BRITISH STANDARD

BS ISO 14837-1:2005

Mechanical vibration — Ground-borne noise and vibration arising from rail systems —

Part 1: General guidance

ICS 17.160; 45.080; 93.060

British Standards

National foreword

This British Standard reproduces verbatim ISO 14837-1:2005 and implements it as the UK national standard.

The UK participation in its preparation was entrusted by Technical Committee GME/21, Mechanical vibration and shock, to Subcommittee GME/21/3, Measurement and evaluation of mechanical vibration and shock, which has the responsibility to:

— aid enquirers to understand the text;

— present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep UK interests informed;

— monitor related international and European developments and promulgate them in the UK.

A list of organizations represented on this subcommittee can be obtained on request to its secretary.

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Part 1: General guidance

Vibrations mécaniques — Vibrations et bruits initiés au sol dus à des lignes ferroviaires —

Partie 1: Directives générales

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 14837-1 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock*, Subcommittee SC 2, *Measurement and evaluation of mechanical vibration and shock as applied to machines, vehicles and structures*.

ISO 14837 consists of the following parts, under the general title *Mechanical vibration — Ground-borne noise and vibration arising from rail systems*:

— *Part 1: General guidance*

The following parts are under preparation:

— *Part 2: Prediction models*

— *Part 3: Measurement*

— *Part 4: Evaluation criteria*

— *Part 5: Mitigation*

— *Part 6: Asset management*

Introduction

Many if not all ground transportation systems can give rise to ground-borne vibration and/or ground-borne noise. Railways are by far the most common and significant source as a consequence of running steel wheels over steel rail.

Rail systems of all types generate ground-borne vibration and/or ground-borne noise, which (especially in urban settings) can have an undesirable environmental impact. An assessment of the likely ground vibration and response of structures at different distances from the source may be required. This requirement may arise for planning purposes where

a) a new or extended railway or new or altered buildings are proposed,

b) changes in dynamic characteristics of track or dynamic characteristics of trains are proposed,

c) a change in train operations is proposed (e.g. change of total length, speed, service pattern), or

d) assistance is needed in the evaluation of vibration mitigation measures.

Appropriate prediction of ground-borne vibration and/or ground-borne noise is the first of the two essential blocks required to assess vibration effects of new or modified rail systems on existing buildings, or the effects on new buildings next to or over existing rail systems. Ground-borne vibration and/or ground-borne noise criteria (and/or limit values) in the receiving building are the second block of any assessment. Criteria and limit values, however, are covered by national standards and other International Standards.

Prediction of ground-borne vibration and/or ground-borne noise from rail systems is a complex and developing technical field. This part of ISO 14837 provides guidelines on the essential considerations associated with developing prediction models to ensure that they are “fit for purpose” and that they are consistent in their approach.

Guidance is given on calibrating and validating a model and verifying its implementation, which are vital steps in quantifying and improving the model’s accuracy.

Table 1 shows in outline the stages to be observed for new or modified rail systems or building developments alongside rail systems. This part of ISO 14837 provides general introduction and guidance. Detailed matters will be covered in future parts, the titles of which are given in the Foreword.

Table 1 — Outline of stages and the appropriate parts of ISO 14837

1. Approach dependent upon: New build, refurbishment or adjacent development (Part 1) Design stage (concept, preliminary, detail) (Part 1)
2. Evaluation criteria Use national standards and/or Part 4 Define assessment location(s) and metric(s)
3. Parameters affecting situation Identify relevant parameters (check list in Part 1) Gather parameter data
4. Measurements Acquire site-specific information using metric(s) defined by criteria (Part 3 and Part 4) Evaluation of model parameters Develop and or validate prediction model Evaluate mitigation performance
5. Predictions Use metric defined by criteria (Part 4) Use appropriate model in the design stage (Part 1 and Part 2) Ensure validation and define accuracy (Part 1)
6. Assessment Compare predictions against criteria Identify reason(s) for exceeding criteria
7. Mitigation Identify mitigation options (Part 1, Part 5 and Part 6) Assess whether mitigation options are reasonably practicable Carry out cost/benefit analysis
8. Solution Develop detail design Implement solution
9. Asset management Implement a programme of condition monitoring and maintenance to observe criteria (Part 5, Part 6)

Mechanical vibration — Ground-borne noise and vibration arising from rail systems —

Part 1: General guidance

1 Scope

This part of ISO 14837 provides general guidance on ground-borne vibration generated by the operation of rail systems, and the resultant ground-borne noise in buildings.

It lists the factors and parameters that need to be taken into consideration and offers guidance on prediction methods appropriate for a range of circumstances (e.g. to support the assessment of effects on human occupants and sensitive equipment or operations inside the buildings in addition to the predictions required to assess the risk of damage to building structures).

Attention is paid in this part of ISO 14837 to

— characteristics of the source: emission (e.g. train, wheel, rail, track, supporting infrastructure),

— propagation path: transmission (e.g. ground condition, distance), and

— receiving structures: immission: (e.g. foundations, form of building construction).

The guidance covers all forms of wheel and rail systems, from light-rail to high-speed trains and freight. This part of ISO 14837 provides guidance for rail systems at-grade, on elevated structures and in tunnels.

This part of ISO 14837 does not deal with vibration arising from the construction and maintenance of the rail system. It does not deal with airborne noise. Structure-radiated noise from elevated structures, which can have a significant environmental impact, is also excluded.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 2041, *Vibration and shock — Vocabulary*

3 Terms and definitions

For the purpose of this document, the terms and definitions given in ISO 2041 apply, together with the following.

3.1
ground-borne vibration
vibration generated from the pass-by of vehicle on rail, propagated through the ground or structure into a receiving building

3.2
ground-borne noise
noise generated inside a building by ground-borne vibration generated from the pass-by of vehicle on rail

NOTE 1 Ground-borne noise is sometimes also referred to as re-radiated noise, structure-borne noise and solid-borne noise.

NOTE 2 Ground-borne noise excludes direct airborne noise.

3.3
model parameter
factor or function describing the physical behaviour of a mechanical element (property) in a mathematical model

3.4
model component
principal (fundamental) element of the whole physical system

3.5
model development
drafting a model of a physical structure

NOTE The model development is an iterative process through which a parameter, component or the whole model is modified to provide better agreement between predicted and measured values.

3.6
model calibration
calibration function(s) which are evaluated to ensure agreement between the model output and measured data

3.7
model validation
comparison between the output of the calibrated model and the measured data, independent of the data set used for calibration

3.8
model verification
confirmation that the mathematical elements of the model behave as intended

3.9
metric
indicator used to express an evaluative criterion and measured or predicted quantity

3.10
insertion gain
ratio between the value of a metric with and without a change to the system

NOTE 1 A reduction in the metric value is shown with a negative sign when the insertion gain is expressed in decibels.

NOTE 2 Although “insertion gain” is the preferred term, the term “insertion loss” is also used. A reduction in the metric value is shown with a positive sign when the insertion loss is expressed in decibels.

3.11
unsprung mass
collective mass of elements such as wheels, axles and, where appropriate, brake discs, axle hung motor, gearboxes, that bear on the rail below the vehicle suspension

4 Overview of ground-borne vibration and ground-borne noise

4.1 Circumstances of interest

Ground-borne vibration and/or ground-borne noise can give rise to effects on human occupants of buildings. Very sensitive equipment or its operation can also be adversely affected. In extreme cases, ground-borne vibration can be such that there is a risk of damage to buildings and other structures.

This part of ISO 14837 provides guidance on the prediction models required to assess the effects of vibration on human beings (but not animals) and very sensitive equipment inside buildings, and on the buildings themselves.

People will perceive vibration in different forms, depending on the frequency range, as mechanical vibration of the human body (relevant frequency range 1 Hz to 80 Hz) and/or as sound, ground-borne noise emitted by vibrating parts of a building; i.e. the walls, floor and ceiling (relevant frequency range 16 Hz to 250 Hz).

