Breakthrough in Japanese Railways 7

Conventional Line Speed Increases and Development of Shinkansen

Asahi Mochizuki

This article explains some technical developments in speed increase until the opening of the shinkansen in 1964, centred on lines belonging to JR companies (formerly Japanese National Railways or JNR).

Increasing Speeds on Conventional Lines

Non-shinkansen lines (often including non-JR railways) in Japan are commonly called conventional lines. Japan is a mountainous country, and most conventional lines were built to the narrow gauge of 1067 mm, but some private lines use standard gauge (1435 mm). When trying to increase operating speeds in the era of stream-hauled trains, narrow gauge proved to have intrinsic disadvantages and the many curves and grades in Japan's mountainous areas also hampered speed increase.

Against this background, electric trains—especially electric multiple units (EMUs)—seems to offer the greatest potential for increasing speeds, because the distributed powered axles along the train length had advantages in reducing axle load while increasing tractive effort as a whole. Efforts were made in electrification of railways for that reason, but there were few developments on major trunk lines before World War II at the request of the military. As a consequence, major speed increases were only achieved on a wide scale as postwar electrification proceeded.

Speed constraints on conventional lines

Trains on conventional railways (including both JR and non-JR lines) face the constraint of a maximum emergency braking distance of 600 m. In the early days, this distance was considered the distance at which signals could be surely seen by train drivers. But today it is to ensure the ability of a train to stop in an emergency on a line with level crossings. This 600-m limit imposes a maximum speed of 130 km/h due to physical constraints such as loss of adhesion between steel wheels and rails at emergency braking. On lines without level crossings, maximum speeds up to 160 km/h are permitted on an exceptional basis. Europe does not have such constraints and 160 km/h is the normal maximum operating speed on non-high-speed lines.

Increasing speeds on conventional lines

In a nutshell, the history of railway technology is the history of increased speeds and enhanced transport capacity. Looking at the example of the Tokaido Line, Japan's main trunk line, many modifications were constantly being made to shorten the travel time between Tokyo and Osaka. Even so, the maximum speed up to the 1950s was 95 km/h. However, electrification toward the end of this era made it possible to shorten journey times without increasing maximum speed (Figure 1).

The limiting factors were the tractive power of steam and the weak ground under the roadbed, which limited maximum axle loads. For comparison, on the standard-gauge South Manchurian Railway, operating speed of 110 km/h was attained by express trains built in 1934 using Japanese technology. Some speed increase with electric locomotives was possible by electrification, but electrification was not popular for various reasons.

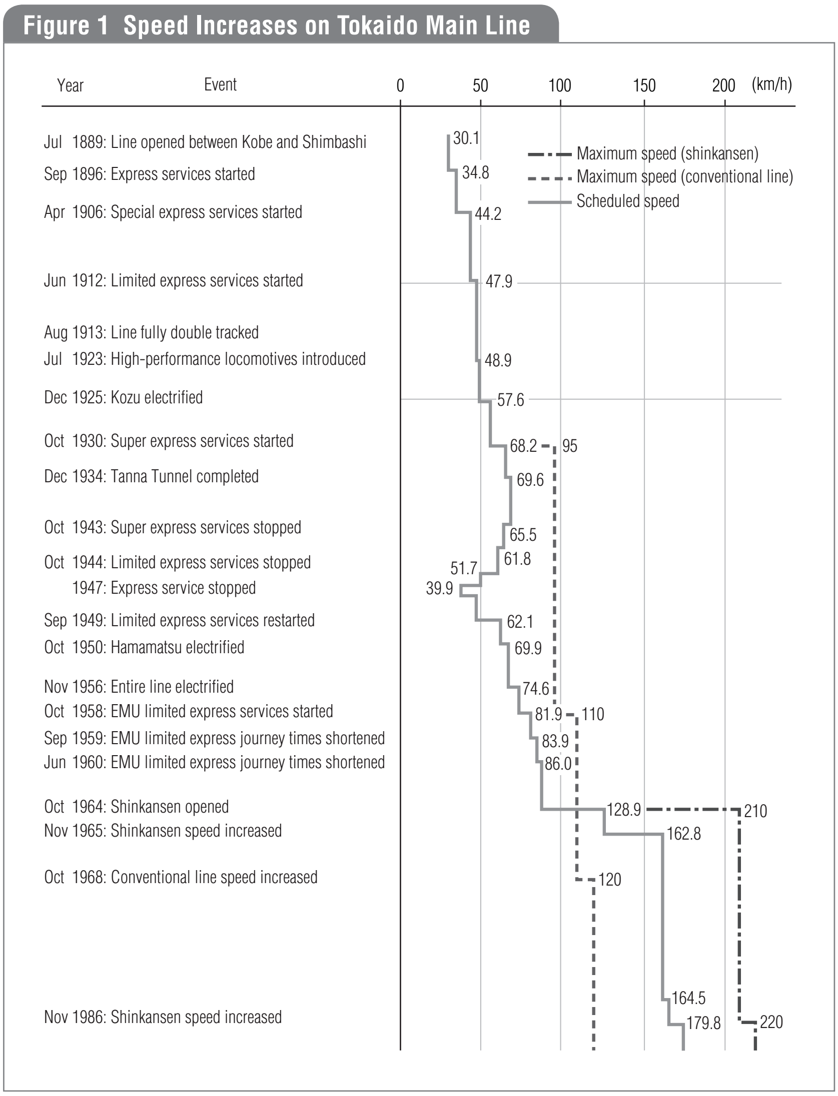
EMUs, which were mainly used for commuter traffic in those days, ran short distances and stopped at many stations, so increasing maximum speed had little effect on journey times. However, in the 1930s, government railways competed with private railways in a contest of increased speeds. After WWII, in the late 1950s, the influence of American technologies developed for PCC car finally reached Japan, and improvements were made mainly in acceleration and deceleration. Such new technologies, coupled with the advantage of light axle load, contributed to the development of high-speed EMUs for intercity services, reaching maximum speeds of 110 km/h first and then 120 km/h.

