Railway Technology Today 9 *(Edited by Kanji Wako)*

Protecting the Trackside Environment

By Tatsuo Maeda

More and more people are calling for measures to protect the environment, and environmental degradation caused by railways is also a matter of concern. It is now well recognized that train speeds cannot be raised further without first considering how the extra speed might negatively impact the environment. Any plan to increase operating speeds must include an assessment of the possible environmental problems, and steps must be taken to ensure that problems do not arise.

Environmental problems associated with railways include: track noise, micro-pressure waves generated at tunnels, pressure variations caused by passing trains, ground vibrations, radio interference, and shade cast by railway structures. This article looks at the first four problems, and discusses how technology can be applied to alleviate them to some degree.

Table 1 Environmental Standards for Shinkansen Noise

Category	Standard
I	70 dB(A) max.
II	75 dB(A) max.

Notes: I = Mainly residential areas
II = Other areas for ordinary economic (commercial and industrial purposes) activities

Railway Noise

Environmental quality standards governing shinkansen noise and compliance

Japan's rapid economic growth in the 1960s had a severe impact on the environment. As a countermeasure, the government enacted the Basic Law for Environmental Pollution Control in 1967. This law remained in effect until adoption of The Basic Environment Law in 1993. Between these two dates, in 1975, the Environment Agency announced new environmental standards directive for shinkansen railway noise (Table 1). These standards, which were based on the 1967 law set the maximum noise level at 70 dB(A) for Category I (mainly residential areas), and at 75 dB(A) for Category II (non-Category-I areas used for ordinary economic activities, such as commercial and industrial activities). It is important to note that the Prefectural governors can determine category designations.

The government also defined how noise measurements were to be conducted, and how the results were to be evaluated.

Measurements must record the peak noise levels of 20 shinkansen trains passing in each direction consecutively. The measurements are taken outdoors with measuring instruments 1.2 m above the ground in places known to have high volumes of railway noise, and where noise from shinkansen is deemed to be causing problems. The measurements are conducted during normal weather conditions when trains pass the measurement point at normal speeds.

The shinkansen railway noise should be evaluated by the energy mean value of the higher half of the measured peak noise level. The measuring instruments used shall be a noise meter with A-weighted calibration and slow dynamic response.

The 1975 directive issued by the Environment Agency allowed for a grace period before the railway had to comply with the standards (Table 2). When the permissible levels were drawn up, two shinkansen lines were already in operation (Tokaido and San'yo), two others were under construction (Tohoku and Joetsu), and more lines were in planning. Lines already constructed and lines under construction were granted a grace period before compliance.

After these provisions were adopted, the railway implemented a variety of measures to reduce noise levels along shinkansen tracks. In 1991 and 1994, the Environment Agency conducted surveys to determine the extent of compliance with the 75 dB(A) standard in first-priority areas (Table 3).

The 210 km/h maximum speed for

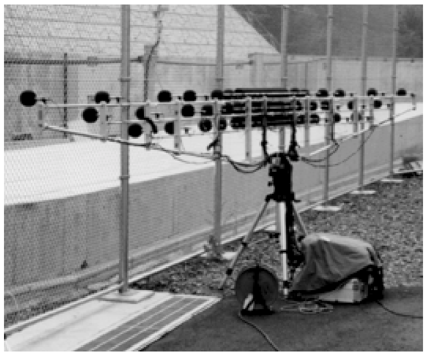
Table 2 Compliance Deadlines for Shinkansen Noise

<table>
<tr><th colspan="2" rowspan="2">Permitted Noise Level for Trackside Zones</th><th colspan="3">Compliance Deadline</th></tr>
<tr><th>Track already built</th><th>Track under construction</th><th>Planned track</th></tr>
<tr><td colspan="2">Zones with permitted level of 80 dB(A) or more</td><td>3 years max.</td><td>At start of operations</td><td rowspan="4">At start of operations</td></tr>
<tr><td rowspan="2">Zones with permitted level of >75 to <80 dB(A)</td><td>Areas contiguous with Category-I areas</td><td>Within 7 years</td><td rowspan="2">Within 3 years after start of operations</td></tr>
<tr><td>Areas not contiguous with Category-I areas</td><td>Within 10 years</td></tr>
<tr><td colspan="2">Zones with permitted level of >70 to ≤75 dB(A)</td><td>Within 10 years</td><td>Within 5 years after start of operations</td></tr>
</table>