NOTE 1 Vibration is perceived in different forms, either as whole body vibration (1 Hz to 80 Hz), or perceived through the tactile sense, which may have a higher frequency range.

NOTE 2 In unusual circumstances, frequencies as low as 16 Hz or as high as 500 Hz may be relevant to ground-borne noise.

NOTE 3 Secondary effects include higher frequency noise emitted by rattling of some items such as glasses, dishes, windowpanes, ceilings, light fittings and some furniture. Guidance is not provided on the prediction of sound generation by this mechanism because it is difficult to quantify, although it can be a significant source of disturbance.

Vibration in buildings can affect technical equipment; i.e. sensitive measuring instruments or manufacturing processes. The relevant frequency range is dependent upon the particular item of equipment and can be up to 200 Hz.

NOTE 4 Typically, dominant frequencies are less than 100 Hz because they represent the response of building elements.

The frequency range relevant to the evaluation of the risk of vibration-induced damage on building structures is 1 Hz to 500 Hz, although high strains associated with higher risk of damage are associated with low frequencies. Most building damage from man-made sources occurs in the frequency range 1 Hz to 150 Hz.

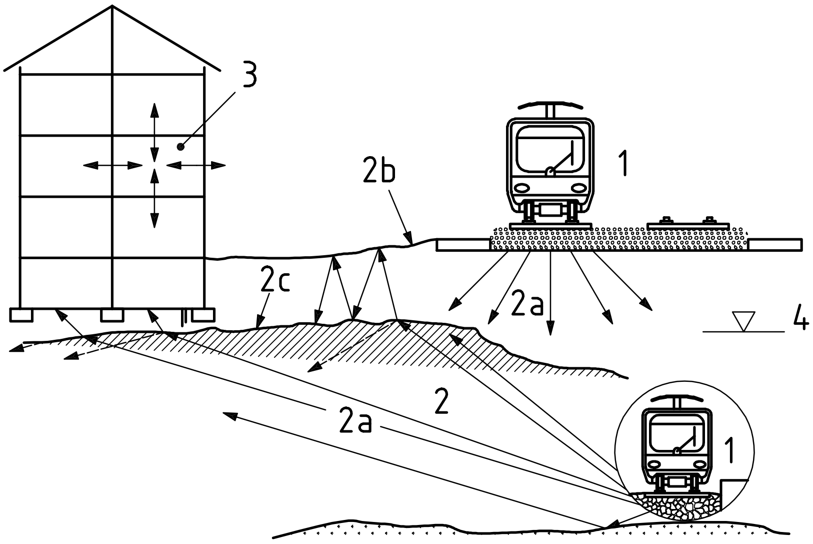
4.2 Source of ground-borne vibration and ground-borne noise

4.2.1 General

Rail systems are a source of vibration. The vibration is transferred and modified through the track system into the supporting infrastructure and then the surrounding ground, and into neighbouring buildings where it can cause perceptible vibration and/or audible ground-borne noise. This source/propagation path/receiver system is shown schematically in Figure 1. The origin of the vibration is the interaction between the rail and wheel depicted in Figure 2.

In the prediction of ground-borne vibration and/or ground-borne noise arising from rail systems, it should be noted that the source, propagation and receiver system depend on many matters (see Annex A), some of which are more significant than others. The parameters must be determined either from experience, data in the literature or expert opinion, or by *in situ* measurements.

The desired accuracy of the prediction model will depend upon the purpose of the prediction and is limited by the knowledge and understanding of system parameters.



Key

1 source

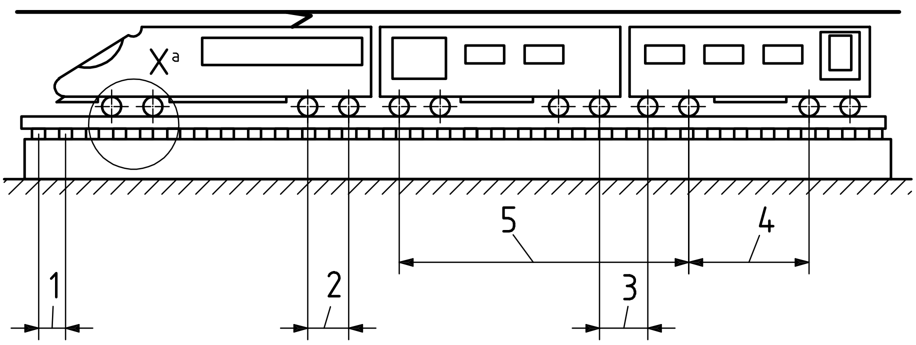
2 propagation:
- 2 a body waves (compression, shear)
- 2 b surface waves (e.g. Rayleigh, Love)
- 2 c interface waves (e.g. Stoneley)

3 receiver (vibration, re-radiated noise)

4 water table

NOTE The components of the system comprising source, propagation and receiver are interdependent.

Figure 1 — Example of source, propagation and receiver system

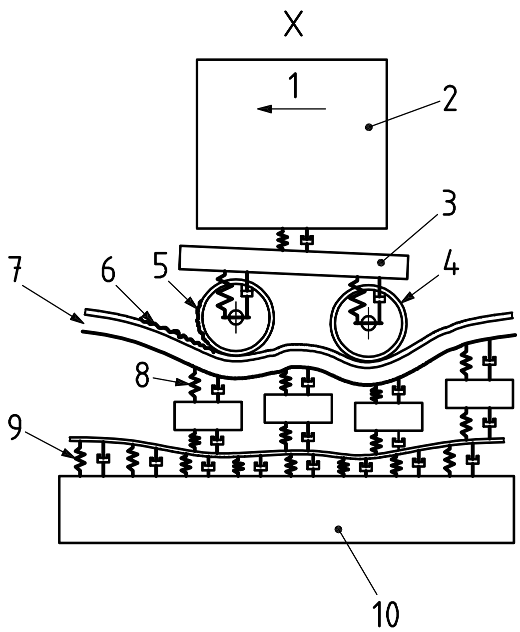


Key

1 rail support spacing
2 intra-bogie axle spacing
3 inter-bogie axle spacing
4 intra-vehicle axle spacing
5 inter-vehicle axle spacing

[a] for detail, see Figure 2 b).

a) Description of source



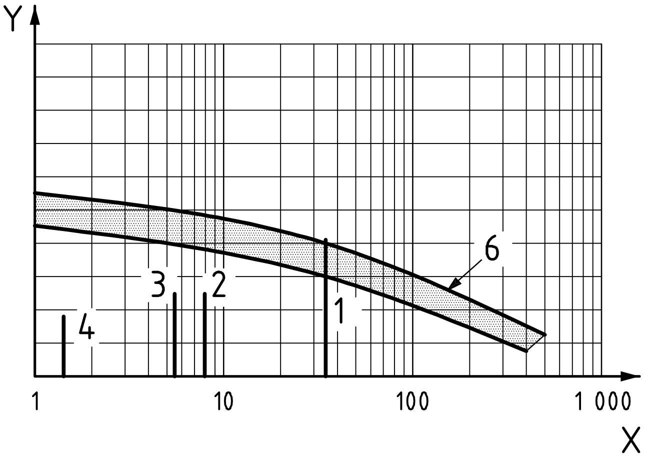
Key

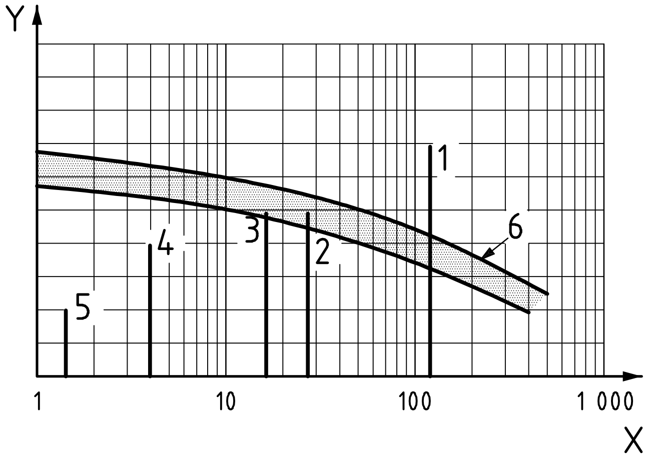
1 train speed, v
2 part of carriage mass, m_C
3 part of bogie mass, m_B
4 unsprung mass, m_W
5 wheel roughness
6 rail roughness
7 rail impedance
8 typical model of rail support
9 typical model of formation/tunnel
10 ground impedance