With an eye to the future, JNR's chief mechanical engineer Hideo Shima (1901–98) established a study group on high-speed bogie vibration in 1947 and started research into speed increases. Shima was a specialist in steam locomotive design. He believed that it would be difficult to increase speeds of loco-hauled trains with their heavy axle loads even on standard gauge tracks due to Japan's topographical and geological nature. He realized that increasing the speed of EMUs with light axles was the key, and started work on developing high-speed bogies for EMUs.

In 1948, a 1930s *Moha* 52 EMU reached a maximum speed of 119 km/h and then a new EMU belonging to Odakyu Electric Railway set a speed record of 145 km/h on the Tokaido main line in 1957. In 1959, a test run using Series 151 EMU reached 163 km/h, followed by a high-speed test car setting a narrow-gauge world record of 175 km/h in 1960. The results of research into high-speed bogies were utilized in developing high-speed intercity EMUs such as Series 151, and also became the development foundation for shinkansen high-speed bogies.

The Series 151 EMU, which attained 163 km/h in 1959, was used for limited express services between Tokyo and Osaka. Inaugurated in 1958, it ran 556 km between the two cities in 6.5 hours. This epoch-making EMU was welcomed by society as a whole and had a major impact on development of the shinkansen.

Figure 1 Speed Increases on Tokaido Main Line



Measures to increase speed of conventional lines

The success of the long-distance EMU service between Tokyo and Osaka spread to other intercity routes across Japan. Many of those were achieved thanks to expansion of main line electrification. Much of the new main-line electrification used alternation current (AC), so many long-distance dual-current EMUs were built to run through both AC (20 kV, 50/60 Hz) and DC (1.5 kV) sections.

Maximum speeds reached 120 km/h by the late 1960s, but these trains had almost reached their limits in terms of the constraint of emergency braking distances of less than 600 m. The maximum speed could only be increased to 130 km, even using anti-slip re-adhesion techniques. Later running tests by the Railway Technical Research Institute

Kumoya 93 High-speed Testing Car that Set a Record of 175 km/h (100 Years of JNR Rolling Stock)

Moha 52 EMU Produced in 1936 (100 Years of JNR Rolling Stock)

481 Series AC-DC Limited Express EMU (100 Years of JNR Rolling Stock)

(RTRI) and JR Shikoku verified that maximum speeds up 160 km/h were possible using rail braking, which were common in the USA and Europe at that time, but rail braking was not put to practical use in Japan for various reasons.

Japanese railways are characterized by many curves and grades, so increasing the maximum speed was ineffective in reducing travel time on most inter city routes. To reduce travel times, the speed in curves and on grades had to be increased, not the maximum speed. As a result, the development of tilting trains started in the late 1960s.

Development of Shinkansen

Measure to increase capacity on Tokaido main line

The rapid postwar recovery led to increasing traffic volumes, and insufficient rail transport capacity soon became major bottlenecks for Japan's economic development. Above all, by 1955, the Tokaido main line was facing such severe lack of capacity that another double-track was thought to be necessary.

