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# REDUCING GROUNDBORNE VIBRATIONS: STATE-OF-THE-ART STUDY

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The project RENVIB has been sponsored by the Union of International Railways to further the knowledge on train-induced ground vibration. The long-term aim is to develop a general model that will predict the vibration caused by trains operating in tunnels and on the surface. A State-of-the-Art survey was carried out during Phase 1 of the project and that is summarized in this paper. This highlighted the lack of standards in the assessment of groundborne noise and inconsistencies in the treatment of low-frequency vibration in other standards. Phase 2 is current and is concentrating on some preliminary validation of existing models using measurement data from national vibration mitigation projects.

## 1. INTRODUCTION

Public concern regarding the impact on society of rail transport systems is growing, in particular with the trend towards higher speeds. Coupled with this is the introduction of increasingly stringent environmental standards and legislation. Noise and vibration are therefore important issues for railway companies and may increasingly affect their future operations and development.

The competitiveness of rail over other forms of transport is enhanced by its ability to operate from the centres of population and commerce. However, in order to achieve this, tunnels are often required in residential or commercial areas of large cities. This has led to the acceptance that vibration created by trains in tunnels can be a potentially serious issue for mainline railways. Vibration in the frequency range 30–200 Hz can cause an audible rumble (groundborne noise) inside buildings as trains pass beneath. Additionally, lower-frequency feelable vibration in the range 2–80 Hz can also be present, although it is generally less serious than groundborne noise.

Railway administrations have also been concerned for some years about the levels of low-frequency feelable vibration from trains operated on surface railways. This has been particularly highlighted by the use high axle load freight wagons. This vibration can cause not only disturbance, but also anxiety over structural damage to property. In some cases, where noise barriers have been erected, problems have occurred due to levels of groundborne noise inside buildings exceeding the direct (airborne) noise from the trains.

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Some rail projects have faltered at the planning stage because of lack of confidence in the predicted level of impact and the effectiveness of reduction measures. The lack of easily applicable national Standards or Codes of Practice in this area has made the process even more difficult. The need for progress towards standards for the assessment of groundborne noise and vibration from existing, modified and new railways is clear.

The Union of International Railways (UIC) recognized the lack of background information on train-induced vibration and in 1997 provided funding for a project (RENVIB) to attempt to answer a number of the outstanding questions.

The project was planned to investigate five key areas:

- Environmental standards and guidelines.
- Prediction of groundborne noise and vibration levels.
- Mathematical modelling of railway vibration.
- Reduction measures for tunnel lines.
- Reduction measures for surface lines.

The project was originally planned in three phases with Phase 1 being a State-of-the-Art review. Phase 2 was intended to be an assessment of short to medium-term investigations. Phase 3 was planned as a longer-term investigation which could be put forward to the EU for additional funding if an appropriate EU programme was available.

The project was managed by ERRI and the technical elements of Phase 1 were carried out by The Institute of Sound and Vibration Research (U.K.), Civil Engineering Dynamics (U.K.), Centre Scientifique et Technique du Batiment (France), Vienna Consulting Engineers (Austria), Müller-BBM (Germany), AEA Technology Rail (U.K.) and Dr. J Melke (Germany).

A State-of-the-Art review for each of the above key areas was carried out through a review of references, standards and guidelines. Individual working practices and procedures were obtained via questionnaires. In total some 362 references, worldwide, were reviewed and 244 questionnaire distributed. This paper summarizes the results of that review, describes the studies being carried out currently as part of Phase 2 and identifies a number of issues which are still outstanding and should be investigated further.

## 2. ENVIRONMENTAL STANDARDS AND GUIDELINES

### 2.1. GROUNDBORNE NOISE

The results of a survey indicated that the most commonly used measure for the assessment of groundborne noise from train operations in tunnels is the maximum A-weighted sound level as a train passes the receiver point. Inconsistencies have arisen since there are no recognized standards or guidelines to define either the position of the measurement within a building or how the noise level should be measured. For example, a difference of upto 10 dB (A) can be found between measurements with fast or slow time response for the passage of the same train.

This simple measure, the use of which has not been validated by scientific research, takes no account of duration, number and frequency of events or the ambient noise level. Its use can also be criticized since A-weighting does not take proper account of low-frequency noise which is under consideration in this particular situation.

There are no international standards for the assessment of groundborne noise although a number of national standards exist such as ONORM S 9012 (1996) in Austria. Additionally, some railways have developed guidelines for assessing vibration and groundborne noise from train operation.

