USING INSERTION GAINS TO EVALUATE RAILWAY VIBRATION ISOLATION SYSTEMS

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Abstract

The insertion gain describes, all other parameters remaining equal, the vibro-acoustic performance of a particular railway system measured relative to a reference trackform. The insertion gain of a track-system is dependent on the physical *dynamic* parameters of both the train and trackform (including the sub-base), and is therefore highly system dependent. Measured and predicted insertion gains of various railway isolation systems can be used to evaluate the expected reduction (or increase) in wayside groundborne noise and vibration that the isolation system will provide. However, accurately measuring actual insertion gains achieved on site is notoriously difficult, since it is generally impractical to separate the many system or location-dependent effects from the results. Using inappropriate insertion gains based on measurements of 'similar' systems can result in significant inaccuracies in the predicted vibration and groundborne noise levels. For the designer, this can result in unnecessary over- or under-design of the vibration mitigation requirements. Several methods of dynamic analysis are reviewed which allow the prediction of track system insertion gains. This allows more accurate prediction of overall groundborne noise and vibration and therefore better comparison of the benefits of various track isolation systems.

Introduction

Insertion Loss is a term that has long been used in the field of acoustics to describe the change in noise or vibration levels generated by a system brought about by a modification to that system. Resilient track systems are commonly used to reduce groundborne noise and vibration generated by railways. Insertion Loss is therefore a means for quantifying the change in groundborne noise or vibration in the wayside of a rail system brought about by a change in track system or a change in track design, all other parameters remaining equal. However, it is the inverse of Insertion Loss – termed Insertion Gain – that is becoming the norm in quantifying and specifying the vibro-acoustic performance of a track system for several reasons. Firstly, track systems do not dissipate or absorb significant vibration energy. Thus isolation is provided at particular frequencies by tuning the main natural frequency of the train / track system. This means that, by in large, attenuation is achieved by moving a resonant amplification that should be seen for what it is – an increase in vibration at some frequencies. Secondly, referring to the insertion gain is more intuitive when referring to track system performance in isolation. Finally, track systems that mitigate noise and vibration can be costly and it is often easier to defend investing in a gain rather than a loss.

This paper demonstrates how calculated 1/3 octave band insertion gains may be used to evaluate the noise and vibration isolation provided by these isolation systems.

The concepts of groundborne noise and vibration from railways are introduced. Empirical methods are commonly used for predicting groundborne noise and vibration, and the key stages of these models are defined.

Generic types of vibration isolating resilient trackforms are discussed. The performance of these systems is often described by overall A-weighted noise level reductions that are achieved. An alternative 1/3 octave band Insertion Gain (IG) approach is outlined, and the benefits of this approach are discussed.

While it is difficult to measure train/track system IGs, they can be calculated using analytic and numeric approaches. The IGs of various resilient track support systems are presented for the Sydney metropolitan network, and used to determine the typical noise and vibration reduction provided by these systems.

Groundborne Noise and Vibration

Operating railways generate groundborne vibration due to the rolling contact of steel wheels on the rails. Groundborne vibration propagates in the ground and is transmitted into buildings via the foundations. There it may result in either vibration that is directly perceptible to occupants, or noise that is radiated by the vibrating surfaces of the building (referred to variously as groundborne noise, re-radiated noise, structureborne noise or regenerated noise).

Potential impacts of perceptible groundborne vibration include; perception of structural vibration, annoyance, disturbance (including sleep disturbance), disruption to vibration-sensitive equipment or processes, and concern about possible structural damage (which is unlikely to occur in practice).

Although an International Standard is currently in preparation (ISO 14837-4), there are no existing standards defining groundborne noise assessment criteria from operating railways. Criteria for acceptable levels of groundborne noise are therefore often based on published information, particularly from the US where guidelines have been published by the American Public Transit Association (APTA) [1] and more recently, based on the experience of the US Federal Transit Administration (FTA) [2].

As with construction impacts, operational groundborne noise and vibration is not usually an issue of concern for areas adjacent to surface track as, except where substantial noise barriers are employed, airborne noise generated from the railway will generally mask any groundborne noise transmitted into an occupied building during the daytime.

Prediction of Groundborne Noise and Vibration

Currently, there is no agreed methodology for the prediction of groundborne noise and vibration from railways. Predictions are therefore undertaken using approaches that range from simply scaling from site measurements to detailed analytical or empirical models. For example, those developed by Remington *et al*[3] or for the Channel Tunnel Rail Link (CTRL) in the UK[4,5]. The CTRL model, for example, is based on the statistical analysis of over 3000 measurements of groundborne rail vibration adjacent to a wide range of rail systems ranging from low speed mass transit to high-speed lines in Germany and France.