A committee was created in 1956 to investigate how to increase capacity quickly, and measures such as quadruple tracking or building a new line were discussed. Opinions were split, and the easier measure of adding track held the advantage. However, decision by Shinji Sogo (1884–1981, appointed JNR President in 1955) to throw out the old concept and create a more rational system led to favouring construction of a new separate line.

Ideas for the Tokaido Shinkansen

The quickest and most economical way of building a new line along the Tokaido route was to utilize the land purchased and partially constructed tunnels for the so-called 'bullet train' project abandoned in 1943.

The outline of 'bullet train' plan is as follows:
The preliminary survey started in 1938. Construction specifications decided in 1941 settled on building a double-track with a gauge of 1435 mm, minimum curve radius of 2500 m, maximum grade of 10 ‰, maximum axle load of 28 tonnes, and 60 kg/m or heavier rails. Partial electrification at 3 kV dc was planned. The rolling stock gauge (loading gauge) was set at maximum height of 4800 mm and maximum width of 3400 mm. All trains were to be hauled by locomotives, running between Tokyo and Osaka in 4.5 hours at speeds up to 200 km/h.

Purchase of land started in 1939, and tunnel construction started in 1941. Construction was abandoned in 1943 due to worsening war situations.

Sogo proposed construction of a high-speed new line in 1957, and the government set up a Ministry of Transport (MOT) panel to investigate the idea. Around the same time, RTRI presented a lecture on the technical feasibility of rail travel between Tokyo and Osaka in 3 hours, and awareness of high-speed rail spread to the public.

The MOT panel conducted detailed deliberation of the high-speed new line, and the shinkansen plan was finalized in 1958. It followed the prewar bullet train project in many aspects, including the route and technical specifications such as 1435-mm gauge track, minimum curve radius of 2500 m, and maximum grade of 10 ‰. The new plan targeted 3-hour journeys between Tokyo and Osaka using EMU trains on an AC-electrified track. The construction period was 5 years. The framework was approved by the Cabinet and the plan was put into action in 1959. JNR set up a committee in 1958 led by Hideo Shima, who was appointed to JNR Vice President for Enginnering in 1955, to investigate construction standards that were given provisional MOT approval in 1960 and officially adopted in 1962. Construction started in 1959, and the Tokaido Shinkansen was completed in 1964.

Sogo did more than just decide on the construction of a railway with a new system. While not an engineer, he had excellent knowledge of technical subjects, and he made

New RTRI building Completed in 1959 (RTRI)

Shinkansen Test EMU and JNR President Sogo
(History of Technical Development of Tokaido Shinkansen EMU)

the decision in 1956 to provide massive funding to the RTRI to provide better research environment. One of the results was the aforementioned lecture, which is thought to have garnered great support for Sogo's decision.

As an aside, two German high-speed test train cars are famous for having reached 210 km/h in 1903. Those were special test cars that collected three-phase AC power from three pantographs, and the rotating speed of 3-phase asynchronous motors was controlled by changing the frequency at substations. The system did not come into practical use due to technical requirements, but achieving speeds in excess of 200 km/h at such an early date was revolutionary. While it may be only a coincidence, Yasujiro Shima, leading mechanical engineer of Japanese government railways, was at the test runs. Perhaps the prewar bullet train project headed by Shima was influenced by his witnessing the tests and it is fitting that it was his son JNR Chief Engineer Hideo Shima who was responsible for building the Tokaido Shinkansen running at 200 km/h some 60 years later.

Shinkansen Technical Issues and their Solutions

While 160 km/h was a common speed in North America and Europe, there were worries about speeds in excess of 200 km/h in those countries. Although the German AC powered test trains described above reached 210 km/h, it was a struggle to overcome the technical barriers. Another test train set a record of 331 km/h in France in 1955, but limitations pertaining to stable running and power collection performance were highlighted. We can assume that challenging technical innovations were thought to be necessary to go any faster.

Aeroplanes and automobile expressways were also developing rapidly during this time period and the popular feeling was that the age of rail was coming to an end, so the motivation to seek innovations in railway technology could have been declining.

Construction of the Tokaido Shinkansen started amidst this social background. There was no technology anywhere in the world offering day-to-day stable operations at speeds greater than 200 km/h, although the Japanese engineers had some vague knowledge of the results of the French high-speed tests. They rose to challenge of exploring the unknown 'territory' of high-speed operations. The following looks at their major accomplishments on the path to solving the many problems.

