Technology

Railway Technology Today 2 *(Edited by Kanji Wako)*

The Mechanism of Railway Tracks

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Railway Operation in Japan

The history of railways in Japan dates back to September 1872 when commercial operation started over a 29-km track between Shimbashi (Tokyo) and Yokohama. Japan has achieved a tremendous development, both social and economic, over the following 125 years, and railways have been no exception. The railway networks in this relatively small land total over 27,000 km, and up to 2.2 million people ride trains each day. The five shinkansen lines stretch 2200 km with operating speeds of 260 to 300 km/h. Shinkansen cover the 515-km stretch between the two largest cities, Tokyo and Osaka, in 2 hours and 30 minutes. The high efficiency of railway transportation puts railways ahead of air transport in Japan, where the dense population is scattered along the Pacific coastal plain.

The progress of railways and their role in society is supported by new technological achievements in many areas. Safety, speed, and ride comfort have always been major concerns for Japanese railway companies. The other major concerns today are reducing noise pollution for people living near tracks, and preserving the natural environment. More recently, easier maintenance has become an important issue due to labour shortages and the need for higher efficiency.

Track is one of the most important technical elements in railway operations. Track technology has developed in parallel with the railway itself. Current concerns of railways are also technical issue for tracks. This article discusses the present status of tracks in Japan, and the future outlook.

Structural Analysis of Tracks

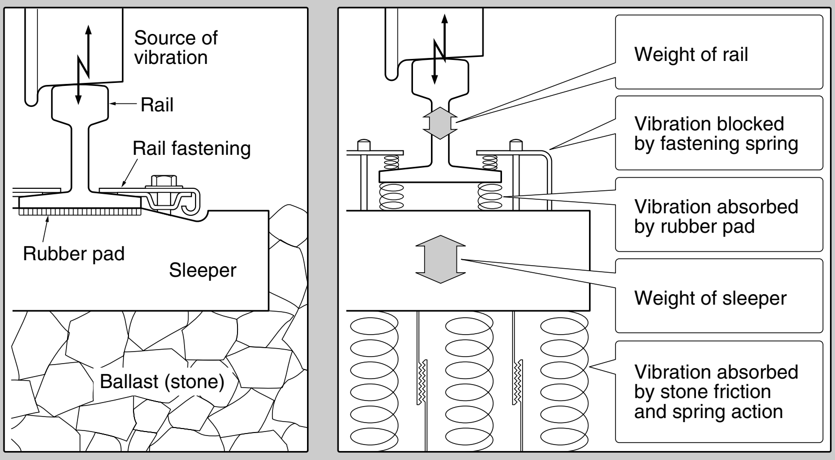
Basic structure

Japan is a mountainous archipelago with narrow coastal plains. Consequently, Japanese railways have many sharp curves, tunnels, embankments, and steep grades. The first railway in Japan was built using a narrow gauge (1067 mm) to meet these geographical conditions and the need for economy; the narrow gauge became the standard for all state-owned railways until the first shinkansen in 1964.

Figure 1 shows that railway track consists essentially of rails and sleepers, laid in and fixed by ballast on a road bed. This economic design, which was chosen on the basis of experience, has remained virtually unchanged irrespective of other subsequent technical progress. Tracks are long, large structures stretching hundreds or thousands of kilometers. In addition to economy, the design is a rational structure for supporting heavy fast trains on soft ground. It is easy to maintain and offers outstanding vibration and noise performance. Many attempts have been made over the past 100 years to develop other designs but none have been good enough to replace the conventional design.

As discussed later, slab track is a recent preference for high-speed operations, requiring less maintenance. However, conventional ballasted track is still found on more than 90% of railways in Japan.

