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Effect of track stiffness on vibration levels in railway tunnels

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Abstract

The paper discusses the difficulties in comparing and drawing conclusions from vibration measurements made in different railway tunnels. A number of new measurements are presented, which have been made and analyzed on a consistent basis. The track stiffness has been determined for each of the measurements. Graphs are presented which indicate the level of rail and tunnel floor vibration likely to occur for different track stiffnesses. The variance in the measurement results also indicates the potential error in using the data to predict vibration levels in new situations.

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1. Introduction

Control of vibration from trains running in railway tunnels is an important issue, and one now receiving increasing attention [1]. New underground railways and extensions to existing systems are being developed around the world. Residents in buildings above and alongside existing railways are becoming less tolerant of vibration from the track, and the noise that results. In the extreme, complaints and court orders can even threaten the continuing operation of the railway.

Means of controlling vibrations from trains in tunnels are known. In most cases the most practical means are at the source—that is in the railway structure itself—rather than in the transmission path or at the receiver (for example by base isolation of buildings). The mechanism that leads to most vibration is the passage of relatively inflexible steel train wheels along a relatively inflexible steel rail. Irregularities on the rail or wheel are forced through the contact between them and this leads to large forces and to vibrations of the rail. The vibrations are transmitted through the track structure into the tunnel base and walls, and then on through the ground. If the irregularities can be controlled, reduced, or removed, then the level of resulting

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vibrations is also reduced. Examples include moving switches and joints to less sensitive locations, re-profiling bad joints, and grinding away rail corrugations.

Another means of controlling vibration is through the design of the track structure. Reducing the frequency of the loaded track resonance, in which the unsprung mass of the train moves on the stiffness of the track, has been shown to be effective in reducing the level of vibrations transmitted from the rail into the base of the tunnel [2–5]. This can be achieved by increasing the mass of the resiliently supported part of the track, or by reducing track stiffness. Floating slab track (FST), which increases track mass, tends to be expensive not only because of the cost of the track itself, but because a larger tunnel is required to accommodate it. It is also often impractical to introduce FST into tunnels not originally designed for it. Reduction of the track stiffness—most often through the use of resilient rail fastening systems—is therefore the most widely employed method of controlling vibrations on both new and existing underground tracks. The track stiffness can be reduced by decreasing the stiffness of individual fasteners or by spacing them further apart. In both cases, the limitation is usually provided by the requirement to maintain track gauge and to limit rail roll under traffic.

A large variety of proprietary baseplates designed to provide low dynamic track stiffness are available. A number of measurements have been made on track which show how individual products perform under particular circumstances [6–8]. These include some tests where measurements have been made before and after installations of fasteners which have modified the track stiffness [9]. Such results may begin to give an indication of how vibration reduction is related to track stiffness.

2. Discussion of basis for comparing vibration measurements

This paper starts from the premise that it would be useful to extend such individual results to cover a wider range of circumstances and track stiffness values. In an attempt to do this, a number of recent measurements have been considered. These measurements were made on the track and in the tunnel itself, and no attempt has been made here to include or allow for the effects of differences in transmission through the ground, building characteristics or background noise level. Details of the tunnel and track structure at the different measurement sites are shown in Table 1.

Existing prediction methodologies for vibration levels in buildings above railway tunnels that are based on previous measurements already include correction terms for track structure [10,11]. The data presented here may be useful in refining these estimates.

There are a number of practical difficulties in comparing measurements at different sites, and a number of issues relating to how data can then be interpreted and used. Firstly, a given track stiffness will not always provide the same attenuation of vibrations between the rail and the tunnel base. Tunnel structures and soil conditions vary, and the combinations have different stiffnesses in different locations. The track structure and the tunnel structure form part of an interacting system. The effectiveness of a given track stiffness depends on the stiffness of the system on which it is mounted. Also, the frequencies of vibration generated from wheel and rail roughness depend on the spectrum of wavelengths of this roughness, and on the speed of the train. Vibration signals with different frequency contents will be attenuated differently by a given track system. So while the trend in attenuation with stiffness is clearly of interest, so too is an estimate of variability. This gives an indication of the potential error in using an ‘average’ result.