Table 3 Compliance with 75 dB(A) Standards for First-Priority Track Sections

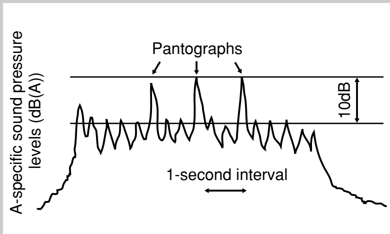
Shinkansen Line	Items	1991	1994
Tokaido	Number of measurement sites	120	
	Average noise level (dB(A))	73.4	72.1
	Percentage of sites registering ≤75 dB(A)	78	98
San'yo	Number of sites measured	62	
	Average noise level (dB(A))	73.1	72.3
	Percentage of sites registering ≤75 dB(A)	84	98
Tohoku	Number of sites measured	26	
	Average noise level (dB(A))	75.8	72.9
	Percentage of sites registering ≤75 dB(A)	50	100
Joetsu	Number of sites measured	15	
	Average noise level (dB(A))	74.1	71.0
	Percentage of sites registering ≤75 dB(A)	67	100
Total	Number of sites measured	223	
	Average noise level (dB(A))	73.7	72.2
	Percentage of sites registering ≤75 dB(A)	76	98

(Environment Agency)



Microphone array *(RTRI)*

Figure 1 Noise Level History from Microphone Array



shinkansen in 1975 had risen to 270 km/h by 1994, but the surveys found no non-compliance along the Tohoku or Joetsu shinkansen lines. The current maximum speed for Series 500 rolling stock on the San'yo Shinkansen is 300 km/h, while that for other shinkansen trains is 270 km/h, but it is very rare for noise levels to exceed 75 dB(A) anywhere on these lines. Indeed, on some sections of the Nagano-bound Shinkansen, 3-m high sound barriers keep noise levels below 70 dB(A).

Shinkansen noise components

Before attempting to reduce train noise, we must first identify the various sources and we must determine how much each contributes to the overall noise at the measuring points. In the case of shinkansen, noise can be classified as pantograph noise, aerodynamic noise generated by the car bodies, running noise generated from the underbody, and noise from concrete structures.

Pantograph noise includes aerodynamic noise generated at the pantograph and pantograph shield, frictional noise caused by the collector running on the catenary, and sparking noise between the collector and catenary. Aerodynamic noise generated by the car bodies is caused by the flow of air over the carriage outer surface and includes noise generated at the train nose, cable head, window louvres, air-conditioning equipment, and the gaps between cars. Running noise is generated from the underbody and includes the rolling noise of wheels on rails, gear noise, noise generated by bogies turning slightly under the carriages, etc. Noise from structures is emitted from the lower surface of the concrete elevated track.

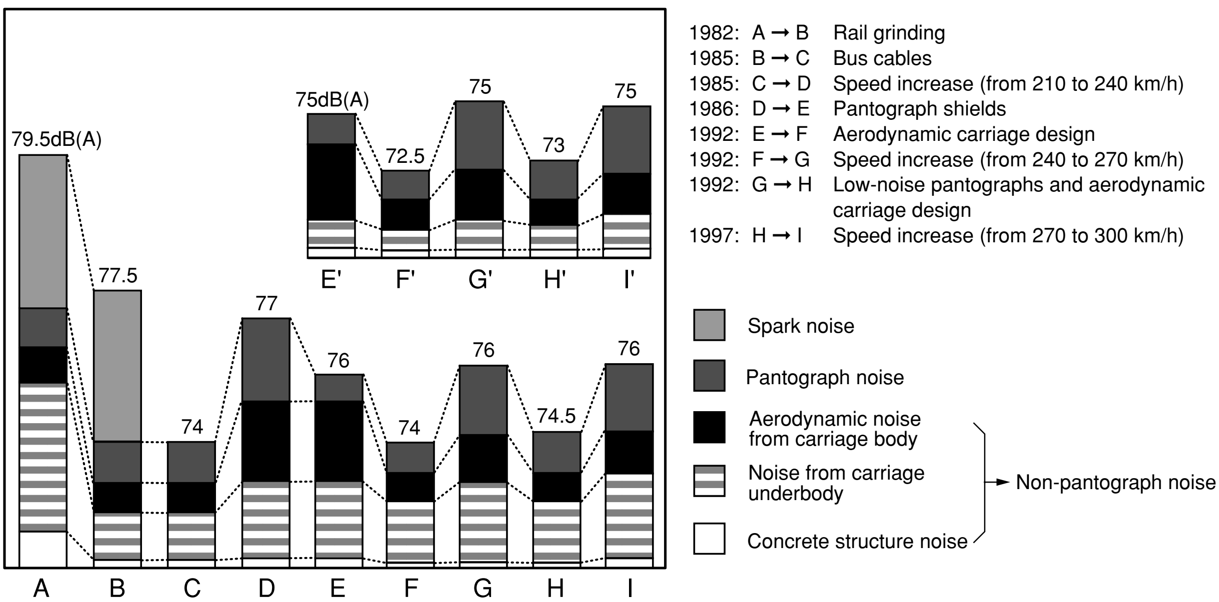
A microphone array is used to identify the extent to which each source is contributing to the overall noise. Each microphone in the array is positioned to register specific half-wavelength intervals in each frequency band. A special directivity is given by weighting each microphone's output and calculating the aggregate. The MY-10 microphone array directivity is such that it is possible to distinguish sounds over a plane width of about 6 m, with the sound arriving from 25 m. Figure 1 shows a noise level time history for shinkansen noise recorded by this array. To determine the extent to which each noise source contributes to the overall noise pattern, the high and low values in the noise level time history are used, and the noise sources are approximated to non-directional noise sources with fluctuating power densities within each 12.5-m interval.