NOTE Damping may not be viscous.

b) Example model for train/track

Figure 2 — Description of source





Key

X frequency, Hz

Y interaction force, dB

1 rail support passage frequency from [1] in Figure 2 a)

2 intra-bogie axle passage frequency from [2] in Figure 2 a)

3 inter-bogie axle passage frequency from [3] in Figure 2 a)

4 intra-vehicle axle passage frequency from [4] in Figure 2 a)

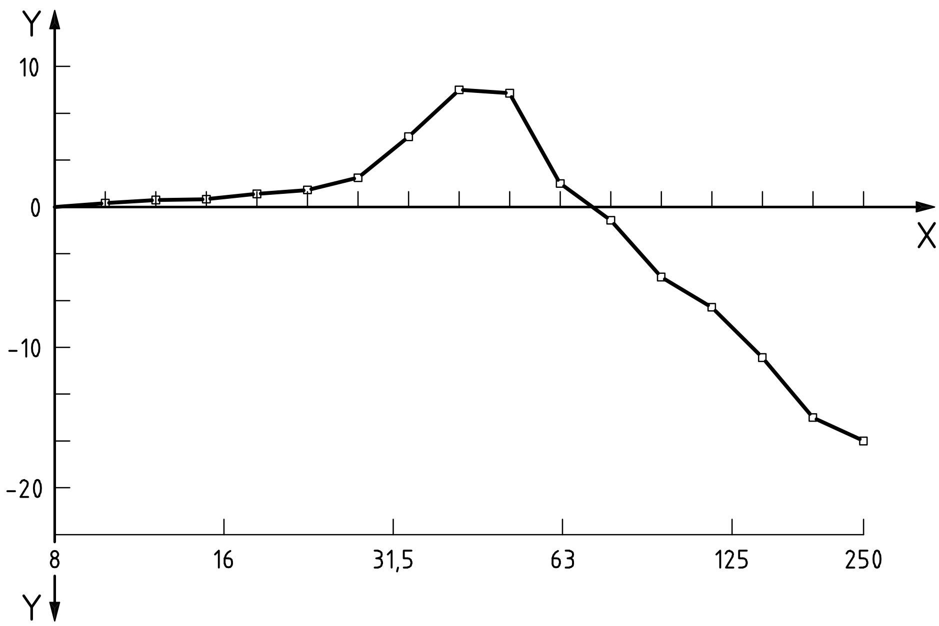
5 inter-vehicle axle passage frequency from [5] in Figure 2 a)

6 wheel and rail roughness

NOTE Passage frequencies are f_n [Hz] = v [km/h]/(3,6 l_n [m]) with l_n being the spacing considered.

c) Sources of excitation at wheel/rail interfaces at 80 km/h (indicative only)

d) Sources of excitation at wheel/rail interfaces at 250 km/h (indicative only)



Key

X frequency, Hz (e.g. one-third-octave mid frequency)

Y insertion gain for train/track relative to a reference defined track, dB

e) Example insertion gain for track predicted by train/track model

Figure 2 (*continued*)

4.2.2 Mechanism of excitation

Mechanisms of excitation are the following.

a) Moving loads (quasistatic) excitation, i.e. the moving distortion of the track and supporting medium due to the train load moving with the train. At fixed locations this is a time-dependent dynamic action and causes flexural waves in the track and the ground. There are mechanisms related to this that are not yet fully understood (e.g. effects of boundary conditions, inhomogeneities in the track and ground giving rise to propagating waves). It is possible for high-speed trains travelling on soft ground to exceed the Rayleigh (surface) wave speed of the ground. Unmitigated, this could generate large vibration levels in a similar way to the sonic boom generated by supersonic aircraft. Its effect in the near field on track stability are more significant. However, this issue is designed out by placing the track bed on stiffened ground or on concrete slab track with piled foundations to underlying stiffer strata. In tunnels, the tunnel lining and invert slab provide the stiff foundation that reduces the levels of vibration in the surrounding ground.

b) Excitation caused by wheel/rail roughness, i.e. random irregularities of the contact surfaces, rail and wheel cause forced excitations of the system (vehicle/track). Roughness will arise first during manufacture. Allowance should be made for the variation in roughness that occurs once in service. These irregularities will vary in service with time.

c) Parametric excitation: For railway tracks with discrete rail support (e.g. sleepers on ballast, resilient base plates on slab as distinct from embedded rail), the wheel "sees" a variation of stiffness depending upon its position along the rail. The moving dynamic forces excite the vehicle and track. The speed of the vehicle and support spacing define the support passage frequency. Similarly, other harmonic components arise due to axle spacing and bogie spacing. Where these frequencies coincide with the natural frequency of the vehicle and vehicle on the track system, considerable excitation of the vehicle track and surrounding environment can arise.

d) Additional wheel/rail defects: More severe forms of wheel and rail roughness can occur in some circumstances as a consequence of operation. For rail, the most severe form of roughness is corrugation. This consists of superimposed periodic irregularities of varying wavelengths. Corrugation can also occur on the wheel with other forms of severe "roughness" being associated with single or multiple wheel flats, ovality, out of balance and eccentricity. These irregularities will vary in service with time. Defects can also arise from insufficient remedial grinding or inappropriate remedial grinding of corrugated track.

e) Discontinuities of the track, i.e. gaps at the switches, at rail joints, dipped rail, etc. cause impact forces. If the length of jointed or welded rails becomes equal to the spacing between bogies of the vehicles, then the levels of vibration can be significantly increased.

f) Vehicle suspension (including the case of locked suspension).

g) Steel hardness, i.e. random or periodic variation in hardness of running surfaces, during manufacture or more usually arising in service.

h) Lateral loads, particularly due to vehicle guidance on tight radius of curvature, and through switches.

i) Driving conditions, i.e. acceleration and braking deceleration of the train form dynamic forces causing vibration.

j) Extreme environmental conditions: For example, railhead temperature and humidity affect wear and hence vibration.

The parameters described under a) through j) above only give rise to vibration as a consequence of the finite driving-point impedance seen at the contact patch between the railhead and the wheel tread.

The impedance seen at the railhead is principally determined by the design of the track, but is also influenced by the supporting structures (e.g. tunnel invert, the tunnel) and the surrounding ground.

For the frequencies of interest, the impedance at the wheel tread is principally determined by the unsprung mass of the vehicle. However, the overall mass of the vehicle and its payload can become important if the suspension becomes effectively rigid (e.g. due to lack of maintenance or the behaviour of dampers at high frequencies).

4.3 Propagation

With rail systems at grade and on elevated structures, the vibration in the ground is mostly carried by surface waves.

For rail systems in tunnels, the propagation of the vibration in the ground is carried via compression and shear waves. At a distance from the tunnel, depending upon the tunnel depth, surface waves may dominate.

The frequency range of interest for ground-borne noise and vibration at the receiver is approximately 1 Hz to 250 Hz. Higher frequencies may be received in certain ground conditions (e.g. rock), or when the building is directly in contact with the tunnel or ground rock, or at a very short distance between tunnel and building or where a soil interlayer between building foundation and rock strata is thin.

The low-pass filter effect of the train-track bed system attenuates the frequencies in the upper part of the relevant frequency range considered in this part of ISO 14837. Due to effects such as damping in the ground, the frequency spectrum changes its shape with distance, and lower frequencies may dominate over larger distances, depending on the ground material.

Where the receiving building is in direct contact with the tunnel (i.e. the tunnel is part of the foundations of a building), the main propagation path is through the structure of the building and therefore the prediction model should take account of the dynamic response of the building structure. Propagation will take place not only through compression and shear waves but also through flexural/bending waves.