Table 1
Tunnel and track forms

Test	Tunnel description	Track form description
1a	Bored tunnel with iron tunnel rings	Stiff baseplate on concreted-in wooden sleeper
1b	Track form modified over 120 m	Very resilient fastener on concreted-in concrete sleeper
2a	Rectangular section double track	Stiff baseplate on resiliently fixed blocks
2b	Track form modified over 40 m	Very resilient fastener on rigidly fixed blocks
3a	Bored tunnel with concrete tunnel rings	Resilient baseplate on slab
3b	Track form modified over 20 m	Resilient baseplate on slab
4a	Rectangular section single track with FST	Stiff baseplate on resiliently booted wooden sleeper
4b	Track form modified over 8 m	Resilient baseplate on resiliently booted wooden sleeper
5	Rectangular section double track	Baseplate with resilient railpad on slab
6	Rectangular section double track	Resilient baseplate on slab

A second, practical, difficulty is in comparing published results from different sources. There are many different ways in which vibration data can be presented. For example, they may be expressed in terms of acceleration, or in terms of velocity. Different frequency ranges may be considered. Data may be weighted, or linear. Peak values or averages may be presented. The time period over which results are averaged may vary. This makes comparison difficult. There are also potential differences arising from the equipment used, and the exact positions at which measurements are made. Finally, there may be difficulties in abstracting from some published reports clear information about important factors such as track stiffness, or in ensuring that these values have been calculated on a consistent basis. An aim of this paper is to draw together a number of measurements which have all been made in different tunnels, but using the same equipment, analyzed using the same software and by the same methods, and with all the supporting data calculated and presented on a consistent basis. In this way at least some of the uncertainties are reduced. A brief description of the measurement and analysis method used is given below. All of the measurements were made by Pandrol Rail Fastenings Ltd.

In comparing measured levels, it should be recognized that the magnitude of inputs that generate vibration also vary from one location to another. For example, both track geometry and rail head roughness give rise to vibrations, and both vary considerably. In theory, these factors can be measured and their effects accounted for by normalizing results. In practice this is difficult and expensive, and is rarely done. A statistic can be produced from which this variability is eliminated by subtracting the vibration level of the slab (tunnel floor) from that of the rail, to obtain a figure for the ‘attenuation’ of vibration across the track support system. Assuming linearity, this measure is independent of the levels of the inputs, and provides a useful basis for comparison between different sites. However, since the ultimate aim is to control slab vibration level, the paper presents both the measured slab vibration level—which includes variability due to the difference in roughness and geometry at different sites—and attenuation, which does not, and can therefore be expected to vary less.

A consistent means of determining track stiffness is also required. The static stiffness of individual baseplates can easily be measured in the laboratory, but the dynamic stiffness is more relevant and there is no widely accepted standard method for measuring this. The dynamic

Table 2
Basic track and vehicle parameters

Test	Rail	Fastener spacing (m)	Axle load (tonnes)	Speed (km/h)
1a,b	BS 113A	0.90	11.0	50.0
2a,b	UIC 54	0.80	12.0	49.0
3a,b	UIC 60	0.70	16.0	55.0
4a,b	UNI 50	0.75	12.0	42.5
5	100 ARA	0.61	11.5	50.0
6	AS 50	0.71	16.0	58.0

Table 3
Calculated track stiffness and measured vibration levels

Test	Deflection (mm)	Track stiffness (MN/m^2/rail)	Velocity (dB) reference 5×10^{-8} m/s		
			Rail	Slab	Attenuation
1a	0.304	147.22	113.3	87.3	26.0
1b	3.503	5.66	115.8	69.7	46.1
2a	0.320	162.25	105.9	74.7	31.2
2b	4.380	4.95	102.3	53.5	48.9
3a	0.855	55.64	100.6	68.0	32.6
3b	1.043	42.71	100.0	66.6	33.4
4a	1.592	19.60	96.8	78.7[a]	18.1[a]
4b	2.199	12.75	101.2	74.2[a]	27.0[a]
5	0.643	93.83	107.7	82.0	25.7
6	1.244	60.04	93.0	66.7	26.3

[a] Measured and calculated for top of floating slab.