Issues with traction power and axle load

The basic issues for high-speed operation are securing power source and transmission of tractive effort. Running resistance increases at roughly the square of speed, requiring enormous power for running faster trains. Adhesion between rails and driving wheels transmitting the tractive effort also becomes a problem. With a conventional loco-hauled train, this can be overcome by making the locomotive heavier but the high axle loads of heavy locomotives require solid and sturdy tracks that are expensive to build. Building such tracks on the weak ground along the Tokaido Shinkansen would have been extremely difficult.

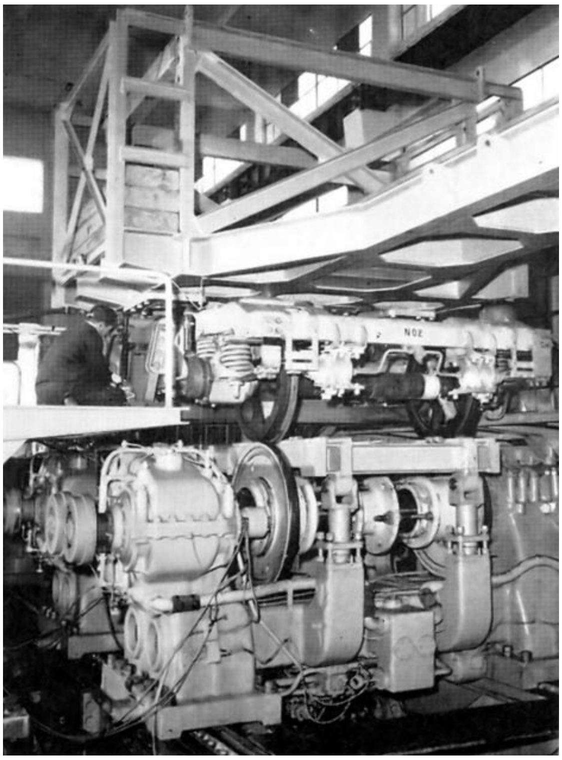
AC electrification was a solution for providing trains with greater power. Electric power supplied at very high voltage could greatly reduce the current required for high-speed running, facilitating power collection by trains. Japan had just acquired the technology of AC electrification on its own account in the late 1950s.

The solution to heave axle loads was switching to EMUs with distributed motive power along the train length producing high traction effort and lower axle loads. Advances in semiconductors for power supply during the late 1950s supported development of AC EMU trains.

Securing high-speed running stability

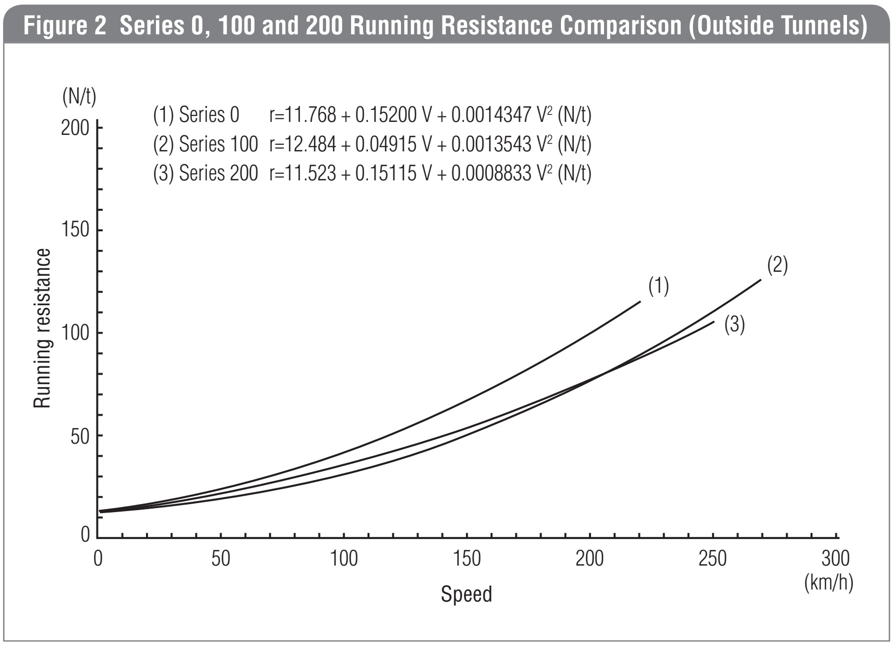
The issue of securing running stability was behind the difficulty in reaching 210 km/h with the German test train in 1903 so track and bogie modifications were made to conquer hunting oscillation. The 1955 high-speed tests in France also experienced serious hunting oscillation, leaving the track very deformed after the test train had passed by.

