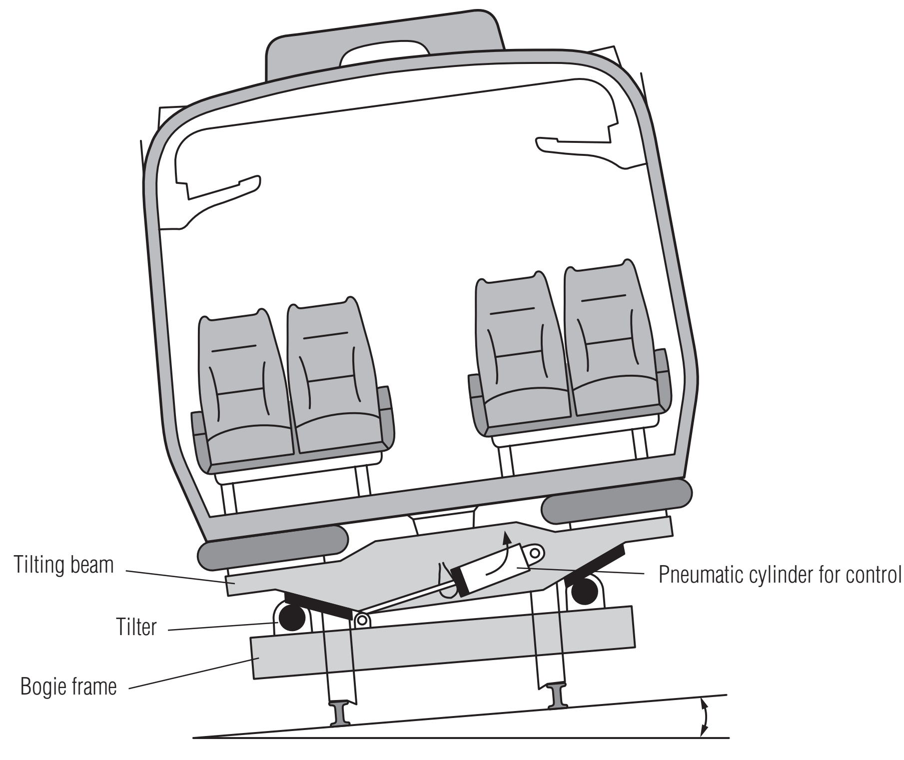
As a result, speed could only be increased to about 120 km/h and today's maximum speed on some sections without level crossings is still 160 km/h. The shinkansen achieved high-speed operation by using gentle curves and gradients, and by eliminating level crossings. When the shinkansen was being planned, JNR engineers received some information on the results of 331 km/h high-speed tests in France in 1955, and technical development for running stability at high speed was diligently addressed. In 1947, Hideo Shima established a forward-looking study group on high-speed bogie vibration. In 1948, pre-war EMU designs reached maximum speeds of 119 km/h, and a record of 145 km/h was set using new EMUs in 1957. In 1959, Series 151 EMUs reached maximum speeds of 163 km/h, and a world record

Figure 3 Bogie for Series 0 Shinkansen



Shinkansen EMU IS-type bogie (JNR Rolling Stock Design Office)

Figure 4 Example of Controlled Tilt (JR Shikoku Series 2000)



Series 381 *Shinano* limited express. This series was the first tilting EMU (A Hundred Years of Progress in JNR Rolling Stock)

for narrow gauge of 175 km/h was set in 1960. Those tests provided the fundamental data for later development of high-speed shinkansen bogies.

At the same time as high-speed tests on conventional lines, scale-model tests started in 1957 at the Railway Technical Research Institute. The difficulty of securing stable running at high speeds was confirmed, and full-scale high-speed rolling-stock test equipment that could handle speeds up to 250 km/h was completed in 1959. Basic tests started in 1960 using full-scale bogies with changeable structures and conditions. As a result, various bogies were designed in 1962 and were given a bench test, followed by a test on shinkansen test track, giving good stability results at speeds up to 250 km/h.

Work started on design of mass-produced shinkansen bogies in 1963. The structure was proposed by JNR engineer Masahiko Ishizawa (1924–) and was named the IS-type bogie. It continued in production until the 1980s.

Shinkansen technical successes were mainly in bogie technology and AC electric car technology.

Meanwhile, it was proving more difficult to increase speeds on conventional narrow-gauge lines due to grades and curves that could not be reconfigured easily. The solution was high-output pendulum EMUs that could travel through curves without speed reductions. Tests cars were built in 1970 followed by introduction of Class 381 pendulum EMUs on the Chuo West Line in 1973. Europe was using active tilt control. However, due to that, introduction of pendulum EMUs was delayed in Europe. Japan adopted natural pendulum by centrifugal force first. Active control was added later, eliminating poor ride comfort due to delayed tilt and contributing to speed increases on conventional lines across Japan.

More recently, body inclination using simple air springs has been used on both the Tokaido Shinkansen and some narrow-gauge lines.

Conclusion

Electric rolling stock was developed in the West from the late 19th century through the early 20th century and was soon being built in Japan. These developments came about due to people such as electric engineer Ichisuke Fujioka and entrepreneur Bunpei Takagi being greatly influenced by their experiences in the USA. Later advances came from visionaries like Kiichi Asakura and Hideo Shima who, despite being a steam locomotive designer, actively learned Western electric rolling stock technology, brought together the technology of the domestic manufacturers, and started domestic production to build Japan's technology base and finally give birth to the shinkansen.

National railways are disappearing in countries across the world and countries other than Japan with advanced railway technology where infrastructure and rolling stock are operated together are becoming scarce. As a result, there are high expectations for Japanese railway engineers meeting the conditions for advancing railway technology. ■

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Mr Mochizuki is a Consultant at Japan Railway Rolling Stock & Machinery Association. He joined JNR in 1960, where he was involved in rolling stock maintenance, and designing EMUs, shinkansen, and electric rolling stocks. Subsequently, he served as a Chief Engineer Transportation System Division at Toshiba Corporation prior to assuming his current position.