Consideration should be given to man-made structures in the ground (such as tunnels, services, ground treatment and/or anchors) and the effect that they may have on propagation characteristics. It may be necessary also to consider the effect of ground water.

Damping in the ground should be considered carefully. Water saturation of porous soils can introduce viscous damping at higher frequencies. However, caution should be exercised in using major simplifications, such as the presumption of viscous damping generally, as this may give rise to significant errors in predicted values particularly at high frequencies. At low strains, it is common to treat the soil behaviour as linear, although non-linearity is implicit in the behaviour of soils to a varying degree as a function of strain. The need to consider these issues and the approach adopted will vary depending on the type of model used. Further guidance is provided in Clause 9.

NOTE 1 The presence of layering can give preference to some frequencies.

NOTE 2 In some situations, there may be errors in assuming clear and simple boundaries for the layers.

4.4 Receiver

The frequency range of interest for the immissions (ground-borne noise and vibration) at the receiver is approximately 1 Hz to 250 Hz. Higher frequencies may be received in certain ground conditions (e.g. rock), or when the building is directly in contact with or very close to the tunnel.

The prediction model should allow for the transfer function between free-field and building foundation. The model should allow for the response of building elements (e.g. floors) that may magnify or attenuate the incoming vibration as a function of frequency.

Ground-borne vibration can radiate noise in rooms where the magnitude will vary spatially and will depend upon the radiation efficiency of the structure and room use, which will be a function of frequency.

The modelling of the receiver should have due regard to structural form and fitting out as a consequence of use (e.g. the models used for rooms in residential property may need to be different from those used for large rooms such as auditoria).

5 Effects of ground-borne vibration and ground-borne noise

5.1 General

This clause provides guidance on the effects of ground-borne vibration and ground-borne noise on buildings, occupants and sensitive equipment, and the frequency range relevant in each case. It also puts the magnitude of ground-borne noise and vibration from rail systems into context.

5.2 Perception of ground-borne vibration (1 Hz to 80 Hz)

Structural vibration inside buildings can be detected by human occupants and can affect them in many ways: their quality of life can be reduced as can their working efficiency. These effects are considered by ISO 2631-2. The levels of vibration generated inside buildings close to rail systems are such that in some situations they give rise to (in order of magnitude) annoyance, discomfort, activity disturbance and, at extreme levels, might in rare cases affect health.

ISO 2631-2 provides a frequency weighting curve related to human response to whole-body vibration inside buildings and guidance on evaluating complaints.

NOTE Vibration can also be visually perceived (e.g. swaying of pendulum light fittings, light lever action on reflective surfaces). This mechanism is more likely to be associated with rail systems at grade as distinct from rail systems in tunnels.

5.3 Perception of ground-borne noise (16 Hz to 250 Hz)

Ground-borne noise occurs when often imperceptible levels of ground-borne vibration give rise to vibration of building surfaces, and some contents that in turn cause an audible “rumbling” sound, usually by radiation to the air inside rooms. Ground-borne noise is more often associated with rail systems in tunnels, as distinct from railways at grade, because the receiving building is completely screened from any airborne noise in the tunnel. Ground-borne noise could, however, also be an issue for an at-grade situation in a room that is on the remote façade to the source.

Ground-borne noise can give rise to annoyance or activity disturbance. Higher levels of ground-borne noise may give rise to sleep disturbance.

NOTE 1 The primary perception of ground-borne noise is through the air, although people lying on beds may also perceive ground-borne noise/vibration at much lower levels as it propagates through the bed structure (bone conduction).

NOTE 2 Higher frequency noise can be emitted by rattling of some elements (see 4.1, NOTE 3).

5.4 Effect on buildings (1 Hz to 500 Hz)

Extremely high levels of ground-borne vibration or a large number of vibration cycles of high magnitude can, in unusual circumstances, give rise to risk of damage to building structures either through direct stress/strain on building components or through induced settlement in cohesion-less soils and fill. The vibration levels required are of the order of 10 to 100 times larger than those associated with human perception and thus levels of vibration sufficient to damage a building, even cosmetically, would be intolerable to occupants. For further guidance, see ISO 4866 and national standards.

The risk of vibration-induced damage to buildings associated with the operation of railways should be considered in the context of the greater risk of damage posed by construction work from induced settlement both during and after construction.

NOTE 1 There can be effects on other structures (e.g. adjacent tunnels, utilities) that may need to be considered.

NOTE 2 Most building damage arises in the frequency range 1 Hz to 150 Hz.

5.5 Effect on very sensitive equipment and sensitive tasks (*circa* 1 Hz to 200 Hz)

Concerns are often raised about the potential effect of vibration on equipment and its operation (computer hardware such as hard disc drives and electrical relays). Guidance is provided in ISO 8569 and ISO/TS 10811. Generally the majority of such equipment is not adversely affected at the levels of vibration that occur from rail systems, particularly those in tunnels. The levels of vibration and shock experienced by computer installations in their normal service environment (e.g. due to footfalls and door slams) are far higher than those experienced as a result of environmental sources.

There are, however, a range of very vibration-sensitive equipment and particular (tasks); for example: computer microprocessor manufacture; some types of laser technology; sensitive laboratory equipment and its operation (e.g. microscopy and spectroscopy); and some forms of medical surgery.

Very low levels of vibration, well below the threshold of human perception, can disrupt these types of equipment and their operation. The principal forms of disruption are adverse effects on sensing, positioning and focusing of equipment and on the activities of the operators in performing these tasks.

Vibration from the railway may itself be at a level to cause interference or it may sufficiently add to the background levels in a building and cause interference.

In very sensitive applications, such equipment will by necessity be subject to extensive vibration control. Background levels are likely to be controlled; for example: by isolation of sensitive equipment from floors or vibration isolated floors; use of high-mass and high-rigidity floors; anti-slam doors; control of foot falls (floor covering and footwear); and isolation of power and mechanical-services equipment from the receiving rooms within the building structure. Floor design and equipment isolation can also reduce the effects of railway vibration. It is useful to compare levels of vibration on the floors of a laboratory from a new rail scheme with existing ambient vibration from internal activities.

There are only a few International Standards that specifically relate to sensitive types of equipment and/or their operation. The manufacturer generally sets serviceability limits or the end user may define limits or targets either by specification or by experience.

6 Metrics

6.1 General

The metric and associated measurement conditions used to quantify the effects of ground-borne vibration and/or ground-borne noise on human beings, the effects on buildings and the effects on sensitive equipment should be defined in detail.

The metric(s) should be predicted at location(s) consistent with the guide value(s) adopted, with due regard to the variation in measurements that will arise at different locations in a room (e.g. vibration levels at mid-span are typically higher than those near the supports; noise levels near walls or at the corners of rooms are higher than those near the centre).

Due regard should be given to the variability in the metric that will arise due to many factors (e.g. inter-train variability). Predicted levels should be qualified by confidence limits in a manner that is consistent with the form of the guide value adopted, and measurements should report variability based upon a sufficient number of samples.

Preferably, time histories should be maintained to enable other metrics to be evaluated if required.

6.2 Perception of ground-borne vibration

Ground-borne vibration should be evaluated in the metric advocated by the relevant national standards and should be consistent with the form of the guide value to be adopted. Appropriate guidance is provided in ISO 2631-1 and ISO 2631-2. Human perception and whole-body response to vibration inside buildings should be based principally on the overall (and running) r.m.s. frequency-weighted acceleration in the three orthogonal directions. ISO 2631-1 and ISO 2631-2 also provide guidance on measurement locations.

The raw time histories should be maintained to allow the derivation of any metric.

In general, vertical vibration measurements in the middle of a floor characterize the environment adequately except in tall buildings where horizontal measurements should be included.

NOTE 1 Human perception may also be rated as frequency-weighted velocity according to some national standards.

NOTE 2 The r.m.s. frequency-weighted acceleration can be derived from the r.m.s. frequency-weighted velocity with an appropriately adjusted weighting.