In light of these tests, some technology was needed


Shinkansen Bogie Tests on a Rolling Stock Test Stand (RTRI)

to prevent hunting oscillation of shinkansen running at commercial speeds and this proved to be the most important issue in developing shinkansen technology. Hunting oscillation is inevitable with railway cars due to their structure, but it can be avoided if the speed range in which hunting occurs could be made higher than operating speeds. However, the methods known at that time was not appropriate for high-speed bogie design.

Figure 2 Series 0, 100 and 200 Running Resistance Comparison (Outside Tunnels)



A main theme of the study group on high-speed bogie vibration was bogie hunting, and research was already in progress. Theoretical analysis and experiments were done mainly by aeronautical engineers who had transferred to the RTRI from former imperial navy research labs. Bogies were designed and redesigned for repeated tests using prototype bogies on a test stand at RTRI and prototype rolling stock on shinkansen test tracks. As a result, hunting was not a problem when the shinkansen opened at maximum operating speeds of 210 km/h. However, some signs of hunting were seen as wheels became worn so great attention was paid to maintenance of running gear. Running maintenance requires frequent and troublesome works, so research into preventing hunting continued to enable future speed increases.

Running resistance of high-speed trains

Train resistance is a key factor in determining train performance. It includes running resistance, grade resistance, curve resistance, and acceleration resistance. But the most fundamental is running resistance on straight, flat lines. Running resistance is composed of mechanical resistance and air resistance, so it is most affected by speed. Air resistance (drag) in particular is nearly proportional to the square of speed, so the value of running resistance at high-speed operations is important in train performance.

However, running resistance at speeds above 200 km/h was unknown territory at that time. Since train performance cannot be designed when running resistance is unknown, realistic estimates were needed. In 1958, the shinkansen study group looked at RTRI running resistance tests using train mock-ups, investigations by JNR rolling-stock designer Shuichi Sawano (1918–) into SNCF's 1955 test running at 331 km/h using electric locomotives each hauling 3 carriages, and results from tests using Odakyu Electric Railway's Type SE EMU.

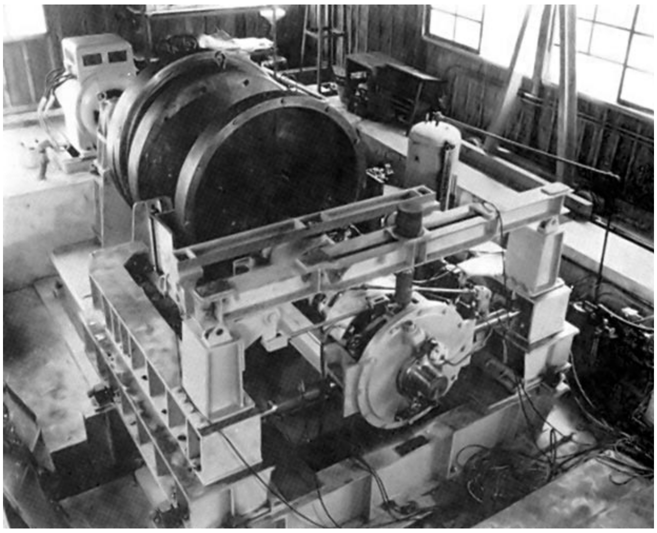
Qualitative trends were found from mock-up tests, but there were no quantitative data, so tentative values were fixed on estimation. Values deduced from running tests of Series 80 EMUs between 1952 and 1956 were also used. Based on these estimates and tests, the rated power of the traction motors was decided, and test cars were built. By luck and good judgment, the results from the test cars were close to the formula estimates and a rough value of 10 kg/ton was used when running at 200 km/h in the open (outside tunnel). When the final trains were completed, the running resistance was surveyed frequently to improve the accuracy of the formula, including running in tunnels.

Adhesion coefficient of high-speed trains

Adhesion is the fictional grip which transfers acceleration or deceleration force between wheels and rails, and is normally only about 30% in locomotives but is almost 100% in gears. Consequently, adhesion is an important element in locomotive traction.

The planned shinkansen EMU consisted of powered cars only with low acceleration and deceleration. As a result, adhesion was not thought to be a problem, although the adhesion coefficient when braking from high speed was unknown and caused some concern. It is one of the basic factors for setting train deceleration and determining the length of deceleration sections in the automatic train control system. However, in the late 1950s, there was little reliable information on the adhesion coefficient at high speeds. The RTRI could only find data from overseas for speeds at about 160 km/h, and there were only two or three examples of guesses for the 200 km/h or greater range.