Figure 1 Basic Structure and Function of Railway Tracks

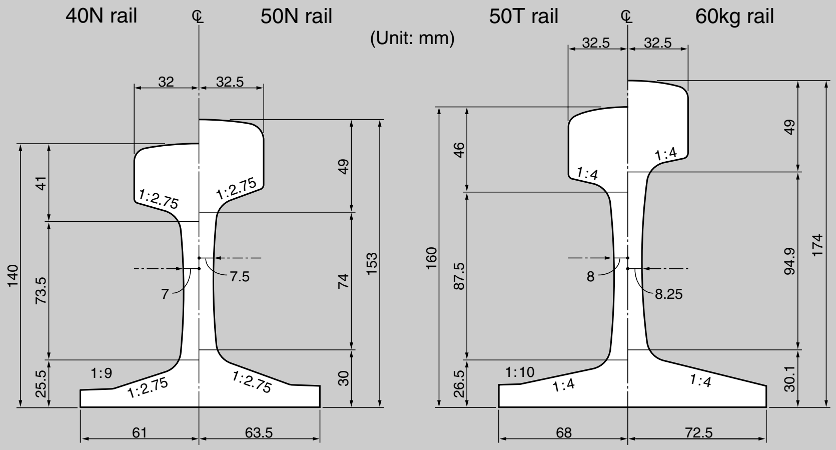


Rails

Japan's first line used vertically-symmetrical, wrought-iron double-headed rails. They were soon replaced around 1880 by asymmetrical steel flat-bottom rails of greater toughness. These first rails weighed 29.8 kilograms per meter (kg/m) and were 7.3-m long. The weight and length were later increased to carry more trains at faster speeds. Today, Japanese trains run on 50- or 60-kg rails. The 60-kg rails have the largest cross-sectional area and are used on all shinkansen tracks and other major sections (Figure 2).

The standard rail length is 25 m, but continuous-welded rails (CWR), or long rails, are used on main sections to improve ride quality and reduce noise and vibration. The CWR is subject to compression loads due to temperature changes, which can cause buckling, or sharp lateral displacement. These phenomena are prevented using reinforced fastenings, sleepers and ballast.

Figure 2 Typical Rail Cross Sections



Welding

Continous-welded rails are being promoted in Japan to cut noise, vibration, and maintenance costs. Rails can be welded end-to-end using any of four processes: flash butt, thermit, gas pressure, and enclosed arc. Japan is unique in using the gas pressure process and the enclosed arc in addition to the other two, commonly used in other countries.

In 1996, the JR group completed about 79,000 welds; 40% were by thermit welding, 26% by gas pressure, 25% by flash butt, and 9% by enclosed arc. The gas pressure process is less efficient than the flash butt process, but it is widely used for both factory and track-side welding because the equipment is easily portable and the joint quality is as good as that of the flash butt process.

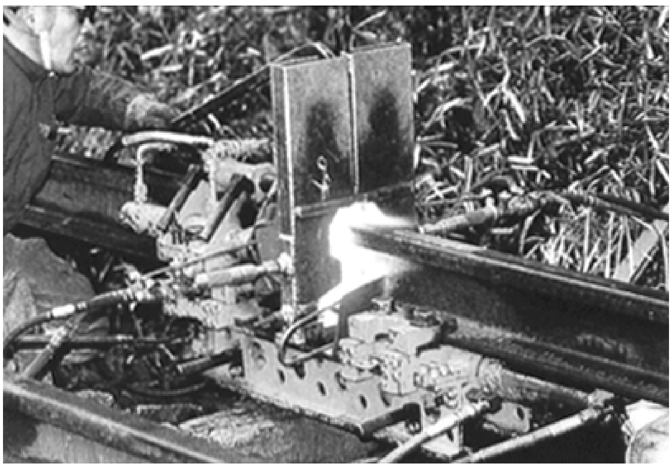
Sleepers

The sleepers binding the rails were usually made of hardwood timber. Concrete sleepers, introduced in early 1950s, are used on most trunk lines today because of their longer service life and greater track stability. Although timber sleepers have good elasticity and are lighter and easier to handle than concrete sleepers, their main drawback is short service life due to deterioration. Synthetic sleepers made of hard polyurethane foam and glass fiber are a recent unique development in Japan. They are designed for long service life (more than 60 years) while maintaining the physical properties of wood sleepers. They are being used increasingly over steel girder bridges, switches, and other sections where maintenance or replacement is difficult.