NOTE 3 National standards also use other metrics for evaluating response to whole-body vibration, such as peak particle velocity (PPV), KB_F value, vibration dose value (VDV) and statistical maximum value of weighted velocity or acceleration.

6.3 Perception of ground-borne noise

Ground-borne noise should be evaluated in the metric recommended by the relevant national standards and should be consistent with the form of the guide value to be adopted.

To assist in future standards development of rating values, ground-borne noise should also be quantified using the maximum A-weighted sound pressure level with a slow time constant, L_{pASmax} and the raw unweighted sound pressure time history should be preserved so that metrics such as event L_{pAeq} and the one-third-octave band linear spectrum of the event can be derived.

The metrics should be predicted or measured near to, but not at, the centre of rooms to avoid undue influence by acoustic standing waves in the room.

NOTE 1 The L_{pASmax} metric measured near the centre of rooms is most closely associated with the body of information on this subject currently available.

NOTE 2 All other parameters remaining equal, L_{pAFmax} with a fast time constant will be approximately 1 dB to 2 dB greater than L_{pASmax} for rail systems using continuously welded rail, and 3 dB to 4 dB greater for jointed rail.

NOTE 3 Ground-borne noise levels predicted or measured near the walls of a room may be 2 dB to 3 dB greater than those near the centre.

Account should be taken of the difference in noise levels with horizontal and vertical location of the room in a building.

During measurements, rooms should be furnished, unoccupied and with the windows closed.

NOTE 4 If the ground-borne noise is dominated by very low frequencies, overall A-weighted sound pressure levels can underestimate the subjective response.

NOTE 5 When there are high ground-borne noise levels or a large number of events, it is relevant to not only look at the L_{Aeq} of the event but also the longer duration (e.g. 1 h) L_{Aeq}.

6.4 Effects on buildings

Guidance is provided in ISO 4866 and its amendments on the prediction, appropriate measurement locations and evaluation. The generally used metric for assessing building damage is PPV (peak particle velocity).

NOTE See national standards for rating values.

6.5 Effects on very sensitive equipment

The metric and assessment location defined in the manufacturer’s serviceability limit, user-defined limit or ISO 8569 should be used. ISO/TS 10811 provides a new approach to classify environments for sensitive equipment.

NOTE 1 Relative displacement (between parts within sensitive equipment) is ultimately the issue that can affect sensitive equipment and its use.

NOTE 2 It is common practice in industry to refer to generic sensitivity curves, such as VC (vibration criterion) curves for rating sites for sensitive equipment.

7 Ground-borne noise and vibration measurements

7.1 Equipment (instrumentation chain)

7.1.1 General

The characteristics of the instrumentation chain, which may comprise transducers, amplifiers/signal conditioners, cables, data acquisition and data storage means, shall be fully understood. The frequency range should be appropriate to the source and evaluation required. The dynamic range should be sufficient to span the source magnitude from ambient levels to the peak of an event.

The calibration of the measurement system should be traceable to national standards or International Standards.

7.1.2 Ground-borne vibration

Reference should be made to ISO 8041 for the specification and calibration of vibration-measuring equipment.

The instrumentation chain (from transducers to recording device) should be capable of measuring ground vibration over an appropriate range of magnitudes (as velocity from 5×10^{-4} mm/s to 100 mm/s or as acceleration from 3×10^{-6} m/s^2 to 500 m/s^2) and frequencies (1 Hz to 500 Hz) of interest. The actual range required for a specific measurement will depend upon the assessment (e.g. evaluation for sensitive equipment could demand a range covering the lower end of magnitudes, from 5×10^{-4} mm/s). Ground-borne vibration measurements may be used to predict ground-borne noise, which should therefore influence the measurements (e.g. demand a broader frequency range and higher sensitivity measurements). Therefore special care is required to ensure that the signal of interest is not affected by noise that may arise within the instrumentation itself.

Digital acquisition of data is to be preferred. The acquisition system shall include necessary pre-processing to ensure accurate recording (e.g. anti-aliasing filters). Precautions in hardware and site set-up should be taken to minimize the effect of external interference (e.g. electrical or magnetic interference, triboelectric noise, ground loops). The phase characteristics should be known where time domain analysis is being undertaken.

Displacement, velocity or acceleration transducers may be used, provided that the frequency range and sensitivity are appropriate for the measurement required. Transducers (and instrument chain) should be capable of enduring outdoor and rail system environments.

Faithful coupling with the vibrating medium shall be achieved (e.g. burying sensors or using 300 mm long steel spikes according to ground conditions; fast setting epoxy resin for measurement on building foundations or walls; double-sided adhesive tape on hard floor finishes; and heavy metal plates with spiked feet for vibration measurements on floors with resilient covering. In all cases, the mounted resonances in the frequency range of interest should be avoided.

Vibration measurement on track components [e.g. rail(s) or sleeper(s)] generally requires transducers to be mechanically fastened to the component to ensure faithful reproduction of the very high levels of vibration that can occur. Precautions are required to ensure that measuring equipment mounted on or in close proximity to track components does not interfere with track or signalling electronic systems.

7.1.3 Ground-borne noise

Sound level meters/analysers should comply with Type 1 of IEC 61672-1:2002.

Equipment should be calibrated using equipment in accordance with IEC 60942.

Ground-borne noise may be derived from ground-borne vibration measurements (see 7.1.2).

7.2 Measurement locations

Different measurement locations are required for the following:

a) research, problem investigation and model development;

b) effect of ground-borne vibration on buildings (generally measurements on building foundations);

c) effect of ground-borne vibration on human beings (generally measurements at the centre of floor spans);

d) effect of ground-borne vibration on sensitive equipment (generally measurements at the point of entry to the equipment);

e) effect of ground-borne noise on human beings (generally measurements near to but not at the centre of rooms or consistent with the ISO 140 series).

Measurement for research, problem investigation and model development may require, for example, evaluation of the propagation of ground-borne vibration with distance, or the evaluation of vibration source levels in the immediate vicinity of a rail system.

At the site of interest, there may be variation in, for example, the source or local ground conditions along the length of the rail system. To ensure statistically reliable results, measurements should therefore be repeated at a number of otherwise similar locations along the length of the rail system, for example measurement of propagation from a rail system (with transducers at say 8 m, 16 m, 32 m, 64 m and 125 m from the track) should be repeated at two locations 25 m apart.

Where practicable, the orientation of tri-axial vibration measurements should be vertical, parallel to the rail system and perpendicular to the rail system. Alternatively, the orientation may be aligned with the axes of a building or room in which measurements are being made, and the relationship with the axes of the rail system recorded.

7.3 Data to be acquired

To evaluate inter-train variability, measurement of at least five representative train pass-bys of each generic category of train (e.g. freight, local commuter, intercity, high speed) is required. Levels should be checked on site and a larger number of train pass-bys recorded if the scatter in the initial measurements is larger than ± 25 % or ± 2 dB.

Measurement samples of the background or ambient conditions should also be recorded.

7.4 Data analysis

Time responses (e.g. FAST or SLOW) and one-third-octave band filters should comply with IEC 61672-1 and IEC 61260.

Analysis software and hardware should be fully verified.

Rail system vibration events are transient and time varying. There is no single definition of the frequency content for such signals. The form of frequency analysis used [(e.g. running r.m.s., FFT analysis, running r.m.s. with “max hold”) can have a significant impact on the frequency spectra identified)]. The form of analysis should be carefully considered and recorded (see also Clause 6).

7.5 Measurement report

The following should be reported as a minimum:

a) reference to this part of ISO 14837 and any other protocol/guidance adopted;

b) identification of date, site location, testing organization and named personnel;

c) complete definition of measuring instrumentation chain, including serial numbers of transducers and all other components, and the form of coupling to the vibrating medium under investigation;

d) complete definition of measurement locations, directions and their context within the rail system;

e) record of the key parameters for the rail system and the site under investigation that may influence ground-borne noise and vibration (see Annex A for checklist);

f) the metric(s) to be recorded (see Clause 6);

g) results recorded separately for each train and track combination, with a record of

   — train type (including number of carriages),

   — train speed, track and direction of travel,

   — train pass-by time and vibration/noise signal analysis time;

h) any other information that may be of importance to the data recorded (e.g. weather, ground surface water, local made ground, presence of possible sources of electrical or magnetic interference).