To solve the problem, the RTRI built a full-scale adhesion tester in 1960. A pair of huge rotating wheels were used as



Adhesion Tester (RTRI)

a substitute for rails. The test data generally showed higher adhesion than actual rolling stock, so researchers believed it could not be applied to rolling stock design and train operation planning. Therefore, an adhesion coefficient (μ) of 13.6/(V+85) was adopted (where V is train speed) as the planned value for prototype shinkansen rolling stock; the value was halved under wet conditions, taking into account conventional test formulas and empirical data.

Although the ATC system was based on the adhesion formula, the high risk of a disaster if the wheels do slide for some reason resulted in the installation of skid detectors on all axles. Contrary to expectations, the prototypes did skid frequently on the test track in 1962, so the wheel skid protection device was improved for the mass-production cars, and tread cleaners were installed on every wheel.

Rust remained on the surface of rails at the start of shinkansen operations, and skidding frequently occurred. It took many years before most it was eliminated. Skidding almost never occurred about ten years later.

Research on adhesion was actively carried out in development of the next generation of rolling stock as frequent sliding at the start of shinkansen operation unexpectedly occurred. The biggest success was in quantifying to a certain extent the relationship between wheel and rail surface roughness and adhesion coefficient. The wet state at each wheel position of long trains was also identified. Those successes would be applied from the late 1980s.

High-capacity power supply

Long, high-speed trains need a reliable high-capacity power supply—a problem that was easily solved by adopting the increasingly popular AC electrification technology. The feed voltage was set at 25 kV, which was the global standard at that time. The early prewar plans for the bullet train called for 3 kV DC, which was inadequate for longer, heavier trains, making power collection difficult. A 3 kV DC system would also suffer large voltage drop, requiring more substations at closer intervals. Italy runs high-speed trains at 3 kV DC but is switching to AC and Russia has chosen AC for high-speed lines rather than 3 kV DC.

Electric power for Tokaido Shinkansen is provided by local power companies, using 50 Hz along approximately 180 km from Tokyo, and 60 Hz for the remaining 370 km. Deliberation was made as to whether cars should use both 50 Hz and 60 Hz or if power supply in the 50 Hz area should be converted to 60 Hz. As using both would make the cars heavier and cost more with the technology of the time, the whole line was unified at 60 Hz taking future increase in the number of trains into consideration. For that reason, frequency converters are installed along the line at the Tokyo side.

Today, rolling stock that uses both 50 Hz and 60 Hz is designed and produced for use on the Hokuriku Shinkansen. The Tokaido Shinkansen is still all 60 Hz.

Current collection

Due to the high-voltage feed, the current is lower but even so a high-speed train can require collection of 1000 A. Images of the high-speed test of an electric locomotive in France in 1955 showing large arcing between the overhead contact wire and pantograph suggested that high-speed current collection would be a difficult problem.

Of course Japan at that time had no technology for stable current collection at 200 km/h and the French high-speed tests used a locomotive with only one pantograph, but one would not be enough for shinkansen EMUs with distributed traction. Vibration of a pantograph also affects other pantographs when using multiple pantographs, making technical issues even more difficult.

The basic conditions for stable current collection at high-speed are ensuring that the catenary wave propagation velocity is faster than the train velocity as well as having a uniform pantograph uplift spring constant.

However, according to theory of the 1960s considering a mid- to high-speed range up to 200 km/h, speed with no contact loss is, from a pantograph standpoint, found by the up-down movement vibration theory with the contact wire resembling the strings on a stringed instrument. Thinking of the contact wire as springs lined up perpendicularly, speed with no contact loss is found and calculated from uplift characteristics by the pantograph.

As a result, wire contact at faster speeds could be assured by:

- Decreasing the mass of the pantograph, especially the shoe.
- Increasing the contact wire tension, and making the wire thinner.

- Minimizing the irregularity of spring constant.

This theory dominated until the early 1980s and catenary wave propagation velocity was not thought to be a problem at the predominant operating speeds of that time.

The RTRI started full-scale research in 1955 to develop a high-speed current collection system. The first tests were run on the Tokaido main line for the speeds of 95 to 120 km/h, but research started from the end of 1957 on what was at the time super high-speed current collection for the shinkansen speeds of 200 to 250 km/h.

Keeping the catenary spring constant fixed is impossible, because the overhead line is supported by poles. However, to keep it as fixed as possible, comparative tests were run on anti-resonance, modified Y-shaped compound catenary, continuous mesh catenary, and composite catenary on the Tohoku and Tokaido main lines. To decrease pantograph mass, overhead contact line height was made constant and pantograph vertical motion was decreased. They thus became smaller and lighter. To make the mass of the collector head in particular smaller, one pantograph was provided for two motor cars and the power collection current was reduced. A 16-car train set would thus have eight pantographs.