'Ladder sleepers' are another on-going development. They consist of 12-m long pre-stressed longitudinal concrete members bound by lateral steel tubes like a ladder. The rails are supported continuously on the concrete members, which distribute the load lengthwise, reducing the need for ballast maintenance.

Rail fastenings

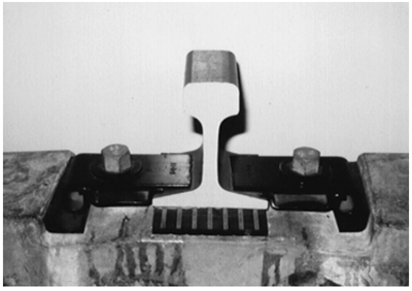
In the early days, dog spikes or other simple devices were used to fasten the rail to timber sleepers. With the introduction of concrete sleepers, the spikes were replaced by double elastic fastenings in which the rail is fastened by a spring using rubber pads or other cushioning materials inserted between the rail and sleeper. Rail fastenings distribute load and dampen vibration and are an essential component in high-speed train operation. Leaf springs are used in Japan primarily because of cost and adjustability, and in France because of fastening force and bearing ability. Wire springs are preferred in Germany because of fastening force



Gas pressure track-side welding *(RTRI)*

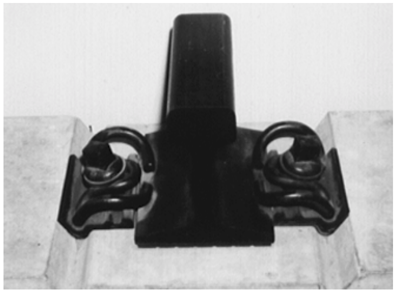
Newly-developed 'Ladder Sleepers' *(RTRI)* and adjustability (Figure 3).

Figure 3 Different Rail Fastenings



Shinkansen 102 Leaf Spring

TGV Nabla Leaf Spring



ICE Vossloh Wire Spring

(RTRI)

Shinkansen track structure

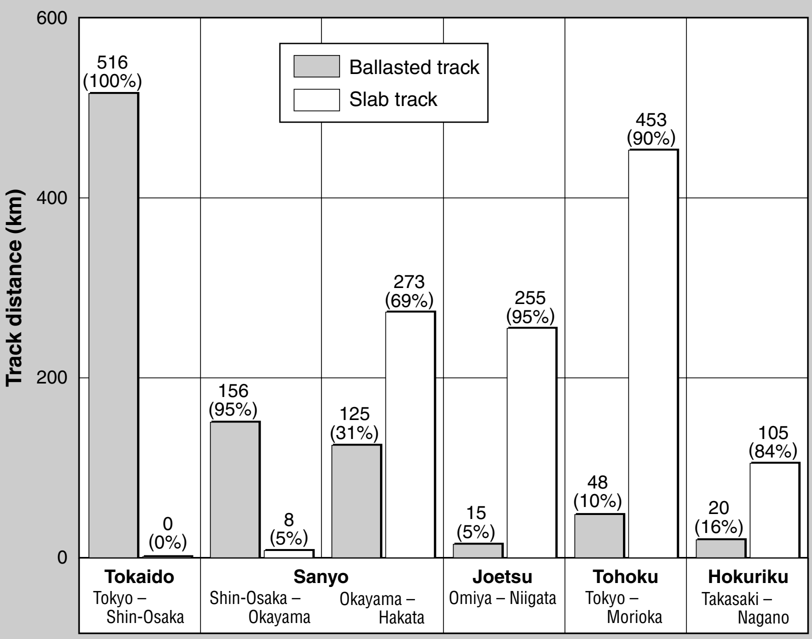
The Tokaido Shinkansen began operation in 1964 between Tokyo and Osaka at a maximum speed in excess of 200 km/h for the first time in the world. When the line was first envisaged, there were two plans for the gauge. One was to increase the transport capacity by adding narrow-gauge double track to the existing Tokaido Line. The other was to increase the capacity while halving the journey time by building a standard-gauge double-track line. The latter plan was eventually chosen, and the new line took a different route from the old Tokaido Line with many viaducts, embankments, and tunnels and without level crossings.