8 Concept of models

8.1 Model development

The development of any model should take account of the fundamental components source, propagation path and receiver.

It is not always appropriate to construct the model in this compartmental way. In some situations the system should be considered as a single system, which may need to be mutually interactive (e.g. rail systems through buildings or elevated structures where there are no distinct source, propagation path and receiver components).

Ground-borne vibration and/or noise and all of its components should be calculated as a function of frequency so that the end result is in metrics according to Clause 6. The basic model construction should yield the level or magnitude of ground-borne vibration or ground-borne noise, $A(f)$, at the required location in the required metric and should be a function of the source $S(f)$, the propagation path $P(f)$ and the receiver $R(f)$:

$A(f)$ is a function of $S(f)$, $P(f)$, $R(f)$ and the cross terms between them and their sub components, where f is the frequency in hertz.

Each of the fundamental components (i.e. source, propagation path and receiver) should be further divided into the relevant parameters presented in Annex A. The number of parameters that should be considered will depend on the stage of the assessment as described in 8.2. Examples of some of the components and parameters are presented in Figures 3 and 4.

It should be noted that in some situations for simplified models, it may be appropriate to assume that the components/parameters are decoupled from one another. However, the components/parameters actually interact and hence detailed design models will need to allow for the cross terms between each of the components.

$S(f)$ will form the basis of predictions. It may be the forcing function at the wheel/rail interface or, alternatively, it may be a vibration response (velocity or acceleration) at a defined location (e.g. tunnel invert, tunnel wall or in the ground to the side of the tunnel, or to the side of the track at grade).

8.2 Stages of assessment

8.2.1 General requirements for models

Generally it is only necessary to predict absolute levels of vibration for new rail systems. Where alteration of an existing rail system, or a new building constructed over an existing railway, is proposed, it will usually be only necessary to predict changes in levels of ground-borne vibration and/or ground-borne noise compared to a measured base case.

For new rail systems, the requirements for the model will vary during the different stages of the scheme's development.

8.2.2 New rail systems

8.2.2.1 General

The type, form and accuracy of the model used shall reflect the stage of a new rail system's development and therefore the design information available.

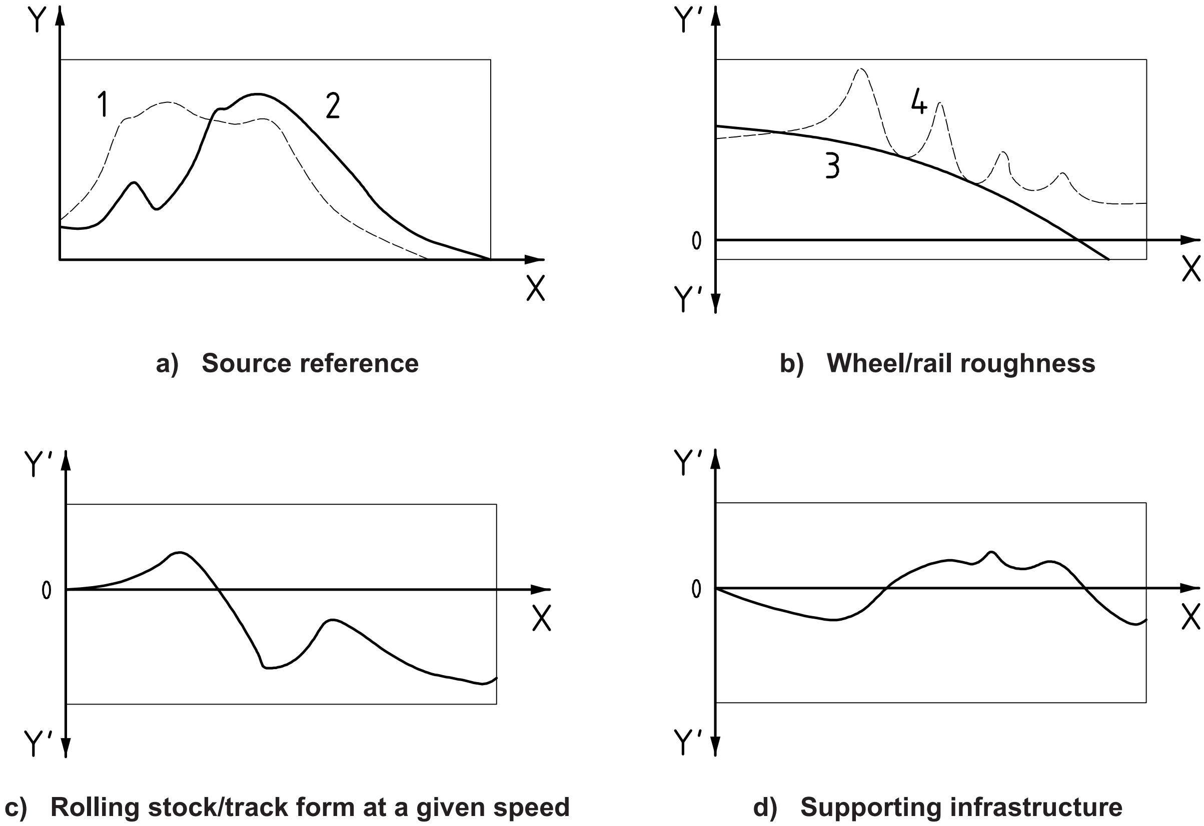
A single model may be used for all stages with appropriate selection of input parameters (e.g. worst case for scoping assessment). Otherwise, three types of ground-borne vibration and/or ground-borne noise prediction model should be considered, as follows.

a) **Scoping model**: to be used at the very earliest stages of development of a rail system to identify whether ground-borne vibration and/or ground-borne noise is an issue and, if so, where the "hot spots" along the length of the system's alignment are located. This type of model should be used to generate input to either environmental comparative frameworks (as part of the selection of a mode of transport) or the scoping stage of an environmental assessment.

b) **Environmental assessment model**: to be used to quantify more accurately the location and severity of ground-borne vibration and/or ground-borne noise effects for a rail system and the generic form and extent of mitigation required to reduce or to remove the effects. This type of model should form part of the planning process for a scheme, developing the environmental statement where required and supporting preliminary design.

c) **Detailed design model**: to be used to support the detailed design and specification of the generic mitigation identified as being required by the environmental assessment model. This type of model should form part of the design and construction stages of a scheme, with particular focus on the rolling stock and permanent-way design.

At each stage, the requirements for the models in terms of complexity, speed of use and accuracy differ (see Figure 5 and 8.2.2.2 to 8.2.2.4).



a) Source reference

b) Wheel/rail roughness

c) Rolling stock/track form at a given speed

d) Supporting infrastructure

Key

X frequency (logarithmic)

Y S (decibels)

Y′ ΔS (decibels)

1 soft ground

2 rock

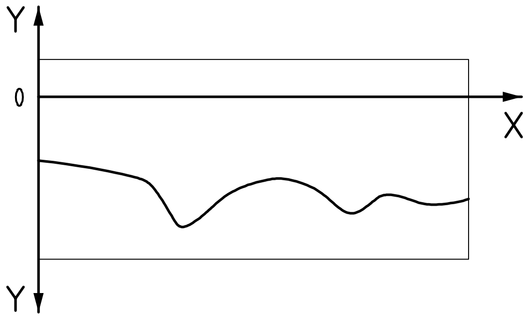
3 smooth wheel/rail

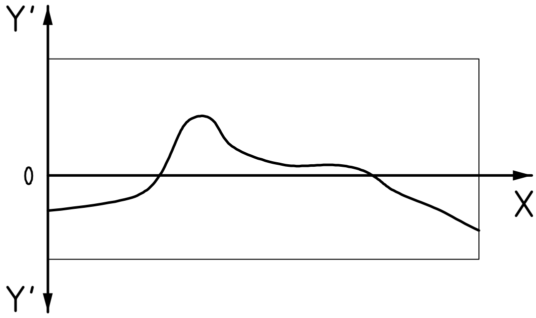
4 corrugated rail

NOTE 1 Spectral shapes are indicative for new systems only.

