Breakthrough in Japanese Railways 9

JRTR Speed-up Story 2

Part 2: Speeding-up Conventional Lines and Shinkansen

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Reducing Journey Times on Conventional Lines

Distribution of factors limiting speed

The maximum speed of any line is determined by emergency braking distance. However, train speeds are also restricted by various other factors, such as curves, grades, and turnouts.

Acceleration and deceleration performance also impact journey time. The impact of each element depends on the terrain of the line. The following graphs show the distributions of these elements for the Joban Line, crossing relatively flat land, and for the eastern section of the Chuo Line, running through mountains.

The graph for the Joban Line crossing the flat Kanto Plain shows that it runs at the maximum speed of 120 km/h (M part) for about half the journey time. Consequently, a 10-km/h increase in maximum speed could reduce the journey time by a few percent. The eastern section of the Chuo Line running through mountains has almost no parts operating at 120 km/h. Most operation is through speed-limited curves and there are very few sections where the maximum speed can be increased.

For lines like the eastern section of the Chuo Line, speed is limited by factors such as curves, grades, and turnouts, so scheduled speed can only be increased by focusing effort on increasing speed at these locations.

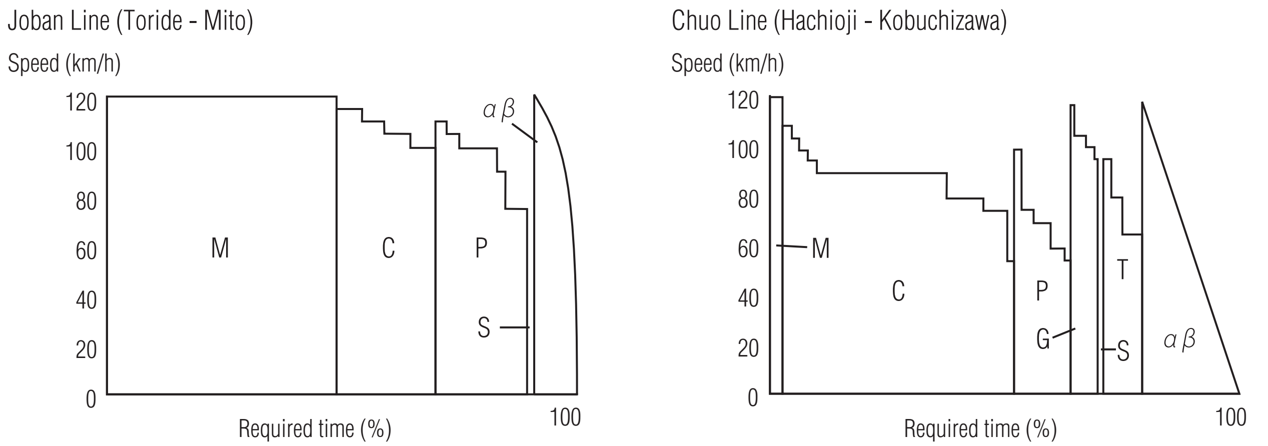
Many of the intercity railways in Japan are lines in mountainous areas. So, objectives for increasing speeds cannot be achieved by simply raising the maximum speed.

Speed-up on curves

The basic measures for increasing speeds on curves are lowering the centre of gravity of rolling stock and canting the track. However, these measures have already been applied fully; cant cannot be increased on lines serving slow freight trains with a high centre of gravity. Conversely, increasing passenger train speed through curves to just below the limit where the trains could overturn causes reduced ride comfort due to centrifugal force. The solution was to develop tilting or pendulum cars to absorb centrifugal force.

Naturally, European operators considered such measures, but building a safe and reliable tilting mechanism proved difficult. One example of practical application in Europe was the UK's Advanced Passenger Train (APT), but it was soon withdrawn from service. Italy also made painstaking efforts to achieve stable control of tilting.

Figure 1 Distribution of factors limiting speed for Joban and Chuo lines



M: Max. speed, C: Curve limit, P: Turnout limit, G: Grade limit, S: Signal limit, T: Tunnel, etc., limit αβ: Acceleration/deceleration

Test Series 591 Pendulum EMU

Test Series 391 Pendulum DMU

(*A Hundred Years of Progress in JNR Rolling Stock*)

The first tilting systems in Japan used a pendulum system where the body is tilted in curves by the centrifugal forces.

Such a tilting system inevitably suffers from tilt lag after the train enters and exits the curve, but the body always tilts reliably in the right direction.

Although it was an incomplete solution, the policy in Japan was to start with this system and make steady improvements later. In Japan, this system is called *natural pendulum* (passive tilting).

Series 591 electric multiple unit (EMU) test cars were built in 1970 for test runs on electrified lines across Japan. In 1972, Series 391 diesel multiple unit (DMU) test cars were built and tested for non-electrified sections.

The first revenue service of a tilting train in Japan was in 1973 on the newly electrified section between Nagoya and Nagano using Series 381 limited express DC EMUs. Speed through curves was 15 to 20 km/h faster than the standard speed, cutting journey times on that section by 16%.

However, the pendulum action on the Series 391 DMU was impeded by the transmission prop shaft, which, coupled with the attempts to improve ride comfort on pendulum EMUs, delayed revenue service until 1989 when JR Shikoku started to run Series 2000 limited express DMUs.