New rails, sleepers, and fastenings were designed for the high-speed line. The Tokaido Shinkansen track features:

- 1435-mm standard gauge
- CWR and concrete sleepers throughout
- Movable nodes eliminating gaps at turnouts and crossings
- Long rails joined by expansion joints to minimize gauge fluctuation due to thermal elongation and shrinkage
- New-design 53 kg/m rail (50T and later entirely replaced by 60 kg/m rail)

The Tokaido Shinkansen was soon followed by the Sanyo, Tohoku, Joetsu and Hokuriku Shinkansen built from 1972 to 1997. The maximum speed was raised from the initial 210 km/h to a more recent 260 to 300 km/h. Around 1967, efforts were started to develop slab tracks to prepare for the expected sharp increase in transport demand and higher operation speeds. Slab track was first introduced on the Shin-Osaka to Okayama section of the Sanyo Shinkansen which started operation in 1972. Today, it is the standard track bed for shinkansen. Figure 4 shows the proportions of ballasted and slab tracks used on each shinkansen.

Figure 4 Proportions of Ballasted and Slab Tracks on Shinkansen



Slab Tracks

Slab versus ballasted tracks

About 30 years ago, European railway engineers in countries with advanced railway technology were examining car and track systems for trains running at speeds over 200 km/h. Their main concern was whether it would be possible to repair the track ballast frequently enough before it was loosened by the severe impact of the high-speed train operation. At that time, Japan decided to use ballasted tracks based on the then new theory of 'optimization of ballasted track considering maintenance requirements'—a wise decision later borne out by the success of the Tokaido Shinkansen. The French and German railway operators had slightly different views about this issue. In France, it was thought that speeds over 200 km/h were possible on ballasted tracks, but in Germany, it was thought that although ballasted track could endure speeds up to 200 km/h, slab track or other types of ballasted tracks would be required for higher speeds.

In May 1988, the German ICE marked a speed of 407 km/h and then in May 1990, the French TGV marked a record of 515 km/h—both records were on ballasted tracks. Meanwhile, in Japan, the highest speed at that time of 425 km/h was reached in December 1993 on slab tracks of the Joetsu Shinkansen. The current speed record in Japan is 443 km/h established on ballasted track on the Tokaido Shinkansen by the experimental 300X shinkansen belonging to JR Central.

Structure of slab tracks

A slab track means a reinforced concrete (RC) slab laid on a viaduct or other rugged bed, and secured to the bed using cement asphalt (Figure 5). Development of slab tracks began in 1965 and, after many experimental installations, they were used in commercial operation for the first time on the section between Shin-Osaka and Okayama on the Sanyo Shinkansen. Today, slab track is the standard on concrete bed sections such as viaducts and tunnels. Slab tracks are also being used experimentally on the earthwork section between Takasaki and Nagano of the Hokuriku Shinkansen (presently called Nagano-bound Shinkansen) which began operation in October 1997.

Economy of slab tracks

A 1990 comparison of the economic merits of ballasted and slab tracks on the Tohoku Shinkansen shows that slab track construction costs 1.3 times more than ballasted tracks. However, this difference balances out after about 9 years due the lower maintenance costs of slab track. Since slab track is lighter than ballasted track as a whole, the construction cost of a new railway based on slab track, including the viaduct cost, can be less in certain cases. The same holds true for tunnel sections because the lower track height reduces the tunnel cross-sectional area, cutting construction costs by about 30%. This alone is more than likely to offset the difference in construction costs between slab-track and ballasted-track railways. As a result, some people claim that slab track is more advantageous.