It should be remembered that this was a topic which generated much discussion at the last workshop in Voss and it remains unresolved.

Despite the lack of standards or guidelines it has been necessary for assessments to be made of the groundborne noise impact of a number of railway schemes. It appears that during the day at levels below 30 dB (A) (maximum noise level from the passage of a train) there is likely to be very little adverse reaction but above 50 dB (A) there is likely to be significant reaction. During the night, a lower level of about 25 dB (A) might be required to ensure little adverse reaction. Thus, the majority of schemes have been assessed using levels in this range with most assessments defining 35 or 40 dB (A) as an acceptable level.

### 2.2. LOW-FREQUENCY FEELABLE VIBRATION

In contrast to groundborne noise, the assessment of low-frequency feelable vibration has been the subject of national and international standards, including ISO 2631-2 (1989), BS 6472 (1992), DIN 4150 (1992) ANSI S3.29 (1983), VDI 2057 (1987) and ÖNORM S 9012 (1996).

These standards normally take into consideration time of day, building usage and vibration duration. It is also generally recommended that the vibration level is specified at the point in the building where the person would feel the vibration (either standing, lying or sitting).

Assessment often depends on whether the vibration is classified as “continuous”, “intermittent” or “transient”. Railway vibration is identified differently in various standards, therefore an assessment of a particular railway vibration “dose” will vary in severity depending on the standard used.

This is an area where a consensus view for standards is required.

## 3. PREDICTION AND MODELLING OF GROUNDBORNE NOISE AND VIBRATION

For new schemes it is necessary to predict vibration levels for environmental assessment purposes. Notwithstanding the lack of standardization in assessment methodology, prediction models of differing complexity have been developed for particular schemes. These vary from a simple scoring system developed by Deutsche Bahn AG to assess where vibration mitigation is likely to be required, to frequency-dependent models which incorporate the effect of a large variety of train, ground and receiver parameters. Often the empirical data are augmented by theoretical analysis to produce semi-empirical models.

The following parameters are considered important in the generation, propagation and reception of train-induced vibration. Not all models include the effect of all variables:

train type, train speed, number of trains per hour (where $L_{eq}$ is predicted),
train length, track design—including the presence of resilience, track quality, surface/tunnel, rail (normal/points),
ground conditions—including the effect of water table, distance, building foundation design, building construction, building use.

For a railway, it is important to be able to predict the effect of changing those parameters over which it has control. In particular, this relates to vehicle and track design options (including tunnel construction where this is relevant) and train operating conditions. Since vibration isolation is frequency dependent, it is therefore necessary to have a frequency-dependent prediction to enable the attenuation specification for the required vibration mitigation to be defined. Even if the final assessment is carried out against a single-number description, the relevant levels must be determined from the summation of spectral data.

An observation of this study was that since each model had been developed for a specific purpose, experimental validation had tended to be for a limited range of a restricted number of variables appropriate to the particular project. As such, there is currently no validated model that can be taken to predict accurately the total vibration process for a wide range of operational and design situations.

A number of areas were identified where either the techniques could be enhanced or where additional data could be obtained to give railway engineers more confidence in the results. These included: (1) experimental validation of track models, (2) parametric studies with train/track models to determine maintenance requirements for vibration control, (3) development of a common method for deriving soil properties and data base, (4) validation of transfer admittance modelling for ground/tunnel interface.

## 4. REDUCTION MEASURES FOR TUNNEL LINES

The objective of this part of the study was to compile a list of measures for mitigating vibration from railway lines in tunnels.

Although it is possible to apply vibration isolation at the receiver and this has been successfully applied in the design of new buildings or by the introduction of resilient elements into the foundations of existing buildings, it was considered that the most effective and economical measures are those performed on the track and this study concentrated on that mitigation as outlined below.

*Resilient rail pads*: These can be effective for frequencies greater than 30 Hz giving a 6–10 dB reduction at about 50 Hz. Limitations on their use are set by fatigue strength, geometric gauge widening and misalignment in case of rail fracture. To date, measurement data are only available for axle loads between 10 and 20 ton.

*Under sleeper pads*: These pads have been successfully used on ballasted track where an insertion loss of 15 dB has been achieved at 125 Hz.

*Sub-ballast mats*: Elastic layers are laid under ballast whereas in tunnels the elastic mat is placed on a concrete layer.