Speed-up on grades and other sections

The many grades on trunk lines through mountains proved a serious impediment to speed increases. Climbing grades at higher speeds requires more traction power and electrification is the easiest way to provide large amounts of power. Consequently, the previously mentioned section between Nagoya and Nagano was electrified at the same time as Series 381 pendulum EMUs were introduced. These powerful EMUs had a configuration of six powered cars and three trailer cars; they could climb grades at high speed, used electric braking when running down steep grades, and could travel faster through curves. The Hakubi Line in west Japan was similarly electrified and served by Series 381 pendulum EMUs.

Later, the engine output of DMUs was greatly increased, offering similar speeds to EMUs on grades.

In Japan, symmetric turnouts are widely used at stations on single-track lines, causing severe speed restrictions for passing trains. To increase train speed, however, new track layouts using simple turnouts have been introduced on some lines, securing one straight track at each station for passing trains.

Improvements to and spread of tilting trains

When Series 381 pendulum EMUs were first introduced between Nagoya and Nagano, they were operated by drivers experienced in driving less powerful DMUs. As a result, these drivers tended to run the trains faster than the scheduled speed through curves, causing heavy swing motion, giving the passengers (and crew) motion sickness, and gaining a poor reputation.

I also observed these problems of early tilting train operations, as I rode with train drivers for a month when the Series 381 was first introduced.

Speeds were later reduced to an appropriate level, but the fundamental flaw of this system—tilt lag—was not overcome. The number of passengers may have increased, but the train's reputation remained poor.

When the tilting system was later introduced on the Kisei Line, a method was developed to alleviate tilt lag by tilting the car before entering the curve. It involved pre-recording curve radii, transition curve lengths, and cant data for the entire line in an onboard computer, and then tilting the car body using actuators as the train approached the curve by calculating the tilt angle and angular velocity based on train speed. The method remains failsafe because the dominant tilting force in the curve is still the natural pendulum.

This method was used successfully with pendulum DMUs introduced to revenue service by JR Shikoku in 1989. The problem with DMU prop shafts impeding body tilt was overcome by using two engines to cancel each other out. Such cars spread later to individual companies in the JR group with EMUs also using this controlled tilting.

The so-called *tilting body* system was also introduced to improve riding comfort by lowering the tilt centre as much as possible and minimizing lateral movement of the cabin floor.

This simplified method does not use pendulum tilting; instead pressure differences between right and left air springs tilt the body. It is used widely on lines requiring small tilt angles and is even used on some shinkansen cars.

Shinkansen Speed-up and Background

As soon as the shinkansen started commercial operation in 1964, development of the next generation started with a goal of increasing speeds to 250 km/h. The initial plan for the first generation had been 250 km/h, but due to practical circumstances, it was reduced to 200 km/h so the aim was to reach the original goal with the next generation.

The type 951 test EMU was built in 1969 and achieved a speed record of 286 km/h. The new technologies packed in this test train included eddy-current rail braking that enabled efficient braking from high speed. However, it became one of the factors that caused markedly increased wheel loads. So, type 961 test EMUs were built in 1973 to overcome this problem.

While the problem of excessive wheel load was solved, the so-called 1970s oil shock and trackside environmental problems (mainly running noise and vibration) became key points of public discussion, making speed increase difficult for Japanese society to accept. As a consequence, the maximum operating speed of the San'yo Shinkansen was restricted to 210 km/h when the line to Hakata was completed; speed-up was not achieved.

Trackside noise and vibration had to be solved before operating speeds could be raised so shinkansen engineers focused on them first. In that effort, the type 961 re-emerged for environmental countermeasures tests, recording a maximum speed of 319 km/h in 1979. Based on these tests for making environmental improvements, the Tohoku Shinkansen could meet the required environmental standards and started revenue service in 1982 at 210 km/h.

However, the development of technologies to increase speeds lacked driving force due to the social environment of the time.

In the midst of this situation, the French TVG high-speed trains started operation in 1981 at 260 km/h—faster than the shinkansen. The news shocked Japan and gave new impetus to work to speed-up the shinkansen. Development of noise solutions and speed-increase technologies was actively pursued, and the Tohoku and Joetsu shinkansen lines reached a maximum speed of 240 km/h in 1985.

Application of similar measures to the Tokaido Shinkansen allowed for a speed increase to 220 km/h in 1986, cutting the journey time between Tokyo and Osaka to less than 3 hours and between Tokyo and Hakata to less than 6 hours.

The JR companies, established in 1987, had renewed enthusiasm for speed-up tests.

A variety of test cars were built, successes were achieved in research on noise countermeasures, and environmental standards were met at even 270 km/h in 1991. As a result, the Tokaido and San'yo shinkansen started running at a top speed of 270 km/h in 1992; JR West's Series 500 could meet environmental standards at up to 320 km/h in 1996, and the San'yo Shinkansen started running at 300 km/h in 1997.

A top speed of 320 km/h was now within reach through such efforts, but many technical obstacles had to be overcome to reach this point. The next section explains the progress in meeting these challenges.