Figure 1 below shows the usual steps in predicting groundborne noise and vibration from railways.

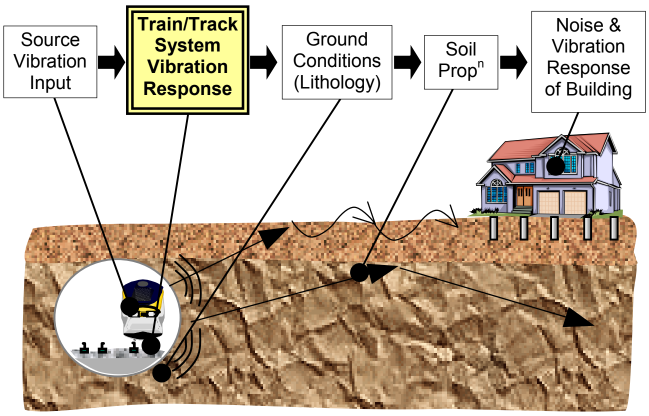

Figure 1. Key stages in the propagation of groundborne noise and vibration.

The source vibration level is based on vibration velocity measurements of representative trains on known track and ground lithology (known as the *Reference Source Spectrum* or *Vibration Reference Spectrum*). The train/track system response usually accounts for the rolling stock and system parameters, such as unsprung mass, overall average mass, axle and sleeper spacing, and the particular trackform Insertion Gain (IG). The vibration attenuation through the ground in the horizontal and vertical directions as well as corrections for varying ground lithology properties are included.

Finally, the building response is represented, including the coupling loss of the foundations, amplification associated with suspended floors and transmission of structureborne vibration into groundborne noise.

It is the train/track system vibration response (shown shaded in the flow-chart in Figure 1) that is the key parameter to understanding the overall level of groundborne noise and vibration generated by a system.

Vibration Isolating Trackforms

Groundborne noise and vibration mitigation for railways is often undertaken by resiliently isolating either the source of the vibration (ie the railway) or the affected receiver (ie a building). When isolating the railway, mitigation is likely to take the form of resilient vibration isolating track structure or fixings. These can take the form of;

- Under rail pads
- Under sleeper pads or boots
- Resilient ballast mats
- Resilient rail fixings or baseplates (RPB), or
- Floated Track Slab

The resilience in the track system combined with the rail vehicle unsprung mass and suspension stiffness result in a 'tuned' vibro-acoustic system that can be optimised to provide varying degrees of vibration isolation. These vibration isolating trackforms usually reduce the track support stiffness, and therefore the fundamental resonance of the train/track system.

This acts to provide vibration isolation at higher frequencies (in vibro-acoustic terms, between 50-250 Hz), thereby reducing vibration transmitted from the railway to the surrounding ground at frequencies that the human ear is more sensitive to, hence reducing resultant groundborne noise levels. However, the amplitude of vibration at the system resonance is seldom changed and levels of perceptible vibration can therefore remain unchanged.

About Trackform Insertion Gain (IG)

For many isolation systems and fixings, the level of vibro-acoustic performance is often quoted by consultants and suppliers as an overall A-weighted noise level reduction, eg 5 dB(A) reduction in groundborne noise and vibration from basic resilient track fixings, or 10-15 dB(A) reduction from higher performance systems. This has usually been determined from in-situ measurements near upgraded sections of railway.

Unfortunately this approach ignores the fact that the overall benefit of a particular system is dependent on the spectrum shape of the source input and that there is no fixed reference track to be used to calculate the IG against.

Furthermore, this ‘single number’ approach does not often provide sufficient detail to allow finely tuned isolation systems. This results in overly conservative (or optimistic) designs that are not cost and risk optimised.

Finally, it should be understood that the level of isolation provided by a particular system is trackform and train/track system dependent and cannot be extrapolated with accuracy to other systems. That is, the level of noise and vibration reduction measured on one system is not immediately transferable to other systems since the vibro-acoustic system comprising the axle load, unsprung mass, axle and sleeper spacing, track modulus/support stiffness, rail type and invert mobility are likely to be different.

The level of isolation provided by a trackform is better described by its 1/3 octave band insertion loss, or, as used in this paper, insertion gain (IG). The IG of a particular train/track system is determined relative to some ‘reference trackform’ (usually a very hard continuously supported trackform such as PACT, referred to as an *inertial reference*) that must be defined by anyone reporting IG information.