Pantograph noise contributes much more to the noise at the ground-based measuring point than any other noise source within the same plane. For all intents and purposes, the only factor contributing to noise emitted when a pantograph passes a specific place is pantograph noise.

The microphone array does not have vertically oriented microphones, so it cannot differentiate vertical sounds. Therefore, the level of noise generated from the underbody is measured close to the rail and the measurements are evaluated in a way that separates aerodynamic noises generated by the car body from noises from the underbody.

Noise from concrete structures is mainly composed of frequencies below 100 Hz that cannot be picked up by a microphone array located some distance from the tracks. Therefore, the noise levels of

Figure 2 Relative Importance of Shinkansen Noise Sources and Results of Noise Countermeasures



Measured at ground level, 25 m from concrete elevated track, 8 to 10 m from ground level to rail level with slab track
Cases A to I: Track with straight noise barrier (2 m higher than rails)
Cases E' to I': Track with inverse L-type noise barrier (sound-absorbing material, 2 m higher than rails)

Parabolic directional microphones *(RTRI)*

concrete structure, are evaluated by measurement using a microphone directly under the elevated track structure.

Sound analyses show that:

- Aerodynamic noise is proportional to the sixth power of train speed
- Wheel and rail rolling noise is proportional to the second or third power of train speed
- Concrete structure noise is proportional to the second power of train speed

Parabolic directional microphones are also used to analyze sound contributions more precisely.

Reducing impact of shinkansen noise sources

The noise analysis method described above is used to determine the extent to which each noise source contributes to shinkansen noise, and to determine the effectiveness of each noise-reduction countermeasure. Some results are shown in Fig. 2. The measurement point was at ground level, 25 m from the centre of the concrete elevated track structure, 8 to 10 m below the track level. A 2-m high sound barrier had been installed. In cases A to I, the barrier is a straight barrier, while in cases E' to I', it is an inverse L-type barrier with sound-absorbing materials.

In cases A, B and C, the train speed was 210 km/h. Case B (1982) shows improvement over A because the rails had been smoothed by grinding to reduce rolling noise, which is the main component of underbody noise. Case C (1985) shows improvement over B because bus cables had been installed between pantographs to reduce sparking noise. When bus cables are installed, even if one pantograph bounces off the catenary, current still flows through the other pantograph, preventing sparks.

In case D (1985), shinkansen speeds had been increased from 210 to 240 km/h, explaining why noise levels increased over case C. In cases D, E and F, the train speed was 240 km/h. Case E (1986) shows an improvement over Case D, because pantograph shields had been mounted to reduce pantograph noise. The shields reduce the speed of the air flowing around the pantograph, reducing aerodynamic noise generated by the pantograph itself and muffling any aerodynamic noise emitted by the pantograph. Case F (1992) shows an improvement over E, because the smoother aerodynamic exterior of the rolling stock reduced the noise.

In case G (1992), shinkansen speeds had been increased from 240 to 270 km/h, explaining why noise levels increased over case F. Case H (1997) shows improvement over case G, because a low-noise pantograph and smoother rolling stock exterior had been adopted, cutting down on both pantograph and aerodynamic noise.

Train speeds were increased with the surprising result that large pantograph shields themselves became a source of aerodynamic noise. To overcome this problem, a low-noise pantograph was developed, and the pantograph shield was reduced in size to the point that it shields only the pantograph insulators. In case I (1997), shinkansen speeds had been increased from 270 to 300 km/h, but on track sections with an inverse L-type noise barrier made of sound-absorbing materials, the sound intensity is no higher than 75 dB(A).

When the Tokaido Shinkansen was inaugurated in 1964, the noise level for Series 0 rolling stock was 90 dB(A) at train speeds of 210 km/h. Clearly the aforementioned changes over the last 35 years have yielded huge improvements.