stiffness of many systems depends on the frequency and load level at which the measurements are made. It is also difficult to determine accurately the stiffness of some track forms by laboratory measurements—for example those in which sleepers or blocks are embedded in to the slab. For this reason, track stiffness has here been calculated from the deflection of the rail relative to the slab, as measured in the track. In each case, the deflection measurements were made by Pandrol Rail Fastenings Ltd. simultaneously with the vibration measurements. A simple beam-on-elastic-foundation model was then used to find the stiffness from the known axle load, rail section properties, and rail fastener spacing. These track parameters are shown for each site in Table 2. The method indicates dynamic track stiffness at axle passing frequency and at high amplitudes, rather than the higher frequencies and smaller amplitudes at which vibration isolation is usually most important. But, while not perfect, the method is at least consistent across different measurements locations and track systems. The track stiffnesses calculated are shown in Table 3.

3. Measurement and analysis of vibration

Some of the data presented here show the change in vibration level resulting from a change in the track support structure. In all of these cases, the measurements were made at a fixed location and within a short space of time before and after the change in track fixing. The configurations and measurements made before the change are identified by the subscript ‘a’ in tables and figures, and those after the change by the subscript ‘b’. The primary objective of the change in track structure was in some cases [1,2] to reduce ground vibration, in one [3] to improve the maintenance of the track, and in one [4] to tune the dynamics of the track system to reduce coupling between the sleepers and the rail. The length of track over which the track structure was altered is shown in Table 1. In all cases, measurements were made at the centre of the modified track section. As well as adding to the variables, the short length of some of the installations is an additional reason why measurements cannot be usefully be made and compared distant from the tunnel.

In some cases [2,4] the change in the track structure was effected by direct replacement of existing fasteners. Here vibration measurements on the rail and on the slab were made on a section at mid-span relative to the fasteners. In other cases [1,3] new fasteners were fitted between the existing ones—these then being removed or decoupled from the rail. In these instances the vibration measurements were made at quarter span relative to the existing fasteners, and the same positions were used once the new fasteners were in place—the distance between the fastener and measurement positions therefore remaining constant. The other measurements presented here [5,6] were made without changes in track structure, and the measurements were made at mid-span. An example of one of the new types of track fastener fitted (2b) is shown in Fig. 1, which also shows some of the deflection and vibration measuring equipment in use.

Vibration measurements were made using Kistler type 8702 and 8712 accelerometers and a Kistler type 5128AM coupler unit. The accelerometers used on the rail had a peak input level of 50 g—those on the slab a peak input level of 5 or 25 g depending on the site and the anticipated

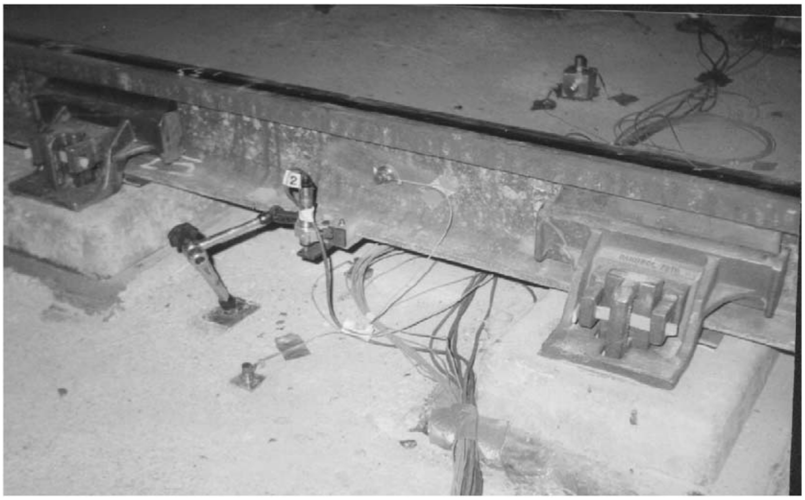

Fig. 1. Example of new track fastenings tested: Type 2a.