The benefits of a 1/3 octave band system IG

The concept of a 1/3 octave band train/track system IG is helpful for several reasons.

Firstly, it allows closer matching of the system performance to the isolation requirement, preventing costly over-design, and minimizing the risk of under-design.

Secondly, it highlights the different performance that could be expected under various rail vehicles, particularly where sections of track are available to a wide variety of railway vehicles (eg. both heavy freight and commuter vehicles).

Finally, the IG is a convenient way to specify vibration isolation requirements for railway infrastructure projects in a contractually sensible manner. Often, infrastructure contractors are subject to unreasonable specifications that attempt to transfer to them the risk of meeting onerous indoor groundborne noise levels. Of course, the contractors (and their consultants) have no control over many of the other factors that influence the level of groundborne noise such as the source vibration level, regularity of rolling stock and track maintenance, operating schedules, or even the horizontal and vertical alignment. Providing an IG performance specification, on the other hand, allows the contractor to be accountable for those elements for which they have design responsibility, but leaves the other risks more reasonably with the project proponent.

Determining System IGs

Train/track system IGs such as those discussed above are not readily measurable, since it is inextricably linked with other system dependent effects, eg wheel/rail roughness, irregularities and defects, sleeper passage frequency, and other harmonic components.

Rather, the emerging approach is to predict the IG numerically using an appropriate dynamic model of the train/track system.

Several researchers and consultants have developed IG prediction tools, eg. AEA Technology Rail’s CIVET (Change In Vibration Emitted by Track), which is based on the work of Thompson and Jones [6, 7, 8]. The track is represented as a two-dimensional, infinite layered beam resting on a three-dimensional homogeneous half-space of ground material.

Arup has recently developed a FEA representation of the train/track system called ATAM (Arup Trackwork Acoustic Model) that is capable of accurately determining system IGs.

As noted above, the calculated IG is dependent on the track and rail vehicle physical characteristics. The key input parameters are;

- Rail type and bending stiffness
- Sleeper spacing and weight
- Stiffness of the track fixing (eg baseplate)
- The dissipative and complex stiffness/damping associated with ballast
- Impedance of the tunnel invert and ground
- Unsprung mass of vehicle

A typical dynamic model arrangement is shown in Figure 2 below.

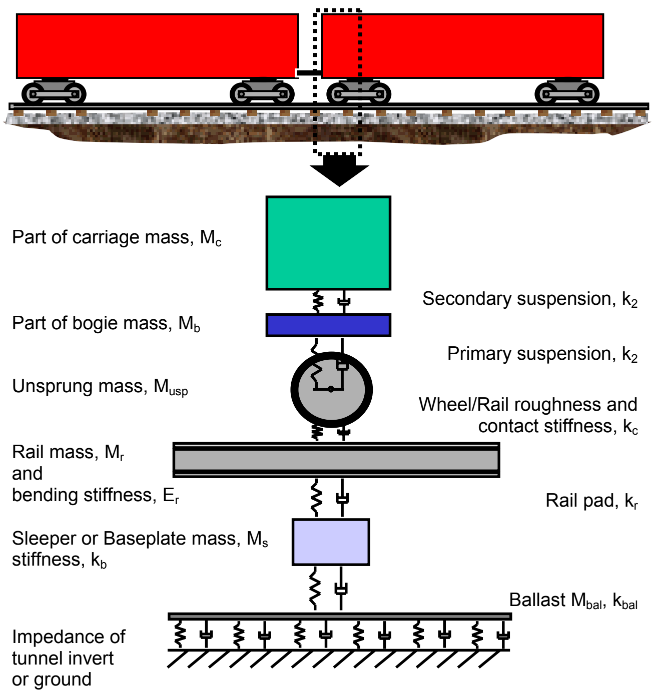

Figure 2. Example train/track system dynamic model (after ISO/DIS 14837-1.2 [9]).

The rail vehicle overall mass parameters are generally not important given the rolling stock secondary suspension usually decouples the sprung mass of the train from the track at the frequencies of interest. (The overall mass is generally corrected against the reference train overall mass in the propagation model.)

By contrast, the unsprung mass is critical to determining IGs, and the unsprung mass of rail vehicles varies greatly between different passenger car types, and between passenger cars and freight cars. For example, often motor and trailer cars have different unsprung masses, as the mass of the motor and gearbox is connected to the axle (see Table 1, below). The analysis of the vibration isolation provided by a resilient system becomes further complicated on rail networks that have a variety of 'standard' vehicles. For example, older K-Set and newer Tangara and Millennium rolling stock are all used on the Sydney metropolitan network. Each of these has subtly different system parameters. For systems such as this it is necessary to evaluate the isolation performance for each of the rolling stock types, and to optimise the desired performance to suit.