Environmental guidelines on narrow-gauge lines

In response to recent public concern over noise pollution, in 1995, the Environment Agency issued guidelines for noise levels on narrow-gauge lines (Table 4). The guidelines specify a maximum of 60 dB(A) during the day and evening (0700 to 2200) and 55 dB(A) at night for equivalent noise levels (L_{Aeq}) on newly constructed lines. The guidelines also call on railways to reduce noise levels further in residential areas, especially residential-only zones. Furthermore, when railways make significant modifications to existing tracks—for example, double or quadruple tracking, or construction of long elevated sections at crossings—the noise levels must be lower than before the modifications. The guidelines do not clearly specify noise levels on existing tracks. However, the public is increasingly unwilling to tolerate railway noise, so railway companies must clearly identify the various noise sources and develop affordable countermeasures.

Low-noise pantograph and insulator cover on Series 500 shinkansen (JR West)

Tunnel Micropressure Waves

Effect of tunnel micropressure waves

Trial runs on the San'yo Shinkansen in March 1975 resulted in protests from residents living along the track because their doors and windows were vibrating from explosion-like sounds generated when shinkansen trains passed through long tunnels on slab track. This new noise problem had not been seen before.

The sound is caused by compression waves that are generated when a train enters a tunnel at high speed. These compression waves propagate at the speed of sound through the tunnel and a part of them is changed into pulse pressure waves radiated from the tunnel exit. These pulse pressure waves are called micropressure waves. In Japan, tunnel micropressure waves are considered to be a low-frequency vibration problem, because they are pulse waves and include low-frequency components. Japan still has no environmental standards or

Table 4 Guidelines for Maximum Railway Noise on Narrow-Gauge Lines

New lines	Equivalent noise levels (L_{Aeq}) of 60 dB(A) max. from 0700 to 2200 and 55 dB(A) max. from 2200 to 0600). Special efforts to reduce noise levels in residential areas.
Large-scale upgraded lines	Noise levels must be lower than before upgrade.

guidelines covering these tunnel micropressure waves.

The tunnel micropressure wave effect has three phases: generation of compression waves when the train enters the tunnel, propagation of compression waves through the tunnel, and radiation of micropressure waves from the tunnel exit (Fig. 3).

The micropressure wave peak is approximately directly proportional to the pressure gradient of the compression wave front exiting the tunnel. At the tunnel entrance, the pressure gradient of compression wave front is approximately directly proportional to the cube of the train velocity, because pressure increases as the square of the train velocity at the tunnel entrance, while the time for the pressure change is inversely proportional to the train velocity at the tunnel entrance.

The pressure gradient of the compression wave front propagating through the tunnel varies with the track structure. In a tunnel with slab track, the wave's non-linear effect is greater than the friction exerted by the tunnel walls and track, so the wave front is steeper, creating a steeper pressure