Figure 3 Overhead Catenary Structure

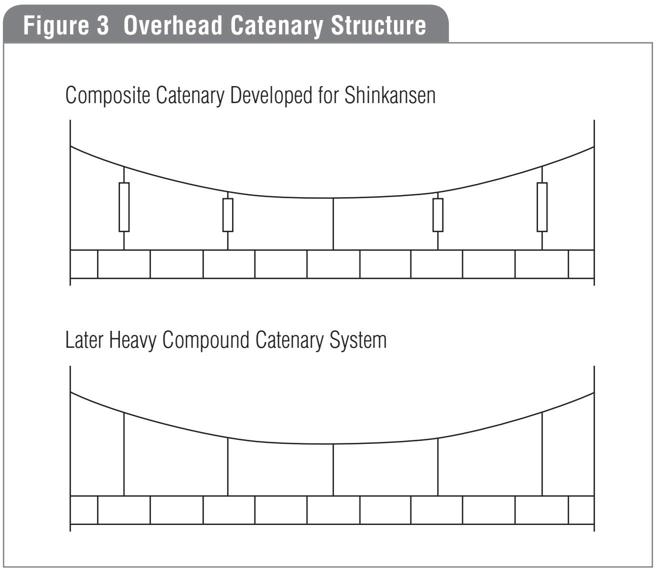
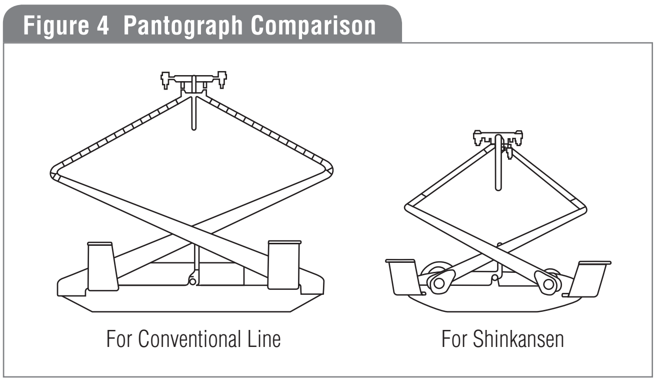


Figure 4 Pantograph Comparison



Anti-resonance catenary, modified Y-shaped compound catenary, continuous mesh catenary had complex structures, and maintenance was difficult, so composite type compound catenary system was chosen. In this method, the contact wire is slung from dampers which absorb wire vibrations from the pantograph, making it ideal for the multi-pantograph shinkansen EMUs. This was the system devised by the RTRI.

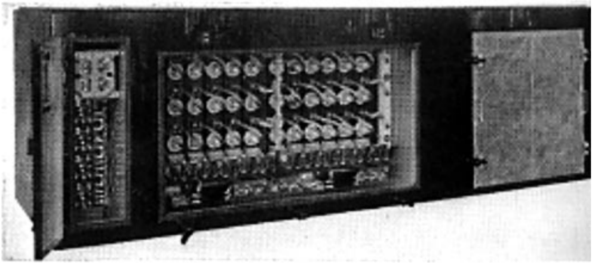
The initial performance of the composite type compound catenary was very good, but increasing numbers of train operations caused wear at the contact wire and deteriorated dampers, leading to many wire breaks. Although contradictory to current collection theory, the countermeasure was to strengthen the pantographs. And from the 1970s, dampers were eliminated and thicker contact wires were used. This heavy compound catenary had fewer wire breaks, but more loss of contact and resultant arcing caused more noise along the line. Such contact loss did not affect AC-based train operations research continued to eliminate contact loss with major later successes.

In pantograph design, the issues facing making them smaller so they are lighter were overcome by fixing overhead contact line height. However, such pantograph design faced issues with wind-generated irregular lift. Wind against pantographs when running is strong, and lift acted up and down irregularly on the collector head and disrupted the contact force on the contact wire. Wind-tunnel tests led to collectors of various shapes offering slight positive lift to increase contact force and each new pantograph design is now subjected to wind-tunnel tests to confirm lift forces.

Traction system

The traction system where the train collects high-voltage AC power to turn the traction motors was made to be a power distributed EMU system in line with Hideo Shima's ideas, which was accepted unanimously. It was designed to lighten axle loads and solve adhesion problems and it also offered stable electrical braking and lowered brake maintenance.