NOTE 2 Δ functions are relative to source reference parameter values given in a).

Figure 3 — Indicative model components for source (see 4.2)





Key

X frequency (logarithmic)

Y ΔP (decibels)

Y′ ΔR (decibels)

NOTE 1 Spectral shapes are indicative for new systems only.

NOTE 2 Δ functions are relative to source reference parameter values given in Figure 3 a).

Figure 4 — Indicative model components for propagation path (see 4.3) **and receiver** (see 4.4)

8.2.2.2 Scoping models

The model should be quick and simple to use. It should rely on very few generic input parameters; i.e. only those that will be available at the very earliest stage of a project's development, namely:

— type of rail system: light-railway tram (LRT), mass transit, heavy rail, freight, high-speed train,

— alignment (e.g. distance between rail system/receiver and depth of tunnel: shallow, medium or deep),

— typical ground conditions: hard, medium or soft ground, and

— sensitivity of receiving building: high (e.g. recording studio, auditorium), medium (e.g. residential) or low (e.g. industrial).

The model should estimate the radial distance between the centreline of the rail system and the nearest point of a receiver beyond which it is highly unlikely that the levels of ground-borne vibration and/or ground-borne noise would exceed the criteria set for the project.

Given the limited design information available at the outset of a project, scoping models should predict the "worst case" overall levels of ground-borne vibration and/or ground-borne noise only and, by preference, be founded on measurements from representative rail systems.

8.2.2.3 Preliminary design and environmental assessment models

Environmental assessment models should be more complex than scoping models to reflect the increased detail of the project's design available at this stage of a project (see Figure 5). The model should quantify more accurately the location and severity of ground-borne vibration and/or ground-borne noise impacts/effects and the generic form and approximate extent of any mitigation required to remove or reduce the predicted effects. The method will therefore need to consider all the parameters that are critical to determine the absolute levels of ground-borne vibration and/or ground-borne noise, and the benefits (or otherwise) of different design and mitigation options. The parameters that require consideration are detailed in Annex A. The key types of mitigation options that, where required, need to be considered (see also Annex B) are

— permanent-way (track form) design and maintenance,

— rolling stock design (where possible) and maintenance,

— track alignment (vertical and horizontal),

— supporting infrastructure design (e.g. tunnel, at grade formation, or elevated structure), and

— design of receiving building.

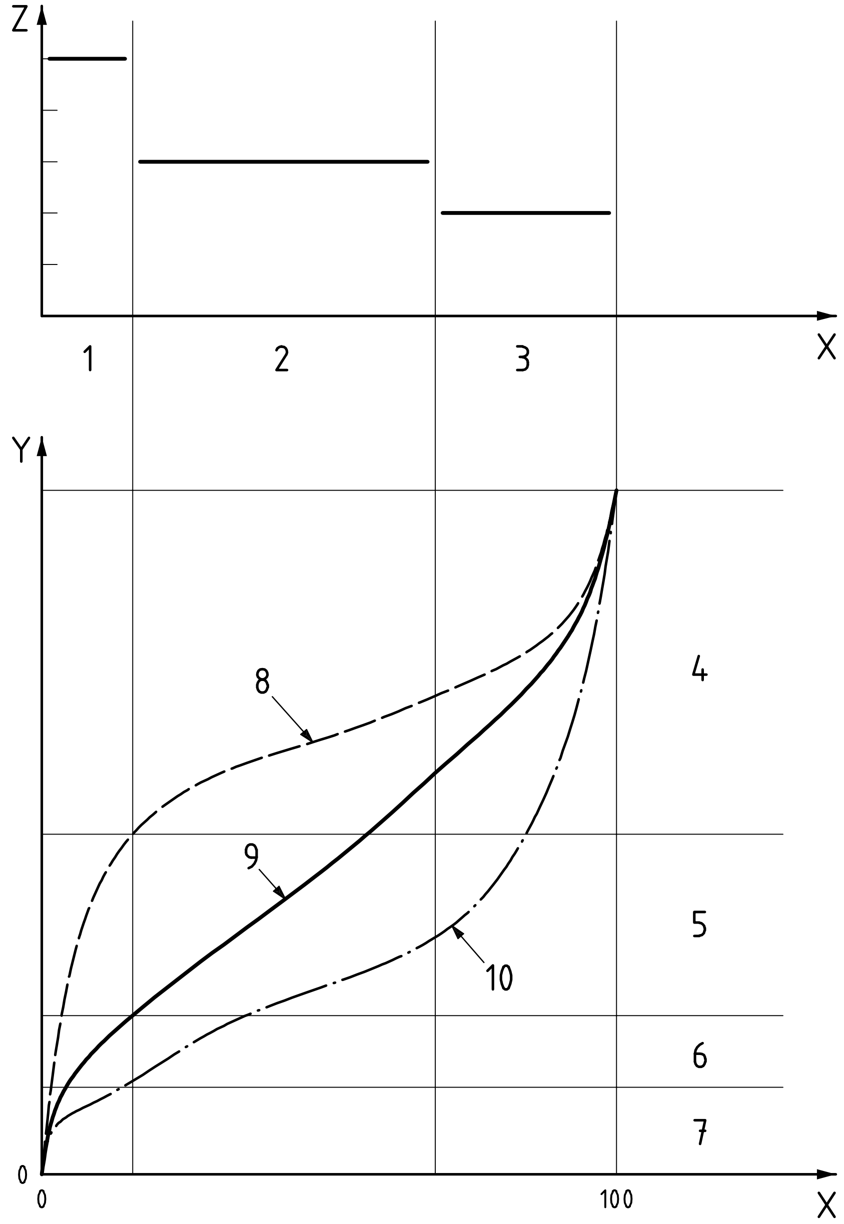
Suitable methods may be developed using either empirical (including experimental) or theoretical approaches, or a mix of both. The models should consider the frequency content of the vibration.

8.2.2.4 Detailed design models

Detailed design models will consider either the absolute values or changes in levels of ground-borne vibration and/or ground-borne noise. Detailed design models are often used to provide more detailed analysis for one or more of the fundamental components of the system; i.e. source, propagation path or receiver of ground-borne vibration and/or ground-borne noise.

The output of detailed design models may be input to environmental assessment models to identify the changes in overall levels of ground-borne vibration and/or ground-borne noise associated with design development. The models should consider the frequency content of the vibration in octaves, one-third-octave or narrow bands.

Given that the detailed design models will support the design and specification of parts of either the railway's permanent works or a receiving building, they will need to consider the influence of all of the relevant parameters defined in Annex A. Suitable methods can be developed using empirical or theoretical approaches, or a mix of both.



Key

X design complete, percent

Y time

Z acceptable error

1 scoping model

2 environmental assessment model

3 detailed design model

4 design and construction stage

5 planning and environmental assessment stage

6 route selection stage

7 master planning

8 project with low planning sensitivity

9 project with moderate planning sensitivity

10 project with high planning sensitivity

Figure 5 — Types of model and acceptable error

8.2.3 Alterations to existing rail systems or the development of new buildings near existing railways

There are similarities with the development of new rail systems but there are also important differences.

First, the level of vibration arising from the existing rail system can and should be measured. The measured data should be analysed using the overall metric to be used for the assessment of the future situation (see Clause 6). The measured data should also be analysed as time-averaged, one-third-octave band or narrow band r.m.s. values/levels.

Predictions will generally be required to evaluate

— the effect of a change in the rail system (i.e. change in rolling stock, track or tunnel), and/or

— the levels of ground-borne vibration and/or ground-borne noise that would be generated in new buildings developed near the rail system.