Figure 3 Tunnel Micropressure Wave Effect

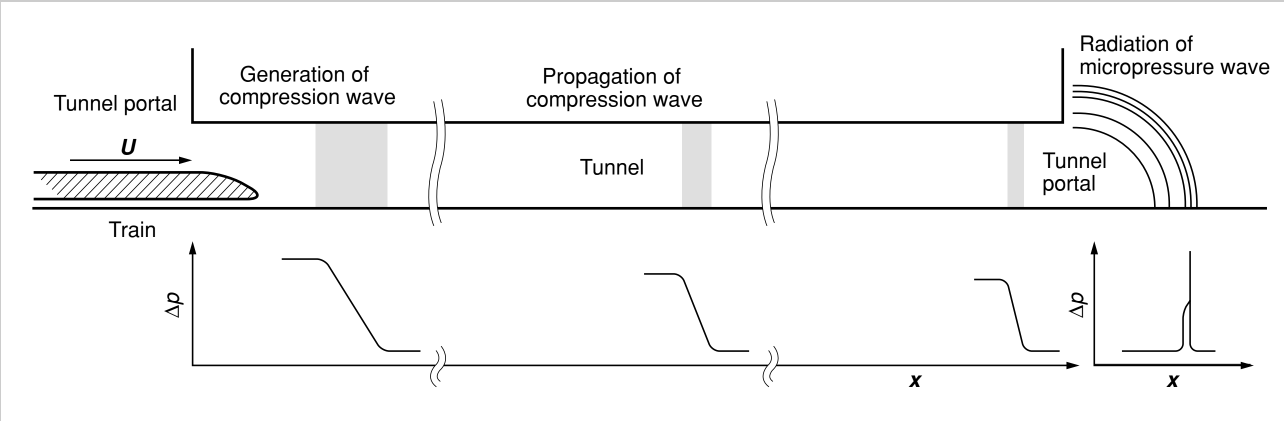


Figure 4 Tunnel Micropressure Waveform

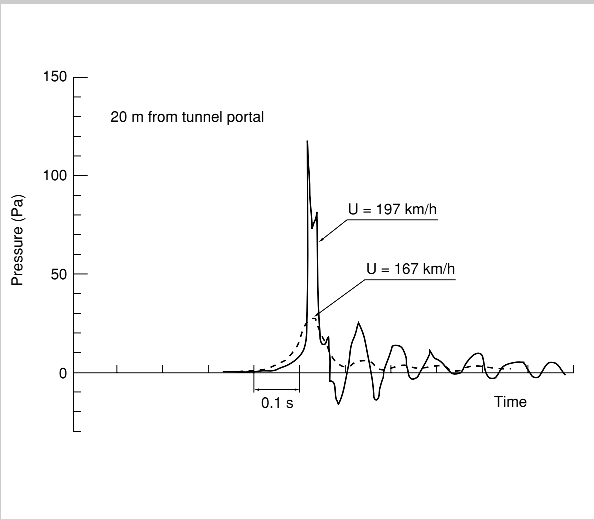


Figure 5 Effect of Tunnel Length and Track Type on Peak Micropressures

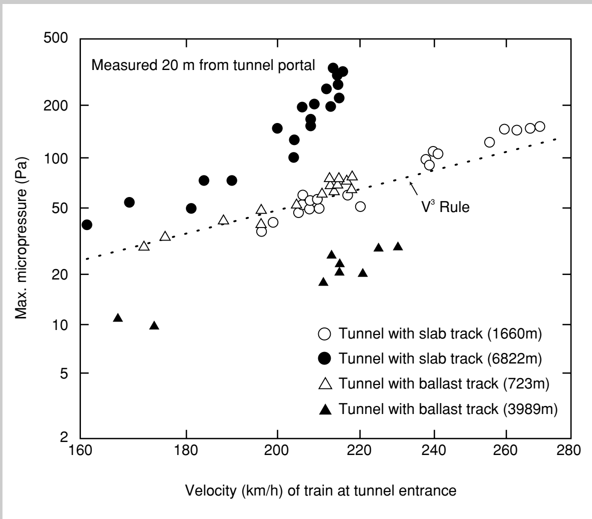


Figure 6 Relationship between Length of Tunnel Hood and Micropressure Wave Reduction

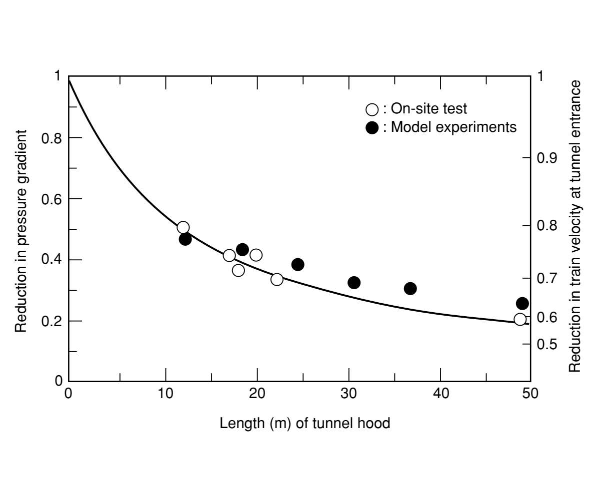
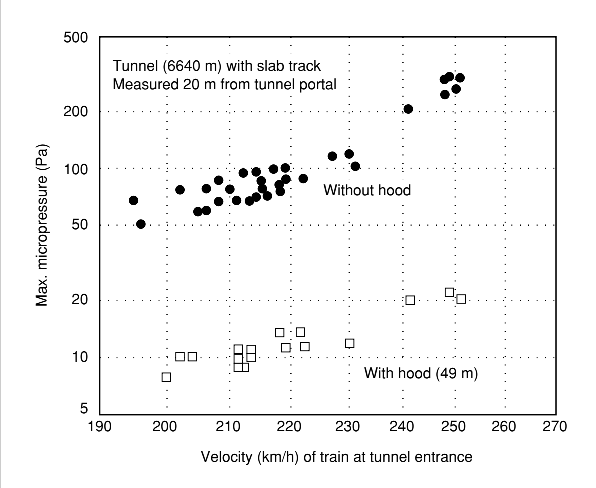


Figure 7 Effect of 49-m Tunnel Hood on Micropressure Waves



gradient. On the other hand, in a tunnel with ballasted track, the wave's non-linear effect is smaller than the friction exerted by the ballast, thereby reducing the pressure gradient of the wave front. This explains why micropressure waves are not an issue on the Tokaido Shinkansen which uses ballasted track for most sections. Micropressure-wave-related noise pollution only became an issue after construction of the slab-track San'yo Shinkansen.

In short tunnels, the peak value of a micropressure wave is approximately in direct proportion to the cube of the train velocity at the tunnel entrance, regardless of track type. This is because pressure gradient variations are not conspicuously great during the propagation of compression waves. On the other hand, track type is an important consideration in long tunnels. In a tunnel with slab track, the peak value for micropressure waves exceeds the cube of the train velocity. However, in a tunnel with ballasted track, the peak value for micropressure waves is smaller than it would be in a short tunnel. The amplitude of micropressure waves emanating from the tunnel exit is inversely proportional to the distance from the tunnel entrance.