New Track Designs

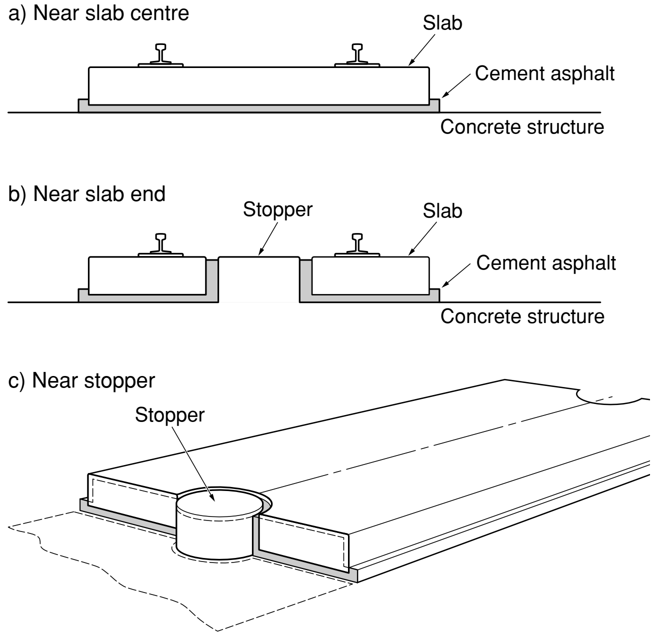
Labor-saving track designs for existing lines

It is generally thought that the following measures minimize normal track subsidence:

- Increasing track rigidity or using larger sleepers
- Increasing track elasticity
- Increasing binding of bed

The photograph on the next page shows

Figure 5 Structure of Slab Track



Labour-saving E-type paved track (RTRI)

the E-type paved track, an example of a labour-saving track that has been developed and is now in use.

Vibration-reducing tracks

A growing social concern is protecting the track-side environment and residents from pollution problems caused by faster train operations or construction of projected shinkansen. Protection from vibration and noise is particularly indispensable. Increasing operation density and other elements are causing growing problems, making it more difficult than ever to maintain normal conditions. Easing the need for maintenance work is also a necessity. The photograph below shows the newly-developed solid-bed track with removable resilient sleepers. In addition to having anti-vibration performance, the sleepers can be replaced easily when elastic fatigue occurs.

High-speed turnouts

Earlier shinkansen used 1:18 turnouts because the operation modes did not require high-speed turnouts. However, the new Hokuriku Shinkansen uses a newly-developed 1:38 turnout because the new line branches off the Joetsu Shinkansen at about 3.3 km from Takasaki Station. This new turnout has a lead curve radius of 4200 m, an overall length of approximately 135 m, and a high turnout side speed of 160 km/h.

Track Maintenance

Need for track irregularity control

The frequent passage of trains on tracks, especially ballasted tracks, loosens and deforms the ballast and/or the bed supporting it. This leads to minor irregularities and bending (collectively referred to as track irregularity). In addition, frequent train passages increase the grade sag at rail joints and welded joints as well as the rail surface roughness.

When a carriage runs on a track with these irregularities, it moves up and down as well as to right and left. The behaviour varies with the nature of the irregularity. A carriage is typically comprised of three elements: body, truck, and axles (Figure 6). Each element has a unique natural frequency affecting movement. A slow change in track irregularity over a long span (known as a long-wave track irregularity) mainly affects the vertical and lateral body vibration resulting in a poor ride. A short-wave track irregularity (rail surface irregularity, etc.) causes shock and high-frequency vibration between the wheel and rail, resulting in increased load on the track, noise, and vibration.