*Mass–spring systems*: This is the most efficient but most expensive solution for inserting resilience under a slab. A fundamental frequency of about 5 Hz can be achieved giving low-frequency isolation. A number of designs are available and have either been implemented or are under test.

## 5. MITIGATION MEASURES FOR SURFACE RAILWAYS

Experimental findings from a number of railways again concentrated on mitigation applied to the track under the following headings.

*Ballast depth*: Ineffective in the mitigation of vibration.

*Rail pad stiffness*: Ineffective in the mitigation of vibration from ballasted track.

*Sleeper spacing, continuous rail support*: Results inconclusive in identifying potential benefit.

*Booted sleepers*: Up to 20 dB insertion loss at frequencies above 63 Hz.

*Sleepers with internal damping*: Theoretical considerations have led to the proposal for a new sleeper with an internal damping layer of sandwich construction.

*Ballast mats*: Between 8 and 18 dB insertion loss for frequencies greater than 63 Hz.

*Slab track*: Theoretical studies indicate reduction at lower frequencies due to higher precision of rail fixation but an increase in vibration at groundborne noise frequencies. A new design is to be tested on DB Karlsruhe-Basel line. This design can, however, have effective added resilience.

*Floating slabs and other mass–spring systems*: Mass–spring systems with resonance frequency of 5–6 Hz have been installed in Metro systems. This system is being used for the high-speed line currently under construction in Korea, but no results are available. Ten decibel insertion loss is available for frequencies above 16 Hz, rising to 25 dB at 125 Hz.

*Soil stiffening including wave impedance blocks*: Varying treatments have been developed including lime modification, lime injection and jet grouting. These are predicted to give benefits of up to 12 dB for frequencies between 4 and 31·5 Hz.

*Trenches*: A limited effect is observed in close proximity to the trench.

## 6. CONTINUING STUDIES IN PHASE 2

The second phase of RENVIB is concentrating on the shortcomings inherent in vibration prediction and modelling. Measurement data from national vibration mitigation projects in Switzerland, Holland, Germany and Sweden are being compared with predictions from existing models. This comparison will be used to validate certain elements of the models and identify areas where further development is required.

This study is already highlighting general problems associated with railway ground vibration measurement. In particular, it has been difficult to obtain accurate values for all the important parameters, especially ground properties, for input into the models. This imposes a limit on the final accuracy of the comparison.

Additionally, a choice has to be made between alternative experimental strategies. Side by side, simultaneous measurements can be made where only one parameter is changed between different track sections. For this strategy it is assumed that the value of all the other parameters remains unchanged. Even for adjacent sections this assumption may not be valid, particularly concerning ground properties.

Alternatively, a series of measurements can be made at the same location with the values of different parameters being changed for each measurement. Although the ground properties are likely to remain constant, physical changes are made to the track and it is not always certain that there has been no change in the value of a parameter that was not deliberately altered.

These problems make validation of vibration models a difficult process.

Results from this study are expected early in 1999.

## 7. OUTSTANDING ISSUES

### 7.1. STANDARDS

There is a lack of standardization, particularly for the assessment of groundborne noise. More definitive advice is required on measurement quantities and measurement locations.

Although national and international standards exist for the assessment of whole body vibration, there are still inconsistencies in the way that vibration duration is included and more particularly whether the vibration from trains is assessed as continuous, intermittent or transient.

From a public perception point of view, there is also a lack of confidence that the levels identified as acceptable in certain national standards provide sufficient protection.

### 7.2. MODELLING

There is a deficiency of general validated prediction models to provide railway designers and operators with the appropriate tools to carry out accurate environmental assessments of their plans. These models need to be accurate enough to specify when vibration mitigation is required for the protection of the neighbouring environment. From the environmental perspective, the design must then provide adequate protection but from a railway viewpoint, all the recommended mitigation must be necessary.

It is also clear that where the need for vibration mitigation is being assessed, a frequency-dependent model is necessary to determine the attenuation which must be provided by the mitigation.

### 7.3. MITIGATION OPTIONS

Overall it can be assumed that a number of track-related measures are available to mitigate groundborne noise. The mitigation of low-frequency whole-body vibration is more problematic. Theoretical studies have shown that wave impedance blocks can be effective for this, but little experimental data is available to validate the theory.

The use of slab track is advantageous but is costly and leads to an increase in groundborne noise unless additional resilience is included.

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