Figure 4 shows a typical micropressure waveform, measured 20 m from the tunnel portal. Figure 5 shows the effect that tunnel length and track type have on the peak values. The horizontal axis in Figure 5 is the train velocity.

Micropressure waves cause a sudden sound, rather like an explosion, before the train exits a tunnel. These sounds are viewed more negatively by the public than other railway noises.

Countermeasures to micropressure waves

Countermeasures involve modifying the design of both the tunnel and rolling stock. The tunnel design can be modified in a number of ways to diminish the wave front pressure gradient by using:

Streamlined nose of Series 500 shinkansen *(JR West)*

- Tunnel portal hoods to reduce the pressure gradient of the compression waves
- A shelter with slits between adjacent tunnels to permit escape of the compression waves
- Inclined or vertical shafts to bypass compression waves

Rolling stock can also be designed to reduce the pressure gradient at the tunnel entrance by reducing the cross-section area and extending the train nose to the optimum shape.

Tunnel entrance hoods

Tunnel entrance hoods are often used to reduce micropressure waves in shinkansen tunnels. The effect depends on the hood length (Fig. 6). A typical tunnel entrance hood has a cross-section area of about 1.4 times that of the main tunnel with openings in the sides. Model experiments are often used to determine which opening sizes and positions minimize the pressure gradient in the actual tunnel.

As Figure 6 shows, when the train enters the tunnel, a hood can reduce the pressure gradient by 20%. Since the pressure gradient at the tunnel entrance is in direct proportion to the cube of the train velocity, a hood has the same effect as reducing the train velocity by 60%.

Figure 7 shows an example of the reduction in micropressure waves achieved by a hood. Without the hood, a train travelling at 250 km/h generates micropressure waves of approximately 300 Pa—falling to 20 Pa with the tunnel hood. This far lower level corresponds to the pressure created by the same train entering the tunnel at 150 km/h and ensures that no explosive sound is heard at the tunnel exit.

Optimum train nose shape

Pressure gradients can also be decreased by reducing the cross-sectional area of cars, but this diminishes space in the carriage, so there is a limit to the usefulness of this method and most efforts are concentrated on optimizing the shape of the train nose. Model experiments show that micropressure waves are minimized by a nose shape with a uniform longitudinal section except at the extreme tip (Fig. 8). Some examples of these nose designs are used by the Series 500 shinkansen operating at 300 km/h by JR West on the San'yo Shinkansen, by the Series 700 shinkansen developed jointly by JR Central and JR West, and by the E1 through E4 shinkansen operated by JR East.

Obviously, the nose design must also reduce other negative aerodynamic effects, such as pressure variations due to passing trains, aerodynamic drag, and aerodynamic noise.

Pressure Variations when Trains Pass

Pressure variations occurring when trains pass in opposite directions cause carriage vibration and ride discomfort. They can also cause vibration in the windows and doors of trackside buildings. The phenomenon occurs when the pressure fields generated at the heads and ends of the moving trains shift in conjunction with the forward progression. This is not a wave phenomenon like micropressure waves, but is a near-field phenomenon in which pressure decreases in inverse

Figure 8 Optimum Train Nose Shape

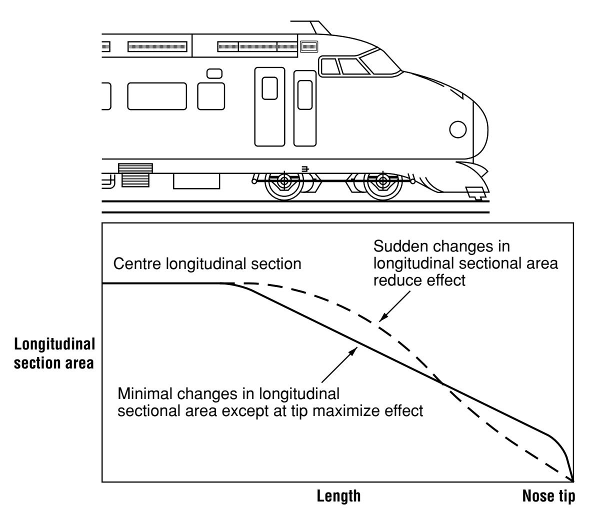
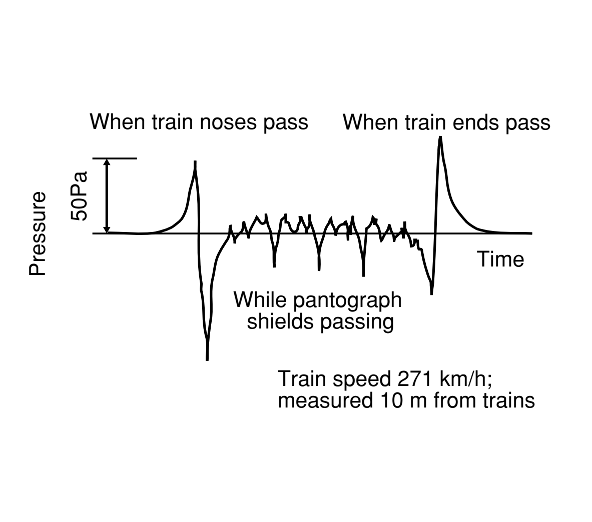