Trackform IGs for the Sydney Metropolitan Network

The IGs of various resilient track systems have been calculated for rail vehicles on the Sydney Metropolitan Network.

The following mass parameters were used as inputs in this study, and are based on previous experience with Sydney suburban rail stock.

Table 1a. Sydney rolling stock unsprung mass parameters.

Train	Unsprung Mass (kg/axle)		
	Motor	Trailer	Mean
Tangara	2170	1660	1915
K-Set	2000	1600	1800

Table 1b. Sydney rolling stock overall mass parameters.

Train	Total Mass, kg/axle			
	Motor, Tare	Motor, Loaded	Trailer, Tare	Trailer, Loaded
Tangara	12560	17000	10560	14700
K-Set	11750	15730	10250	14230

For the purposes of assessing potential vibration mitigation it has been assumed that typical commercially available resilient track fixings and ballast mat have the properties shown in Table 2.

The Dynamic Track Modulus (DTM) is the overall stiffness of the track fixing for two rails, per metre length, including the dynamic to static stiffness ratio of the resilient element (k_{dyn}:k_{stat}). δ is the typical static deflection of the track isolation system.

Table 2. Assumed track support properties.

Track Fixing	Typical Product Type	Track Support Properties
Moderate-performance resilient baseplate	Pandrol Vipa or Contitech Alternative 1	DTM = 35-45 kN/mm/m δ = 1.5 mm
High performance resilient baseplate	Contitech Cologne Egg	DTM = 25-30 kN/mm/m δ = 3.0 mm
Ballast Mat	Phoenix or Getzner Ballast Mat	δ = 1.0 mm

It is assumed that the track systems shown above use UIC60 Rail and typical material properties for timber and concrete sleepers, and ballast have been used. For the purpose of predicting the track vibro-acoustic performance, underlying ground properties input to the model are assumed to be $E = 372\ MN/m^2$, $\nu = 0.47$, $\rho = 2000 kg/m^3$, and $\mu = 0.1$.

The IGs for Tangara rail vehicles on various track systems are shown in Figure 3. The IGs are relative to a very stiff reference track (representing an *inertial reference*).

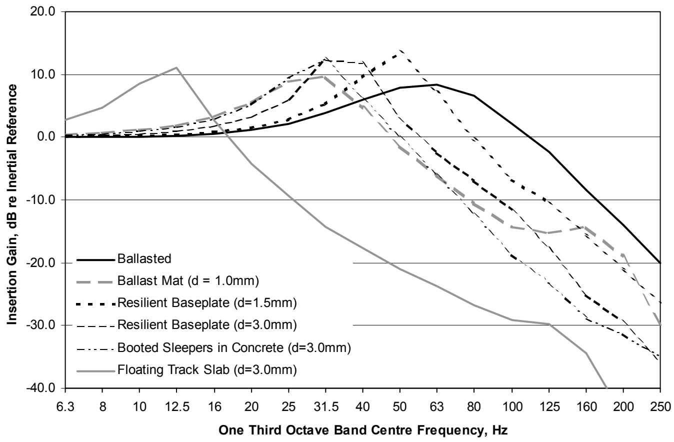

Figure 3. Trackwork Insertion Gains for Tangara rail vehicles on various track fixing and support systems.

For ballasted track, the IG shows the typical primary system resonance at around 63 - 80 Hz. RBPs can reduce the primary system resonance to 31 - 40 Hz, depending on the level of support stiffness that can be achieved. It is not practicable to provide significantly lower stiffness at the track fixing itself, without adversely affecting the rail stability and gauge. Systems such as Pandrol's VANGUARD have been designed to address this.

With floating track slab systems, the primary system resonance can be reduced to around 10 - 12 Hz, since the active mass is greatly increased, and they can provide high levels of vibration attenuation in the audible range, provided they are well designed and carefully installed.

It is interesting to note that low performance RBPs, when used on slab-trackforms, actually result in a similar IG to ballasted track (particularly those that are slightly softer than Sydney's relatively stiff ballast). This is not unexpected, since resilient RBPs were originally introduced to provide an overall trackform stiffness for direct-fix slab trackforms that was similar to ballasted track for maintenance, wear and ride quality reasons.

Using IGs to Determine Track Isolation Performance

Once the IGs of various train/track systems are known, it is straightforward to determine the change in noise and vibration that will occur as a result of using the isolation system.