Technical Issues and Solutions in Shinkansen Speed-up

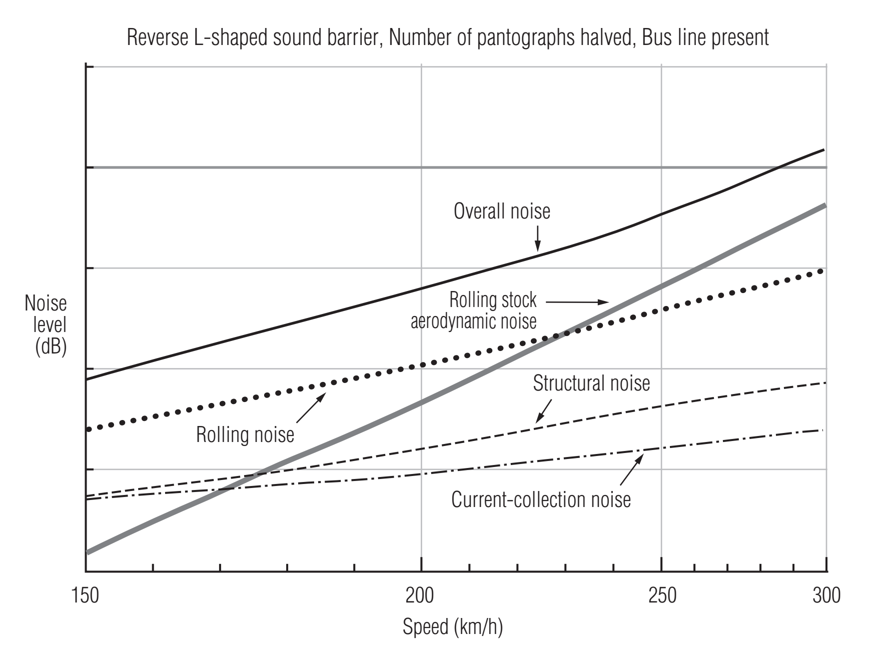
Environmental problems along lines—noise countermeasures

Noise and vibration are the main environmental issues alongside shinkansen lines and, with the sudden increase in the number of shinkansen runs, trackside noise-pollution in urban areas became a great public concern. As a result, the Environment Agency (now a ministry) established noise standards in 1975; there were requests to reduce speeds to meet these standards, which also served to hinder speed increases too. To meet one standard limiting noise to not more than 75 dB, measures were implemented to block noise along with basic R&D into identifying noise sources and reducing noise generation. The sources of the noise were identified as rolling noise, current-collection noise, and aerodynamic noise; the first countermeasures focused on the main contributor—rolling noise created by unevenness of both wheels and rails.

Wheel flats, a form of tread damage caused by sliding, were solved early on and grinding the head of rails proved very effective.

Current-collection noise is composed of arc noise caused by contact losses, pantograph aerodynamic noise, and by sliding noise. Arc noise was the main contributor. The main cause is corrugation of contact wires but the cause of this corrugation was not understood at the time, so covers were added to pantographs around 1984 to block the noise

Figure 2 Contribution of speed and noise source to noise level below 75 dB



The structure of pantographs was also simplified and aerodynamic noise suppressed. The under-body area was smoothed too, reducing noise further. As a result, in 1996, the Series 500 EMUs reached 320 km/h with noise held below 75 dB, and operation started in 1997 at 300 km/h.

Meanwhile, the background noise of the wind tunnel used at that time for high-speed noise tests far exceeded 75 dB, so the Railway Technical Research Institute (RTRI) newly built a huge low-noise wind tunnel in 1996.

The closed test section is 5-m wide, 3-m high, and 20-m long, and can generate winds up to 300 km/h. The open test section is 3-m wide, 2.5-m high, and 8-m long, and can generate winds up to 400 km/h the background noise is 75 dB(A) at the maximum wind speed of 300 km/h. This wind tunnel has made great contributions to research on aerodynamic noise countermeasures.

Micropressure waves generated as a train runs through a tunnel are another source of noise pollution, but additional buffering works at the tunnel portals as well as novel train nose shapes have solved this problem.

instead. Concurrently, pantographs were connected by a high-voltage bus to reduce arc noise when one pantograph lost contact while others were still collecting current. This measure allowed a reduction in the number of pantographs on each train. Aerodynamic noise of pantographs was reduced by fitting covers over pantograph equipment. As a result, the Tohoku Shinkansen could meet the stricter environmental noise standards at higher speeds and started operating at 240 km/h from 1985. Later research identified the cause of the corrugation, so arc noise was solved around 1990.

In work to suppress ground vibration on the Tokaido Shinkansen, the results of tests to reduce axle load showed that efforts were needed to reduce car weight to an axle load of around 10 tonnes and to reduce unsprung mass. Such efforts were made, and the axle load and unsprung mass were successfully reduced.

Noise countermeasures held noise below 75 dB. Along with movement countermeasure, it made it possible for the Series 300 EMU to operate at a top speed of 270 km/h.

The graph above shows how each noise source contributed to total noise and the dependency on speed at that time.

It shows how body aerodynamic noise becomes prominent as current collection noise decreases. Various tests were run with different designs, but the effect could not be measured clearly because aerodynamic noise was masked by other noise.

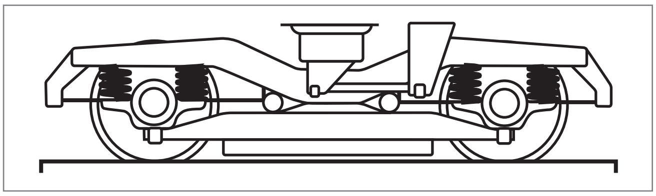
After 1990, smoothing the body surface and lowering the height of the body cross-section proved effective.