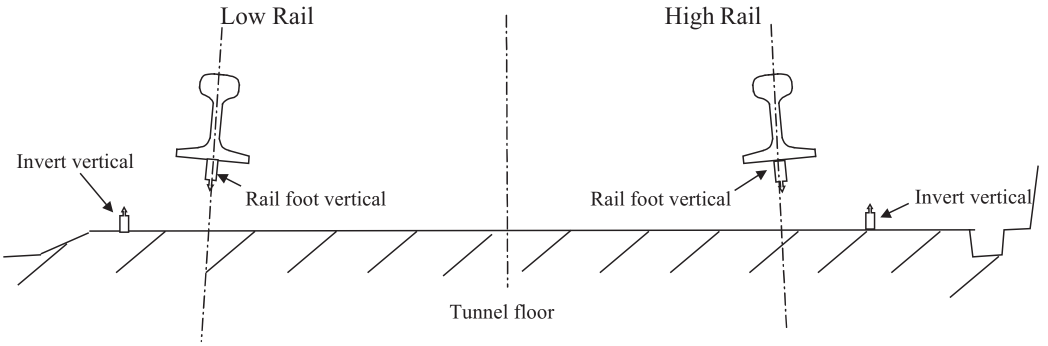

Fig. 2. Positions of measurement transducers.

vibration level. In all cases there was sufficient clearance under the rail for an accelerometer to be attached to the underside of the rail with a magnetic base. The accelerometers on the slab were fixed with magnetic bases to metal plates glued to the concrete close to the edge of the rail. Typical positions of accelerometers are shown in Fig. 2. In all cases the coupler unit was placed as close as was practical to the accelerometers, and in all cases at less than 10 m distant.

The intention in measurements where two track supports have been compared at one location was to eliminate as many variables as possible given the constraints imposed by the need to modify the track structure in a practical manner, while fulfilling all other engineering and safety requirements. The same methodology was applied for each test. Using the same equipment, applying it in the same way, and analyzing data using the same method at each site eliminated a number of possible variables. However, differences remain-for example the tunnels structures at each site are different, as are the depths of the tunnel and the soils though which they pass.

As discussed above, the data from a measurement can be analyzed and presented in a number of different ways. The particular method used here was as follows. Data were recorded on a digital tape recorder, and downloaded into a computer for analysis. The duration of the train pass and the speed of the train were identified from the recordings. The acceleration signals were analyzed only for the period during which the train passed—the average length of the records analyzed was of the order of 10 s. Each record was divided into a large number of small overlapping blocks, each of which was analyzed using a uniform windowing and Fast Fourier Transform routines to give the power spectral density. No weighting was applied to the spectra. The content at each frequency was averaged across all of the blocks. This gave the spectrum over a frequency range between DC and 2.5 kHz. Spectra were averaged for a number (between 10 and 40) of train passages. Trains with speeds more than 10% different from the mean were omitted. In some cases, signals from more than one transducer measuring nominally similar data were averaged. The level in 1/3 octave bands was then determined. Velocity was calculated from acceleration based on the centre frequency of each band. The total level across the frequency range analyzed was calculated. This was expressed in decibels relative to a reference velocity of 5×10^{-8} m/s.

Note that the frequency range of greatest interest for vibrations in buildings alongside the track is not usually considered to extend up to frequencies as high as 2.5 kHz. However, the above analysis has been repeated with different sampling rates to give results over the frequency ranges

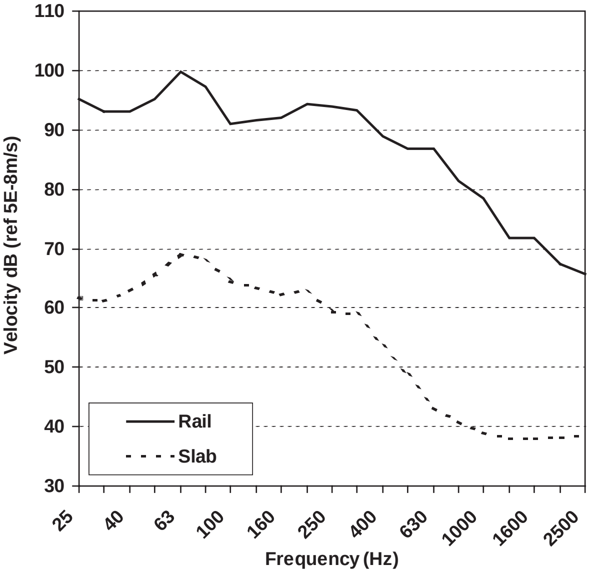

Fig. 3. Typical spectra recorded on rail and slab.

up to 125 Hz, to 250 Hz, 500 Hz, 1 kHz, and 2.5 kHz respectively. Little difference in the total velocity levels was found. This is because most of the energy in the vibration signals is concentrated at lower frequencies—below about 200 Hz. This is illustrated in Fig. 3, which shows typical vibration spectra measured on the rail and on the slab. The particular data shown here relate to the measurements made for site 2a. The general form of the spectra obtained at other sites was similar. The peak level of vibration measured on the floor of the tunnel was usually between 40 and 80 Hz.