A carriage running along a curve at high speed is not affected only by track irregu-

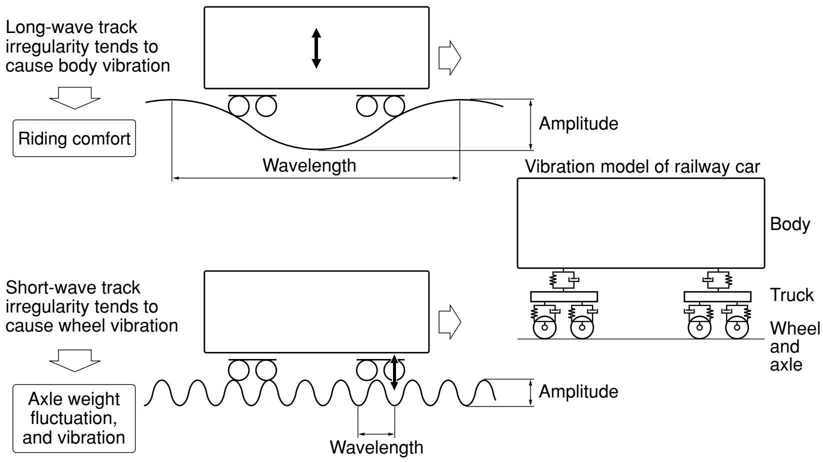
Newly-developed solid-bed track with removable resilient sleepers (RTRI)

High-speed turnout (1:38) (RTRI)

larity. The passengers feel thrown towards the outside of the curve due to the unbalanced centrifugal force which depends on the speed. In addition, a large reaction force is applied to the rail, causing the truck to rotate along the curve. These factors increase the burden of track maintenance. A large, lateral track irregularity can even cause derailment due to climbing or jumping of the wheel over the rail. An increased lateral thrust can spread the rails, also leading to derailment.

Targets for controlling track and rail surface irregularity must be established, and the track must be inspected accordingly at regular intervals, to maintain safety and ride quality, and to minimize dynamic loads, noise and vibration.

Figure 6 Wavelength of Track Irregularity and Car Movement



Role of track inspection cars

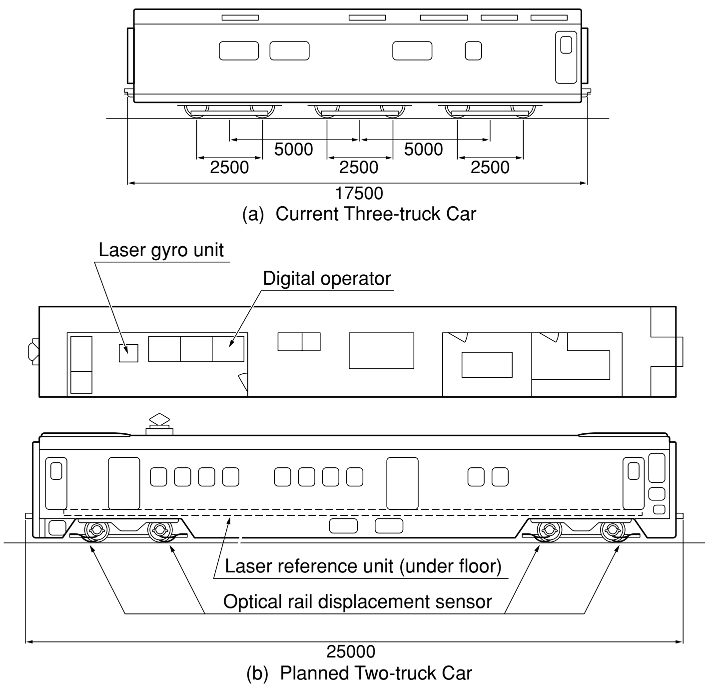
Control of track irregularity is performed at regular intervals and consists of: (1) inspecting track condition, (2) assessing repair need, (3) planning repair, (4) repairing, and (5) confirming repair work. The track inspection car plays an important role in inspecting the track condition, pinpointing sections requiring repair, and confirming the repair work.

Track inspection cars such as the narrow-gauge model built in the 1960s and the shinkansen model nicknamed 'Doctor Yellow' (*JRTR* 11, front page) built in the 1970s, simultaneously measure the track surface at three points at 5-m intervals. Track irregularity is detected based on the relative positions of the measured points. This method (called the '10-m chord alignment method') requires a special car with three trucks. In addition, the design limits the maximum speed to around 200 km/h. These limitations called for development of new track inspection cars allowing higher maximum speeds (for shinkansen tracks), lower costs, and multiple functions (for conventional tracks).