Unsprung mass—countermeasures to excessive wheel load

The maximum static wheel load of the first Series 0 shinkansen EMUs was 8 tonnes, and the maximum wheel load during running at the service start was 11.7 tonnes. When type 951 test cars were fitted with eddy-current rail brakes in 1969 to allow operation speeds of more than 250 km/h, a very high wheel load of about four times the static wheel load was generated. The main cause was the increase in unsprung mass caused by the eddy-current rail brakes, but another important factor was the sudden increase in worn welded rail joints due to the increase in the number of trains.

In these circumstances, reduced unsprung mass was a key condition for speed increases. Type 961 EMUs with hollow-shaft drive systems had been built in 1973, but the structure was complex and speed increases were not seen as necessary at the time. As a result, there had been few tests on increasing speed.

As previously described, Japan was again looking at increasing shinkansen speeds in the 1980s but engineers were pressed with solving both environmental problems and problems of unsprung mass. Complex structures like the type 961 were deprecated by maintenance engineers, so



Type 951 test car eddy-current rail brakes of 1969

wheelsets, axle boxes, and gearboxes were lightened and hollow shafts were used to reach the target unsprung mass. These measures were implemented from the Series 300 EMUs in 1990 to reduce both axle load and unsprung mass by about 30% and allow speeds of 270 km/h to be reached.

Recent advances in rail welding technologies and periodic grinding of the rail head have almost eliminated rail unevenness, cutting fluctuations in wheel load. As a result, the need for reduction in unsprung mass is not as strong as before.

Weight reduction—suppression of kinetic energy

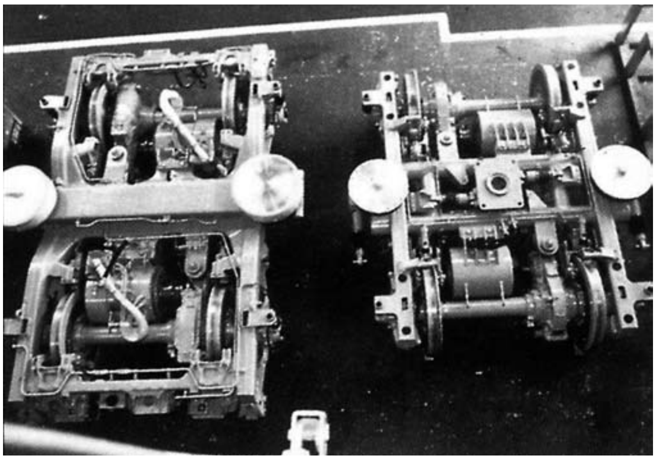
The axle load of the Series 0 EMUs on the Tokaido Shinkansen was less than 16 tonnes, but that of the Series 200 EMUs on the Tohoku Shinkansen was 17 tonnes due to snow countermeasures, despite the aluminium-alloy body. As described previously, weight reduction was the key to increasing speed to the 270 km/h range. On the Tokaido Shinkansen, vibration countermeasures were achieved by reducing axle load to about 10 tonnes by using aluminium-alloy car bodies and a drive system with AC traction motor and regenerative brakes to slash the weight of electrical components.

In fact, smaller axle load reduces the kinetic energy that must be absorbed by the mechanical brakes. The shinkansen EMU design concept is to use electrical brakes constantly, but they must be backed up by mechanical brakes even when stopping from maximum speed. Thus, weight reduction is essential to increasing speed. Consequently, in order to achieve speed increases, the axle load was set to about 10 tonnes even on other shinkansen lines that were built on a solider roadbed than the Tokaido.

The main measures to reduce weight were use of light alloy bodies and regenerative braking, but use of compact AC traction motors also made it possible to reduce the size and weight of bogies. And as cabins hold a large number of seats, aircraft seat manufacturing technology was used to help reduce weight too.

Reducing running resistance at high speed

The main running resistance with high-speed trains is aerodynamic resistance which increases very rapidly as the speed increases.



Series 100 and 300 bogies both with 2500-mm wheelbase
(JR Central pamphlet)

Under-floor equipment with unified dimensions (JNR pamphlet)

Clearly, aerodynamic resistance is an important factor for increasing speeds, but train designs to minimize aerodynamic resistance were uncharted territory.

Series 200 EMUs built for the Tohoku Shinkansen in 1981 used a body mount structure. Aerodynamic comparison with the Series 0 showed that the resistance elements were train cross-sectional area, pressure drag coefficient, length, and side friction coefficient. The contribution of each element to overall resistance was quantified to some degree.

In 1985, the under-floor equipment of Series 100 EMUs was unified to a fixed height and width to prevent snow buildup. Spaces between equipment were blanked off to make the under-floor area smooth. The idea was to achieve the same effects as a body mount structure. While the body cross section and train length were the same as the Series 0 EMUs, the Series 100 running resistance was significantly (about 20%) less.