4. Discussions and use of results

The data shown in the Table 3 are also plotted in Fig. 4. The track stiffness is shown on a logarithmic scale. There appears to be a linear relationship between logarithm of track stiffness and the vibration and attenuation levels. The rail vibration level varies little with track stiffness across the range of stiffness levels measured. The slab vibration level decreases as track stiffness is decreased. Consequently the attenuation between rail and slab increases with decreasing track stiffness. The slope of the lines indicates that a 10-fold change in track stiffness produces a change in attenuation or slab vibration of approximately 13 dB. Note that the data used to generate the best-fit lines shown in Fig. 4 do not include values for site 4, where the track fasteners were mounted on FST. The 'slab' vibration measured was on the FST units. This is the probable explanation for the relatively low attenuation levels measured at that site.

In principle, the best-fit lines shown on Fig. 4 can be used to estimate likely rail, slab, and attenuation levels for new or existing track structures from a knowledge of the track stiffness. There are a number of caveats. The track stiffness should be estimated on a similar basis to that

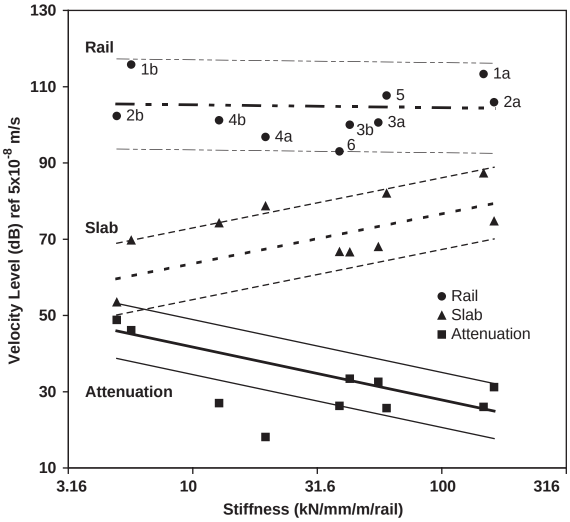

Fig. 4. Influence of track stiffness on measured vibration levels.

used here—that is, from the dynamic stiffness measured under axle passing conditions. Clearly, there is likely to be some error in applying the 'best-fit' data to a new situation. The measurements give an indication of how large such an error might be. Because of the small number of samples, this is done here by finding the maximum difference between each measured result and best-fit prediction of that value from the corresponding known track stiffness. On this basis, the maximum error in estimating the rail or slab vibration level is of the order of 10 dB, while that in estimating the attenuation is of the order of 7 dB. As more data become available, more sophisticated statistical methods can be introduced.

The data do not include situations where the effect of FST has been measured. Note that the data presented have all been measured within the tunnel structure, whereas the vibration levels that are actually of concern are those in buildings alongside the track. Previous measurements have shown that a change in vibration level on the tunnel floor obtained by modifying the track structure (insertion loss) will not necessarily be reflected by a similar change in vibration levels at the surface or in wayside buildings [9]. Finally, note that the track stiffness may influence the rate of growth in the level of the wheel and rail roughness, and this factor should also be considered in designing for the long term control of vibrations from the track [12].

5. Conclusions

A number of vibration measurements have been made in different tunnels, each with different track structure. In some cases it was possible to modify the track structure, so that vibration measurements could be made for two different conditions at one site. The measurements covered a wide range of track support stiffnesses. The same test equipment was used throughout, and all of the measurements were analyzed using the same techniques.

Measurements made at different locations showed broadly similar characteristics. No relationship was found between rail vibration level and stiffness of the track support, but there is a clear trend towards lower levels of vibration on the floor of the tunnel where track support stiffness is reduced. The vibration level decreases by approximately 13 dB for each 10-fold decrease in track support stiffness. Consequently, the attenuation between rail and slab vibration levels increases at the same rate.

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