Figure 9 Passing Train Pressure Variations



This hood at the entrance to Ohirayama Tunnel (6640m) on the San'yo Shinkansen is 49 meters long. If it had been constructed at the same time as the line, it would have been concrete. *(JR West)*

Concrete tunnel hood at the Daini-arikabe Tunnel *(JR East)*

proportion to the square of the distance between the two trains. However, the phenomenon resembles tunnel micropressure waves because it makes windows and doors vibrate. In Japan, these pressure variations are considered to be a low-frequency vibration problem and they are not covered by any environmental standards or guidelines.

Figure 9 shows some examples of measured pressure variations caused by passing trains. If trains have large pantograph shields in the mid-section, the shields themselves cause pressure variations. The pressure peaks are in direct proportion to the square of train speed, while the time for the pressure is inversely proportional to train speed.

Countermeasures to pressure variations when trains pass

There are a number of possible countermeasures to pressure variations when trains pass, such as installation of pressure shield walls on the track, and optimizing the carriage longitudinal-section area and nose shape.

Figure 10 and 11 show the results of on-site experiments on the effectiveness of trackside pressure shield walls. The best effect is achieved with higher walls close to the track.

Pressure variations are less pronounced with rolling stock of smaller cross-section area, but reducing the cross-section area reduces space in the carriage.

Figure 10 Pressure Shield Wall and Pressure Measuring Points

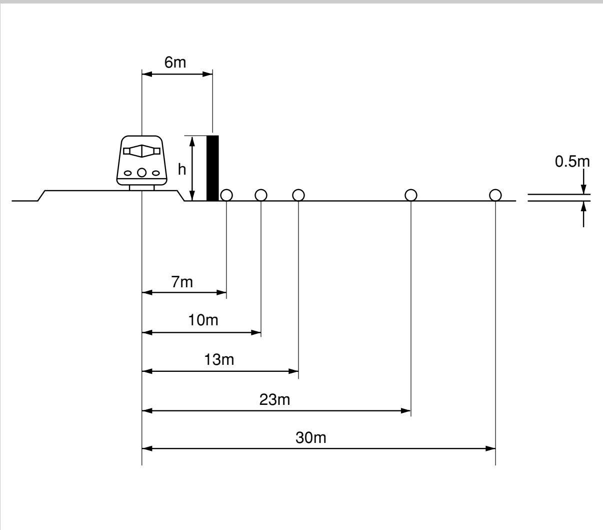
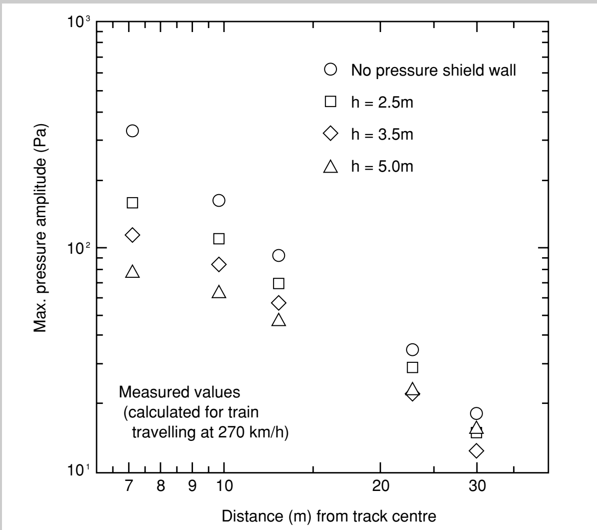


Figure 11 Effectiveness of Different Pressure Shield Walls



Aerodynamic simulations using the three-dimensional boundary element method show that the best effect is achieved when the nose is more extended and has a two-dimensional cross-sectional shape that forces the air flow upwards.

Ground Vibrations

Guidelines on ground vibrations and compliance

In 1976, the Environment Agency issued guidelines on vibrations caused by shinkansen (Table 5). These guidelines required that railways adopt measures to deal promptly with the sources of vibrations and to prevent the negative effects of vibrations in areas where increased speeds were generating vibrations exceeding 70 dB. Special consideration was also to be given to zones where tranquillity is important, such as hospitals and schools. Table 6 shows ground vibration levels recorded along shinkansen tracks during surveys by the Environment Agency in 1987 and 1988. The maximum values specified in the guidelines were not exceeded anywhere along the Tohoku and Joetsu Shinkansen, although some places along the Tokaido and San'yo Shinkansen did register values outside the guidelines.