Later measures, such as lowering body height, reducing

Figure 3 Train resistance (N) of high-speed trains

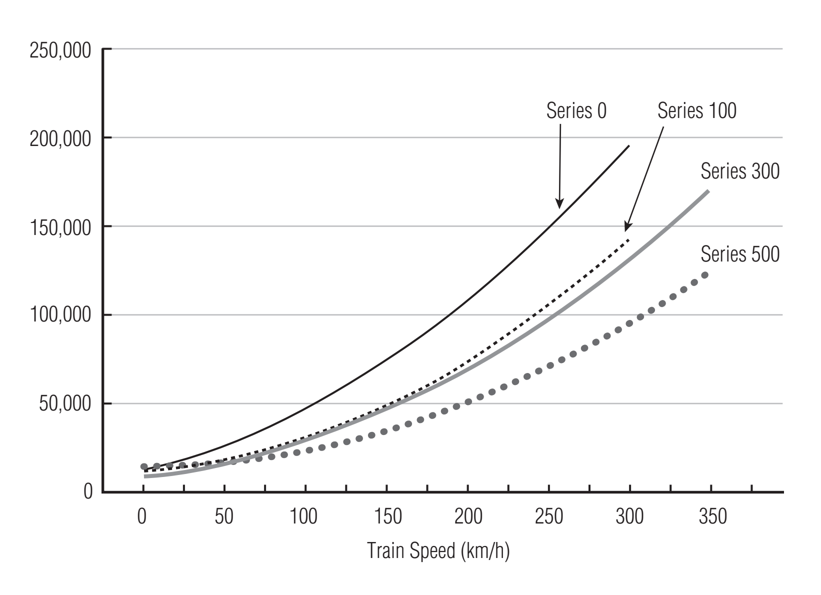
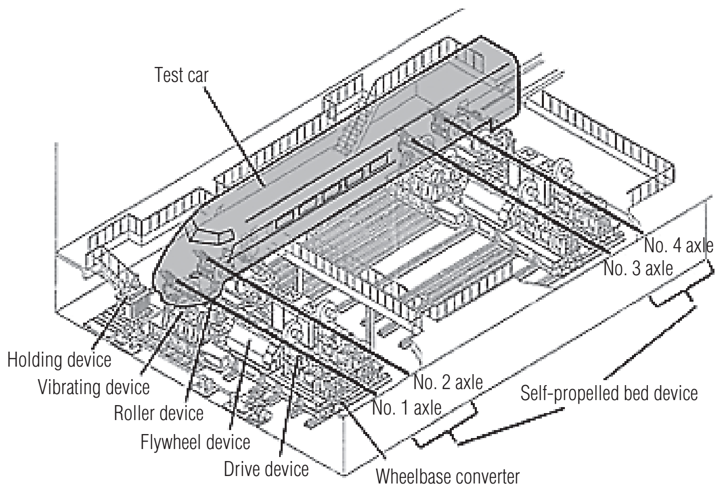


Figure 4 RTRI Rolling Stock Test Plant



(Railway Technical Research Institute)

body cross-sectional area, and expanding smooth underfloor surfaces to the bogies further reduced running resistance to about half that of the Series 0, as shown in figure 3 for 400-m trains.

The reduced running resistance led to great energy savings, but surprised designers of the Series 500 with its much longer braking distances.

Achieving both high-speed running stability and curve negotiation performance

The first Series 0 shinkansen did not suffer from hunting even at speeds well in excess of the maximum operating speed, but wheels and rails on tight curves suffered from increased wear and tear, and wheel tread profiles had to be reground frequently.

The cause of the problem was high lateral force in tight curves. One early solution was changing the tread profile from a cone to an arc. From around 1988, research and tests were performed to find the optimum value for the longitudinal and lateral rigidity of the axle box suspension.

A new Rolling Stock Test Plant was established at RTRI in 1987 to test cars under various conditions. Based on the results, live tests were run on operating lines and then the designs went into practical service. Eventually, the RTRI test plant could not meet demand and JR Central built a rolling stock field test simulator and started tests in 2008. JR East also set up high-speed bogie test equipment and is working to improve running stability.

The RTRI Rolling Stock Test Plant can handle both shinkansen and conventional-line rolling stock at up to 500 km/h to determine when hunting occurs. In addition, vertical and lateral movement, roll, yaw, and pitch trajectory conditions as well as actual track irregularities can be applied to cars.

Such research, conducted on difficult technologies, gradually delivered results on achieving running stability and curve negotiation performance.

From about 1990, the rotational constraint between the bogie frame and car body was changed from side bearing slips to the lateral rigidity of air springs and yaw damper resistance, allowing selection of appropriate rotational constraint. The compatibility of stability and curve negotiation performance was increased, preventing hunting at even higher speed ranges and enabling longer intervals between wheel grindings.

Long-wavelength track management (40 m versine) was also conducted from about 1990 in conjunction with speed increases to suppress rolling stock vibration caused by track irregularity.

High-speed current collection—contact loss countermeasures and low-noise pantographs

The composite compound catenary equipment used at the shinkansen start in 1964 was soon changed to heavy compound catenary as the number of trains increased. Although contact wire corrugation occurred with this system, resulting in annoying noise caused by arcing at contact losses, it was not a hindrance to current collection.

To allow speed-up on the Tohoku Shinkansen, the catenary hanger interval was shortened to match the vibration-followup characteristics of pantographs. Also, springs were added between the collector head and the slider.

Although no significant improvement was seen from these measures, the maximum speed was raised at this time from 210 km/h to 240 km/h by fitting covers over pantograph equipment, reducing the number of pantographs, and running a high-voltage bus between pantographs.