High-speed EMUs designed under that idea were not seen anywhere else in the world back then. At that time, European high-speed trains running in the 160 km/h range

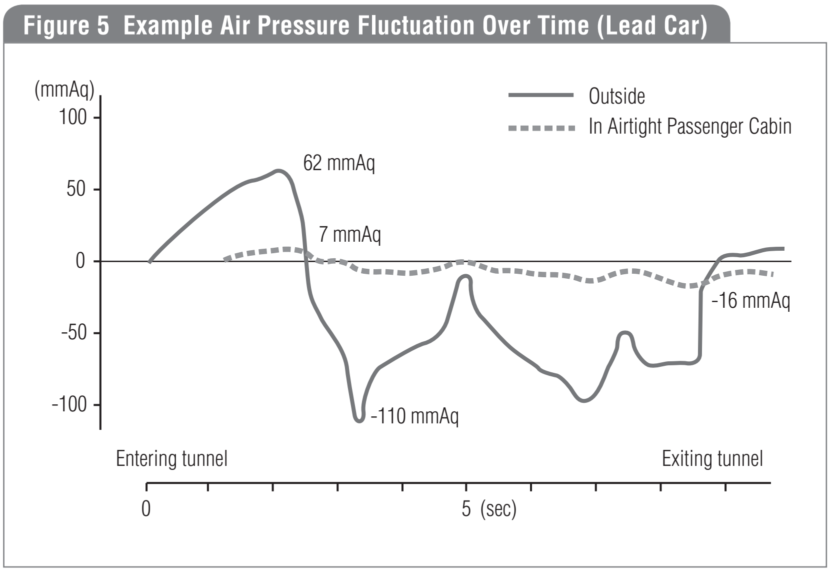


Silicon Rectifier for EMUs (100 Years of JNR Rolling Stock) were mostly loco-hauled but after the appearance of the 200 km/h shinkansen, some European operators increased operating speeds to 200 km/h and more, and soon realized the need for lighter axle loads as roadbeds became damaged.

AC traction systems at that time were either direct types using AC commutation motors (mainly low frequency, such as 16.7 Hz) or indirect types with rectifiers and DC motors. The latter had an advantage for AC electrification using commercial frequencies but the large mercury rectifiers used then could not be mounted easily under the floor of EMUs.

As a result, efforts were made to develop a system using commercial-frequency AC-commutator motors with regenerative braking, but that proved extremely difficult. As JNR designers and electric manufacturers agonized over the development, silicon diodes for electric power semiconductors appeared. Although many elements had to be connected in series and parallel, under-floor mounting became possible and they were put to practical use on dual AC-DC EMUs running on conventional lines in 1960. Shinkansen EMUs were soon equipped with semiconductor rectifiers for a system with DC main motors. It proved incredibly reliable and was used for more than 20 years. Large volumes of the new electric power semiconductors could be stably supplied thanks to the development cooperation of Japanese electric manufacturers.

Figure 5 Example Air Pressure Fluctuation Over Time (Lead Car)



Passenger cabin air pressure

As tests of prototype shinkansen rolling proceeded at faster speeds, the problem of in-cabin air pressure emerged. Air pressure changes greatly as a train enters a tunnel at high-speed, creating an unpleasant popping feeling in passengers' ears. The phenomenon had been seen previously in the single-track tunnels, but its occurrence in double-track tunnels was unexpected.

Although popping ears is not a major problem for healthy people, it can be painful for people with colds, etc., so a decision was taken to make the car body airtight. The structure of bodies is complex, and a fundamental change in terms of design and production technology was needed. Cars that were strong enough to withstand external air pressure changes were needed, but time was short. For early production cars, areas centring on the passenger cabin were made airtight and ventilation ducts were closed when tunnels were detected to secure cabin ventilation. But making the passenger cabin airtight caused problems such as poor opening and closing of doors and backflows in places using water such as the toilets and buffets. Overcoming these problems became a major task. In the end, the whole car body was made airtight. Outside doors were sealed by air pressure; airtight diaphragms were developed for couplings between cars; and waste water for washrooms and buffets water is passed through a seal (U-shaped pipe holding water at a height of 300 mm or higher) to prevent air flow between the inside and outside.

And because air starts leaking with aging wear, criteria were established for checking air-tightness regularly at maintenance shops to keep it at a certain level. ■

Continued to JRTR 58.

Asahi Mochizuki

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 stock. Subsequently, he served as a Chief Engineer Transportation System Division at Toshiba Corporation prior to assuming his current position.