Table 5 Guidelines on Vibration Caused by Shinkansen (received by Minister of Transport from Environment Agency in 1976)

Guidelines

(1) The railway must adopt prompt countermeasures to the source of shinkansen vibrations and must prevent negative effects of these vibrations in areas where increased speeds cause vibrations exceeding 70 dB.

(2) The railway must give special consideration to zones where tranquillity is important, such as hospitals and schools, with a view to reducing vibrations in these areas as soon as possible.

Table 6 Ground Vibration Levels along Shinkansen Tracks (recorded by Environment Agency)

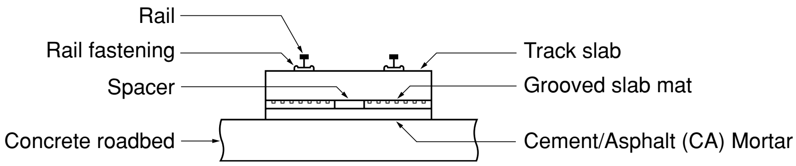
Shinkansen Line	Items	Distance from Track		
		12.5 m	25 m	50 m
Tokaido	Number of survey sites	71	73	59
	Average vibration level (dB)	63	59	54
	Number of sites exceeding guidelines	8	3	0
San'yo	Number of sites surveyed	48	49	51
	Average vibration level (dB)	61	56	50
	Number of sites exceeding guidelines	4	0	0
Tohoku	Number of sites surveyed	46	50	50
	Average vibration level (dB)	58	54	49
	Number of sites exceeding guidelines	0	0	0
Joetsu	Number of sites surveyed	25	25	25
	Average vibration level (dB)	57	53	49
	Number of sites exceeding guidelines	0	0	0

Ground vibration countermeasures

In order to save maintenance (labour) costs, slab track was developed for the San'yo Shinkansen west of Okayama. However, slab track has higher noise and vibration levels than ballasted track because the track springing is hard, the slab rigidity is high, and there is no ballast sound absorber.

These noise and vibrations were reduced by developing a vibration-isolation slab track called the G-type (Fig. 12). Track springing was improved by placing grooved slab mats under the slab in the general area of the rails. In addition, a foam spacer with a low spring constant was inserted in the gap in the centre of the slab. This was effective in reducing contact vibration and concrete structure noise. Table 7 lists some general ways that track can be modified to isolate vibrations.

Figure 12 G-Type Slab Track



Carriage-related measures include:

- Reducing car weight
- Changing axle arrangement
- Changing car spring configuration
- Improving suppression of wheel flats

Track-related measures include:

- Smoothing track surface

Table 7 Vibration Countermeasures

Carriages	• Reduce car weight • Change axle arrangement • Change spring configuration • Control wheel flats	
Track	• Smooth track surface • Soften track springing • Increase track rigidity • Install floating-slab track	• Lengthen rails by welding; grind rails; control track irregularities • Install more resilient pads and vibration-reducing ties, ballast mats, and slab mats; install solid-bed tracks with resilient ties • Switch to heavier rails; install ladder ties; reinforce roadbed
Concrete structures	• Change to rigid massive structures • Use vibration-isolation devices • Use passive dampers • Use active/hybrid dampers • Control vibration direction	• Tuned mass dampers, chained dampers • Foundation modifications (or rearrangements)
Ground	• Dig vibration-breaking trenches • Install in-ground vibration-reducing walls • Install wave-impeding blocks • Improve ground	• Hard walls; soft walls; sandwich walls of hard and soft materials
Dwellings, etc.	• Use vibration-reducing structures • Use vibration isolation devices • Use dampers	• Increase number of foundation slabs; insert additional posts and beams

- Lowering elastic coefficient of track pads
- Increasing track rigidity
- Using floating-slab track

Structure-related measures include:
- Changing to rigid and massive structures
- Using vibration isolation devices

Ground-related measures include:
- Digging vibration-breaking trenches
- Constructing in-ground vibration-reduction walls
- Laying wave-impeding blocks
- Improving ground

In addition, dwellings and other buildings can be made more vibration-proof by use of vibration dampers and vibration-isolation devices.

Conclusion

Any attempt to increase train speeds must be accompanied by efforts to deal with the resulting increase in environmental problems, such as railway noise, tunnel-related micropressure waves, pressure variations when trains pass, and ground vibrations. Unwanted environmental phenomena must be anticipated and the countermeasures must be comprehensive, including new rolling-stock designs, better track structures, and improved trackside facilities. ■

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