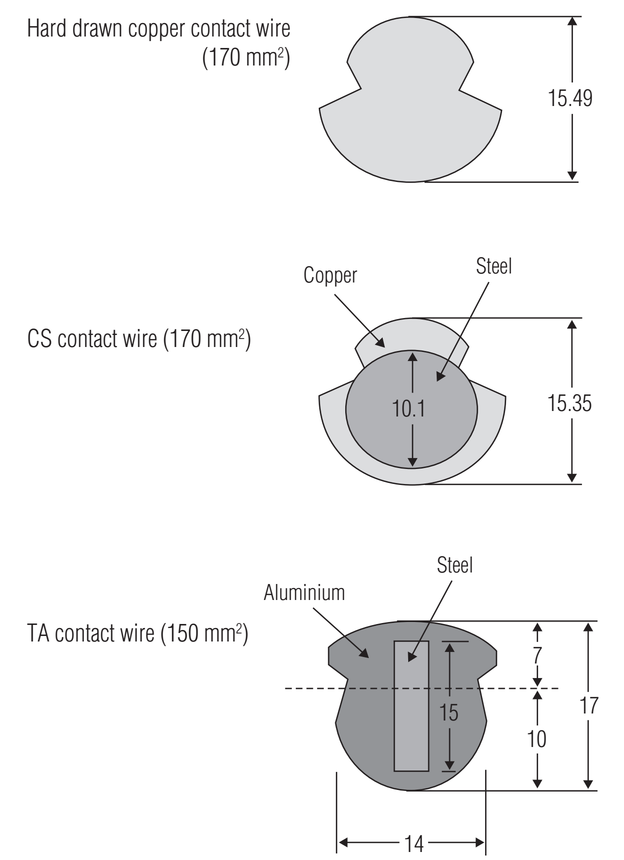
The changes caused heavy wear of sliders, which were widened as a stopgap measure. Unexpectedly, this measure eliminated the corrugation and subsequent analysis by RTRI identified the exact cause of contact wire corrugation, thus finally solving the problem.

The RTRI conducted research on overhead catenary systems in the 1980s ahead of further speed-ups and developed high-speed current collection theories based on the wave-propagation velocity. Because there is very little contact loss when the train maximum speed is less than 70% of the wave-propagation velocity, the wave-propagation velocity must be increased to increase the train maximum speed. In simple terms, this means increasing the contact wire tension and decreasing its mass. Such measures were practically difficult using the conventional copper-alloy wire, so a new wire was developed in 1986. It had an aluminum-covered steel core wire, but was changed again in 1991 to copper-covered steel core wire to facilitate easy replacement.

Entering the 2000s, newly introduced copper-covered steel core contact wires had a cross sectional area of 110 mm^2, a tension of 19.6 kN, and a wave propagation velocity that had been increased from the 355 km/h of conventional copper-alloy wire to 519 km/h. It guaranteed stable current collection at up to 360 km/h. Moreover, the simple catenary structure resulted in huge cost reductions for overhead line equipment. Existing overhead contact lines also were replaceable, but tension is increased if left as-is.

Meanwhile, operators in the JR group are designing simpler pantographs to reduce aerodynamic noise. The

Figure 5 Cross sections of test contact wires



Kyushu Shinkansen new overhead contact wire equipment (Author)

Kyushu Shinkansen pantograph (Author)

pantograph developed by JR East in 2002 is the simplest and does not even need a pantograph cover. The above photograph is an example of a pantograph for Series 800 rolling stock for Kyushu Shinkansen in 2004.

Today, most shinkansen have two pantographs connected by a high-voltage cable.

Propulsion systems

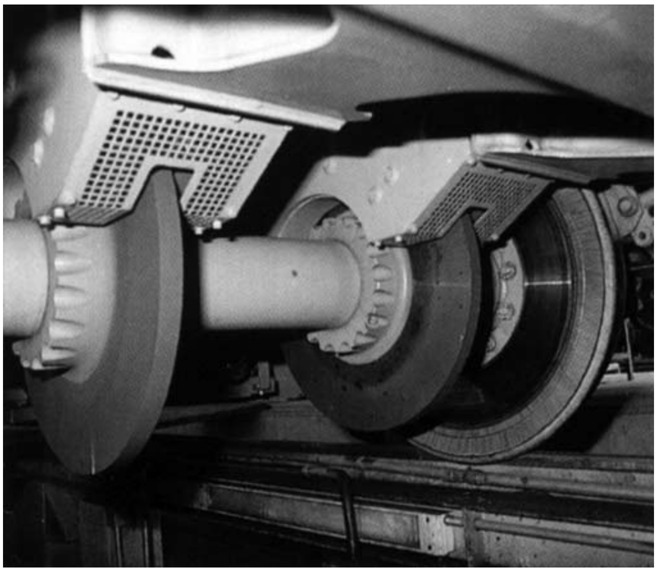
The first shinkansen EMUs received 25-kV, 60-Hz single-phase AC power, which was stepped down by transformers and rectified by silicon diode bridges to provide power for DC motors. The DC motors were converted into power generators when the dynamic braking system was working, and brake energy was dissipated as heat by resistors.

Type 951 test cars (1969) used choppers for brakes, while type 961 test cars (1973) used phase control by thyristor bridges. However, the Series 0 EMU power system was very stable, so it remained basically unchanged.

The Series 200 EMUs on the Tohoku and Joetsu shinkansen (1980) used propulsion technologies from the types 951 and 961 with thyristor phase control for acceleration and resistance control with chopper devices for braking. This helped improve adhesion performance in snow. Series 100 EMUs in 1985 also used phase control by thyristor for power running, and eddy-current disc brakes were developed for trailers. Introduction of trailers cut both costs and weight.