The IG of the *existing* trackform is subtracted from wayside vibration measurements to determine the *reference source spectrum*, ($L_V$ref). The IG of the proposed trackform is then added to the reference source spectrum.

The typical measured wayside vibration spectrum from a train pass-by on ballasted track in Sydney is shown in Figure 4. The result of changing the track system to a slab track with a high performance resilient baseplate system (see Figure 3) is also shown. Vibration at the main train/track system (ballast) resonance of around 63 Hz is considerably reduced, while vibration at the new track resonance (40 Hz) increases slightly. In A-weighted terms, this would correspond to a 14 dB(A) decrease in noise levels.

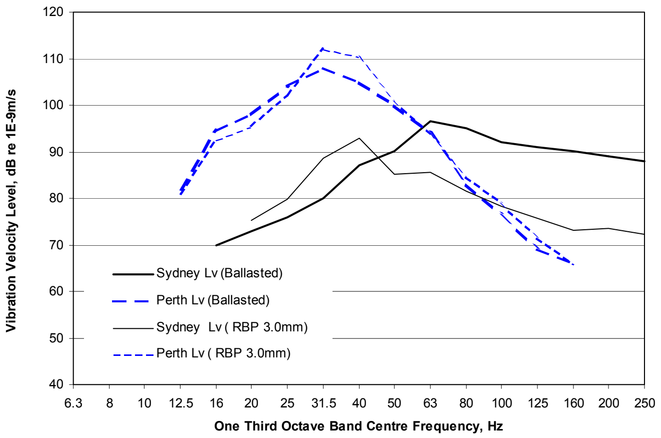

Figure 4: Effect on wayside vibration levels using a moderate performance resilient baseplate track support compared to ballasted track in Sydney and Perth.

The effect of using a slab track with high performance resilient baseplate system in place of a ballasted system on a typical Perth track system is also considered in Figure 4. (As noted above, the IGs for the Perth system will be *different* to those for the Sydney system, however for the purposes of this comparison the Sydney moderate performance RBP IG has been used, since the system parameters are broadly similar). Typical wayside vibration levels adjacent to ballasted track in Perth show a much lower primary resonance due to the lower impedance of the ground – Perth has predominantly sandy ground. In this case the result of using a moderate performance baseplate system would be to marginally *increase* the vibration levels at the primary track resonance. In A-weighted terms, this would correspond to a 3 dB(A) increase in noise levels. This is considerably different to what might be anticipated based on in-situ measurements of the fastener isolation performance in Sydney.

Similar care must be exercised where low-stiffness track fixings are retro-fitted onto bridge or viaduct structures where interactions with low-frequency structural response modes can undermine the vibro-acoustic performance.

Conclusions

Resilient track support systems are commonly used to reduce groundborne noise and vibration generated by railways. The insertion gain (IG) of these systems is difficult to measure, but can be calculated using dynamic models of the train and track support system. The IGs for several track support systems and Sydney metropolitan rail vehicles are presented. These offer detailed information about the level of groundborne noise and vibration reduction provided by these systems.

It is demonstrated that systems that provide a certain level of noise and vibration reduction in one location, cannot be expected to provide the same level of performance when used in other locations or with other rolling stock.

References

[1] American Public Transit Association. Guidelines for Design of Rapid Transit Facilities, 1991.

[2] Federal Transit Administration, US Department of Transportation, Transit Noise and Vibration Impact Assessment, April 1995.

[3] Remington P, Kurzweil L and Towers DA, Ch. 16, "Transport noise reference book", Nelson P ed., Butterworth & Co. 1987.

[4] Greer R, "Prediction of Re-radiated Noise from Trains in Tunnels", *Proc InterNoise 93*, 1993.

[5] Greer R, "Methods for Predicting Groundborne Noise and Vibration from Trains in Tunnels", *Local Authority Railway Impact Forum (LARIF)*, 1999.

[6] Jones CJC "Ground-Borne Vibration From Trains – A Three Dimensional Model", BR Research Technical Report RR SAV 004, October 1991.

[7] Jones CJC "Groundborne noise from new railway tunnels", *Proc. InterNoise 96*, Liverpool, UK, pp 421-426, July 1996.

[8] Thompson DJ, "Wheel-rail Noise: Theoretical Modelling of the Generation of Vibrations", PhD Thesis, University of Southampton, January 1990.
[9] Draft ISO/DIS 14837-1.2:2004(E). "Mechanical vibration – Ground-borne noise and vibration arising from rail systems – Part 1: General guidance".