These needs are currently being met by developing a two-truck track inspection car for shinkansen tracks with a maximum speed in the range of 300 km/h, approaching that of commercial trains. The new inspection car uses three of its four axles to obtain data that are converted to similar data to those obtained by the earlier three-truck car. It also features laser-based equipment, a lightweight optical sensor for measuring rail displacement, a high-performance gyroscope, and other technologies (Figure 7).

Similar developments are also under way for an entirely new low-cost track inspection car for narrow-gauge tracks. This new system computes displacement from eas-

Figure 7 Design of Track Inspection Cars



ily-measured acceleration; it also features other non-contact equipment, such as optical and electromagnetic displacement sensors.

Track irregularity control indexes

Ride quality is noticeably affected by long-wave track irregularity; passenger cars on both shinkansen and conventional lines tend to sway at a frequency of 1.0 to 1.5 Hz. The track irregularity wavelength inducing this sway frequency corresponds to 60–80 m at about 300 km/h on the shinkansen, or 30–50 m at about 160 km/h on conventional lines (Figure 8). However, the current 10-m chord alignment method is designed primarily for inspecting 10- to 20-m track irregularity, not for longer irregularities. Consequently, the JRs generally use a 40-m chord alignment method for shinkansen and a 20-m chord alignment method for conventional lines. These methods have a better correlation with carriage behaviour, contributing to easier data processing and easy-to-identify control indexes.

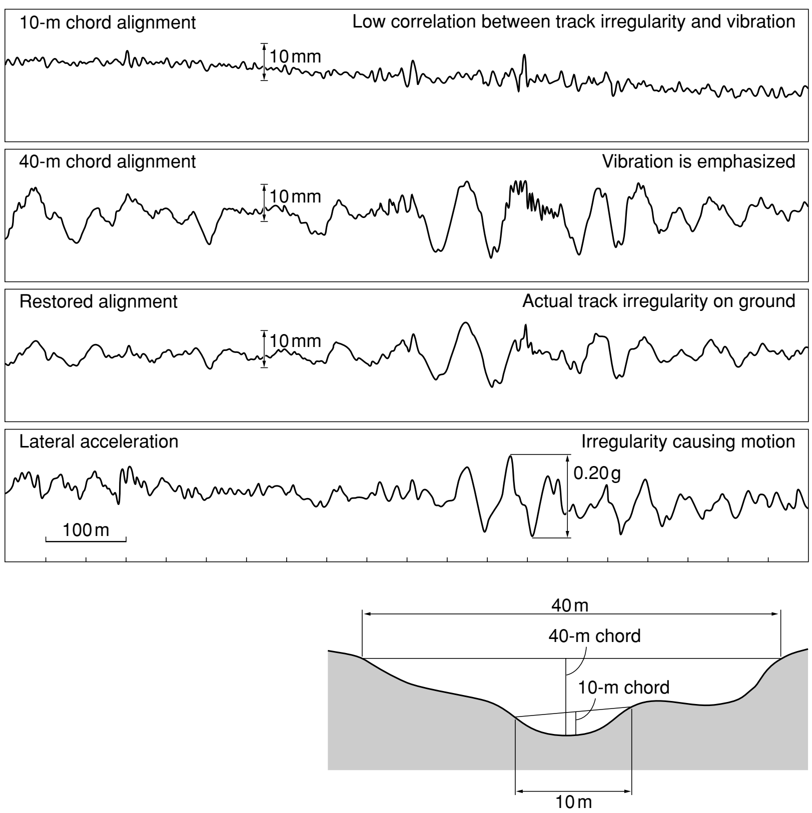
The car's lateral behaviour or ride quality on curves is affected by two factors: the unbalanced centrifugal force which depends on the cant and the train speed, and the lateral motion due to track irregularity. Ride quality evaluation taking these factors into consideration is used to determine the alignment maintenance target for curves.