A four-quadrant converter, variable voltage variable frequency (VVVF) inverter AC induction motor system, which had been developed from 1985 for the Hokuriku Shinkansen with its long steep grades was nearing completion by the end of the JNR era. However, the construction of the Hokuriku Shinkansen fell behind schedule, so the technology saw first practical use on JR Central's Series 300 EMUs (1990). All shinkansen EMUs introduced after the Series 300 adopted this system. These new EMUs had regenerative brakes, which, together with smaller and lighter electrical equipment, offered great weight reductions, making major contributions to speed increases. The power factor could also be controlled, assuring highly effective utilization of collected power, and curbing increases in collected current required for higher speeds.

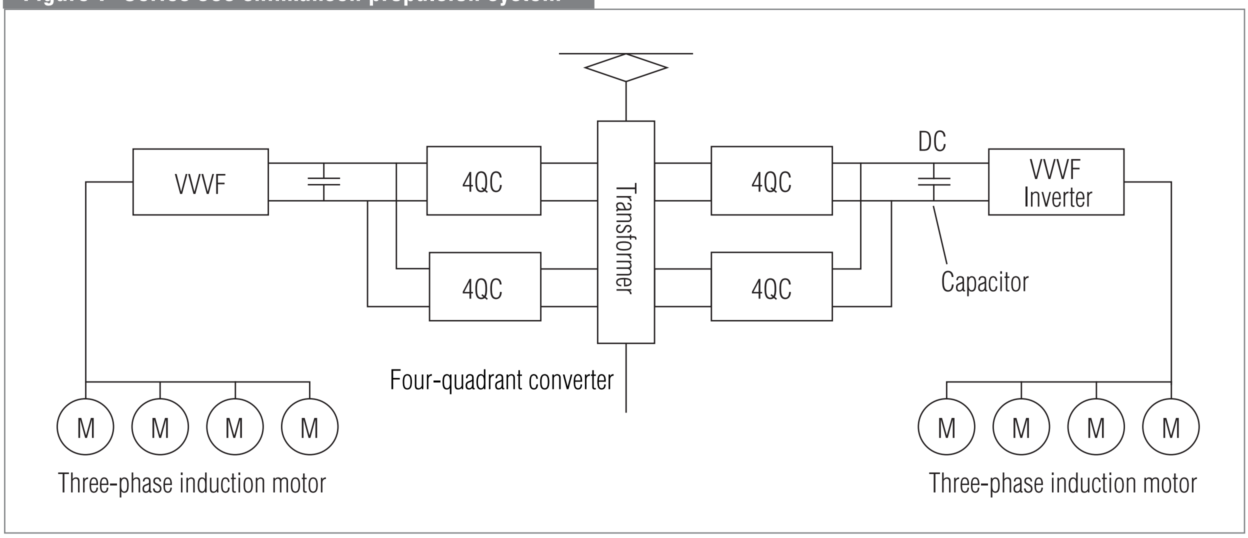
Initially GTO thyristors were used for the four-quadrant converter and VVVF inverters but have been replaced by insulated gate bipolar transistors (IGBT) to greatly suppress inductive obstruction current and other problems. So-called vector control is also used due to its high adhesion properties and to suppress increases in braking distance caused by higher speeds. Braking distances are also cut by injection of ceramic particles on rails to increases adhesion.



Eddy-current disc brake (JNR pamphlet)

Energy disposal of high-speed braking

Figure 7 Series 300 shinkansen propulsion system



Braking from high speeds requires disposal of huge amounts of kinetic energy. Dissipating such high energy with mechanical brakes alone is impractical, if not impossible, because it requires frequent and intense maintenance works and results in shorter service life.

To overcome this problem, motors are thus installed on all axles, and are braked using dynamic braking to dissipate energy as heat. If this electrical braking fails, the mechanical brakes function as a backup.

To handle the high frictional heat generated by mechanical braking from top speeds with maximum deceleration, the wheel-mounted brake discs are made of nickel-chromium-molybdenum low-alloy cast iron with sintered metal brake pads.

The mechanical brakes are controlled by electromagnetic straight air brake equipment, and the foundation brake rigging uses hydraulic control, offering compact size with low weight and high responsiveness.

For braking force, non-adhesive brakes were avoided and only adhesive force was used. However, there was more sliding than expected and the added precautionary slide detection and re-adhesion system was insufficient. Tests on the type 951 for next-generation test rolling stock were made by fitting non-adhesive eddy-current rail brakes, but failed due to undesirable effects on rails.

However, chopper control proved successful in matching speed characteristics of braking force to that of adhesion coefficient.

To increase adhesion, an abrasive block was initially used to polish wheel treads, but in the 1990s, injection of ceramic particles was added as an additional measure.

From around 1995, the service braking force of the front cars in the direction of travel was reduced or eliminated, eliminating sliding and allowing for a shorter braking distance of the train as a whole.

Induction motor vector control was added from the late 1990s and improvements in adhesion technologies offered improved deceleration supporting speed increases to 300 km/h.

With the introduction of trailers, eddy-current disc brakes were developed due to the need for electrical braking. Dynamic braking changed to regenerative braking, and with the improved re-adhesion performance of AC induction motors (adoption of vector control, etc.), the braking equipment for trailers became unnecessary as sufficient braking forces were provided from motor cars.

Brake commands were sent initially using the electro-pneumatic straight air brake method but switched to electric commands from Series 200 EMUs in 1981.