Climbing derailment is caused primarily by alignment irregularity and twist. The former increases transverse pressure, while the latter lifts wheels due to relative twist between the truck and the track. Until the 1970s, multiple-cause freight car derailments were quite common. They were found to be due to level irregularities inducing car rolling, and alignment irregularity causing increased lateral thrust and attack angle. Based on these findings, compound track irregularity was set as a new control index. Freight car derailments due to multiple causes decreased significantly with improved carriage performance and stricter inspection based on the new control index.

Shinkansen wheel-rail noise during high-speed operation primarily refers to rolling noise, occurring when sound is emitted as a result of vibration of the wheel and the rail due to minor irregularities between them. Therefore, rolling noise can be reduced effectively by grinding out rail surface irregularities. Rail surface irregularity is evaluated by a rail roughness index based on a 20-cm chord alignment. An index of 20–50 µm is the target for sufficiently reducing rolling noise.

Irregularities due to rail welds and waving wear of the rail cause rolling noise, increased vertical vibration of the wheel, and track deterioration. These irregularities must be located and corrected by rail grinding. Rail surface roughness can be inspected directly but is inefficient due to the slow measurement speed. As a result, a new inspection method has been developed using axlebox vertical vibration acceleration, which has a close correlation with fluctuation in the load on wheels of passenger cars. This method more efficiently identifies trouble spots causing such fluctuations.

Figure 8 Waveforms of Track Irregularity and Shinkansen Car Behaviour

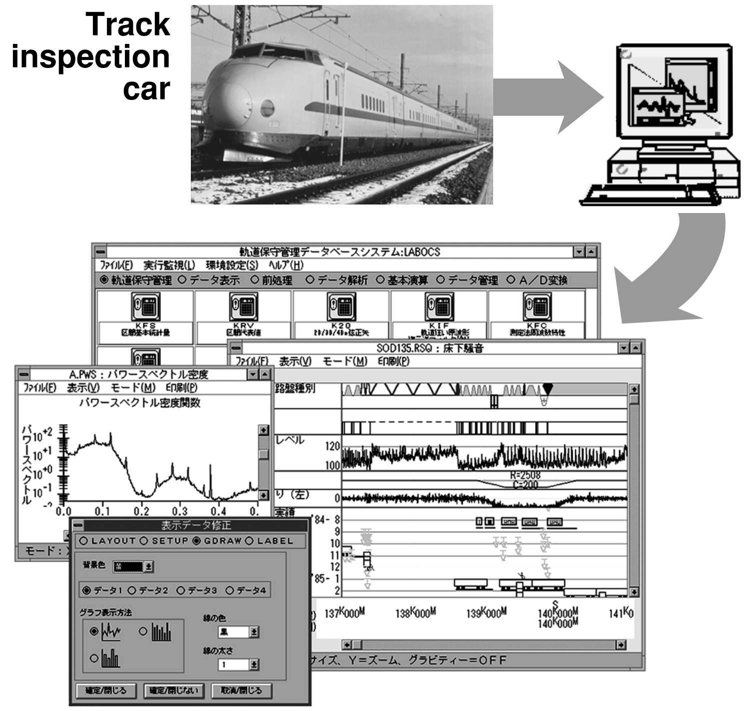


Use of track irregularity data

Track irregularity data obtained by a track inspection car can be converted into digital data, combined with track environment data and stored in a database. A track maintenance database system called 'micro-LABOCS' (Figure 9) is commonly used to store these data. It calculates track section evaluation indexes and long-wave track irregularity, analyses the track irregularity wavelength and relationship with car behaviour, and identifies long-term changes in track irregularity.

The system provides a restored waveform calculated from 10-m chord alignment data that accurately represents the actual track profile over a limited waveband (for example, 6–100 m). This is compared with the track design profile and track maintenance is performed to restore the design track alignment. Efforts are currently under way to coordinate this system with an automatic control system for tamping machines to introduce a completely new dimension in fully-automated track maintenance. ■

Figure 9 'micro-LABOCS' Track Maintenance Database System



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