The early brake disks had a shorter service life, because its ability to handle the frictional heating loads at top speeds of 210 km/h was lower than expected.

Clad metal discs of bonded cast steel and cast iron were used for a time but were changed to forged steel to handle increasing speeds.

Forged steel discs deform with frictional heating and the engineers struggled to overcome this problem. Fortunately, as mentioned, the great reductions in rolling stock weight suppressed the amount of brake energy to be dissipated and improved the problem to some extent.

Automatic train control (ATC) started with a stepped braking curve, but there was some surplus in braking distance set for each step. To raise maximum speed without increasing headway, this was changed to a non-step deceleration curve with new ATC technology from 2002.

Developments in airtight body design and window glass

Air pressure around a train changes greatly as it passes through a tunnel.

The solution is to build airtight bodies, thereby eliminating pressure changes. The bodies were constructed from aluminum alloy to decrease weight to facilitate higher speeds. Train bodies were made perfectly airtight, but cabin pressure rose gradually during running, which caused problems, so valves were added to release pressure build up.

As air pressure fluctuations caused when passing through a tunnel increased as trains were made to run faster, cars were made with small windows to reduce the impact on body shell strength, although passengers seated in two rows prefer larger windows for better panoramic views. Reinforced glass was used, and new unbreakable polycarbonates were adopted in some later series shinkansen.

Increased speed through curves

The minimum radius of curves on the Tokaido Shinkansen was to 2500 m. When the maximum operating speed was changed to 270 km/h, the maximum cant on curves was increased from 180 mm to the standard maximum of 200 mm.

Steady lateral acceleration was set at 0.09 G to give some leeway for acceleration, and maximum cant deficiency was increased from 90 to 110 mm. These changes allowed Series 300 shinkansen to pass 2500-m curves at speeds of 255 km/h and 3000-m curves at 270 km/h. However, there are still many sections with speed limits of less than 270 km/h and the only method for cutting journey times further by running through 2500-m curves at 270 km/h was to introduce tilting body.

JR Central set up a Vehicle Dynamic Simulator at its research facility in 2003.

The simulator moves a ride comfort test platform to generate centrifugal forces and assess ride comfort. Therefore, it is a huge system.

Eventually, the Series N700 was fitted with an air-spring-driven system, tilting the body by about 1° in a 2500-m curve. The system helps reduce centrifugal force felt by passengers and permits trains to run through 2500-m curves at 270 km/h.

Conclusions

The origins of Japan's shinkansen high-speed railway are relatively old, dating back to the 'bullet train' plan, which started construction in 1941.

Half a century has passed since design for the current system started in earnest in 1958. At the time, there were no railways operating faster than 200 km/h, and this was uncharted territory in terms of technology. However, our predecessors faced the challenge dauntlessly and succeeded in their efforts.

EMU and AC electrification technologies were still in their infancy in 1941, and there were no semiconductors or computers. So, from the technical viewpoint, starting in the 1960s was good timing.

Although it may be discourteous, with hindsight, the first shinkansen engineers had good luck and skill in equal measures. Difficulties arose in quick succession once shinkansen operations started, and social pressures slowed the momentum of speed increases. These issues were overcome by diligent research, and things that were considered ideal targets at first were achieved eventually. Shinkansen development was truly an amazing process.

Today, environmental standards have already been met for speeds up to 320 km/h, so operation at that speed will be achieved. However, it will be difficult to increase shinkansen speeds further under Japan's current environmental regulations so magnetic levitation high-speed railways are the future hope. Concrete plans are already being made and the chances of achieving revenue services at maximum speeds in the 500 km/h range still seem good.

This article contains a lot of technical information, and I hope that you were able to digest it. I thank you for taking the time to read it. ■

Table 1 Maximum speed chronology

Date	Shinkansen Line/Rolling Stock	Max. Speed
1 Oct 1964	Start of Tokaido Shinkansen	210 km/h
Nov 1965	Operation between Tokyo and Osaka in 3 h 10 min.	
1972	Type 951 Shinkansen test car	286 km/h
15 Mar 1972	Start of San'yo Shinkansen to Okayama	210 km/h
10 Mar 1975	Start of San'yo Shinkansen to Hakata	210 km/h
7 Dec 1979	Type 961 Shinkansen test car	319 km/h
27 Sep 1981	Start of French TGV South-East Line at 260 km/h	
23 Jun 1982	Start of Tohoku Shinkansen to Omiya	210 km/h
14 Mar 1985	Start of Tohoku Shinkansen to Ueno	240 km/h
Sep 1985	Series 100 test	260 km/h
1 Nov 1986	Series 100 operating on Tokaido and San'yo shinkansen	220 km/h
Mar 1989	Series 100N on San'yo Shinkansen	230 km/h
Mar 1990	Joetsu Shinkansen in operation (in tunnel)	275 km/h
28 Feb 1991	Series 300 test	325.7 km/h
14 Mar 1992	Series 300 operating on Tokaido and San'yo shinkansen	270 km/h
8 Aug 1992	JR West WIN350 test car	350.4 km/h
20 Dec 1993	JR East STAR21 test car	425 km/h
21 Jul 1996	JR Central 300X test car	443 km/h
22 Mar 1997	Series 500 operating on San'yo Shinkansen	300 km/h
5 Mar 2011	Series E5 operating on Tohoku Shinkansen	300 km/h

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