Where the rail and/or wheel treads of rolling stock are likely to change, account should be taken of changes in wheel/rail roughness in the assessment of the future situation.

As with new rail systems, the same stages of development apply (as do model requirements, see 8.2.2).

a) **Scoping**: to identify whether (usually in the worst case) a new building will require mitigation against ground-borne vibration and/or ground-borne noise or whether modification to a railway system is necessary.

b) **Environment assessment**: this stage will confirm the severity of any ground-borne vibration and/or ground-borne noise and define the generic form and extent of mitigation for new buildings (e.g. whether base isolation is required) or the generic form of any change to the proposed rail system modification (e.g. the generic type of a different permanent-way design).

c) **Detailed design tools**: these more detailed and accurate tools will support the detailed design of new building structures (foundation, floor and base isolation designs) and/or modifications to the rolling stock, permanent way or tunnel.

The output of the models at any of these stages should be insertion gains or the modulus of transfer functions. These transfer functions should then be applied to the measured data for the current situation to calculate the values of the overall metrics (ground-borne vibration and/or ground-borne noise).

9 Prediction models

9.1 General

The checklist in Annex A should be used to define the relevant parameters to be considered for each situation. The parameters used in a prediction should be documented. The reason for not considering certain parameters may need to be justified. The effects on the prediction from the uncertainty in the input parameters should be considered and reported.

Models for the prediction of ground-borne vibration and/or ground-borne noise may be either parametric or empirical, or a combination of the two. These alternative methods are widely used and their suitability will depend on the nature of the available input data and the purpose for which the results will be used. Geoseismic vibrators or impulse excitation by drop weights or controlled blasting may be used to establish transfer functions, although corrections are needed to account for the difference between these measured sources and the operational railway (e.g. going from a point to a line source). The use of physical scale models is a potentially useful approach.

Parametric models include algebraic and numerical models. Empirical models make use of data obtained by field measurements, together with methods of interpolating predictions within sets of measured data. The parametric models (and some empirical models) are deterministic, generating a unique prediction for a given set of input data. Given the dependence of this type of model on the accuracy of the input data, reliance should not be placed on a single set of input parameters unless it is known that they are exact. It is necessary to test the effect of varying the parameters over a range of possible values. The values used for design calculations should be selected using either formal risk assessment methods or using engineering judgement.

Caution should be exercised in applying a model to situations that fall outside the range of conditions against which the model has been calibrated and validated. The degree of uncertainty associated with an extrapolation increases with the magnitude of the extrapolation.

The significance of vehicle entry into a model should be considered, for example starting transients and appropriate modelling time for the event (vehicle pass-by).

9.2 Parametric models

9.2.1 General considerations

The physical dimensions of the model (1D, 2D, 3D) and the associated accuracy that improves with model dimensions need to be considered, particularly in the context of the stage of the assessment.

It is important to make appropriate assumptions concerning the soil profile (including ground water table) and corresponding loss factor, soil density and wave propagation speeds. In particular, geotechnical data such as shear modulus must be applicable to the small strains that occur in the propagation of ground-borne vibration and/or ground-borne noise.

Soil parameters should be obtained from measurement of wave propagation speeds, ideally as a function of depth and water saturation. Shear modulus should not be derived from static measurements.

Caution should be exercised in using soil parameters from literature, which may not be at the appropriate strain.

9.2.2 Algebraic solutions

Algebraic solutions are of necessity simplified. The following matters should be taken into account.

a) Limitations should be clearly stated, including valid frequency range and wave types.

b) Limitation of prediction to one type of wave propagation only may lead to a significant error. For example, while compression waves can dominate at a distance from deep tunnels in homogeneous ground, at shorter distances shear waves can be significant. Moreover, conversion between compression and shear or Stoneley, Lamb or Love waves can occur, particularly at interfaces, and to Rayleigh waves at surfaces.

c) If a loss factor is used, any frequency dependence should be taken into account.

d) The source term should be relevant and valid. For railway tunnels, it is preferable to use the track-bed as the source, although it is often difficult to measure there. Wall vibration may be used, but only if it is judged to have similar vibration levels to the track-bed. For a rail system at-grade, the source term may be the vibration level on the surface at a specified distance from the track.

Algebraic solutions for porous media are possible if the media properties are known, but require advanced mathematical techniques.

Algebraic solutions may also be used for solving reflection and transmission equations at interfaces between soil types, and for solving propagation through layered media. They are only practical when there is a planar contact between layers of significant impedance contrast, and there are homogeneous isotropic media in each layer (e.g. it is difficult to deal with fuzzy interfaces).

Soil-structure interaction and building response are difficult to solve algebraically for complex situations and numerical solutions or empirical data are normally used.

9.2.3 Numerical solutions

9.2.3.1 General

Numerical solutions may be used as a method of predicting vibration generation (source) and propagation when sufficient information is available concerning the properties of the system. The numerical methods include Finite Element Modelling, Finite Difference Modelling and Boundary Element Modelling.

In all numerical models, the effect of time-step size and element size should be established.

9.2.3.2 Finite Element Method (FEM)

In FEM models, the system may be represented as a mesh of elements and the model iteratively solves functions for continuity across the boundaries of the elements. Specialist FEM packages may be used, but care is needed in the representation of

- elements at the interface between tunnel/ground and ground/foundations, and
- the input function at the wheel/rail interface, particularly the way it varies over time and space.

It is important that suitable elements be included for the boundaries of the model to avoid contamination of the results by boundary reflection.

9.2.3.3 Finite Difference Method (FDM)

Advanced algebraic solutions, involving numerical solution of the wave equation, can be obtained using finite difference methods. FDM modelling involves discretizing a dynamic system and performing step-wise calculations of the states of each element in the time domain, using differential equations with finite time intervals.

9.2.3.4 Boundary Element Method (BEM)

BEM modelling is an appropriate method where Green’s functions can be derived.

BEM is an alternative to FEM, and requires elements only on the surface of a model. In the context of ground-borne vibration, it is particularly suited to modelling the semi-infinite nature of the ground and avoids the boundary wave reflections present, without careful definition of boundary conditions, in FEM.

9.2.4 Hybrid models

It should be noted that BEM lends itself to use in combination with FEM and FDM, with the latter models used to compute the source solutions, and BEM used to solve for propagation from source to receiver (or near field to far field), with computational economy and reflection-free boundaries.

In FEM and FDM models, it is necessary to quantify the error in the results, which is due to reflections from boundaries. This is not necessary in BEM models, which do not involve a boundary reflection problem.

9.3 Empirical models

9.3.1 General

Empirical models are derived wholly from measured data by extrapolation from, or interpolation within, the measured data set(s).

Insertion gains or the modulus of transfer functions should be used to perform the extrapolation from measured data, but should be based on the algebraic/analytical understanding of the underlying phenomena.

9.3.2 Types of empirical model

There are two principal types of model, as follows.

a) **Single site models**: Measurements gathered at a single site are extrapolated to the new site under assessment. The extrapolation functions used shall be derived from other measurement databases, the results of analytical methods or elicited formally using expert opinion.

b) **Multiple site models**: The prediction model (a set of deterministic algorithms) is developed by regression and trend analysis of a large database of measurements from a number of sites, which include variations in all of the main parameters (see Annex A) that will change the ground-borne vibration and/or ground-borne noise between the measurement and assessment sites.

Generally single-site models should be applied to single assessment sites; i.e. to assess the mitigation requirements of a building development at the single site. The assessment of new rail systems should be made using a multiple-site model to allow for the variation in parameters which will be encountered over the length of the new system.

The number of sites included in the database should reflect the following:

— the length of the new system under consideration (the longer the system the greater the number of sites), and

— the number of significant parameters where there is a difference between the assessment and measurement (database) sites. Situations where there are significant differences in all the components require the largest number of sites in the database.

For multiple-site models, as a general rule, the number of measurement sites in the database should be dependent upon the number of significant parameters (see Annex A) that differ between the measurement and assessment sites, and the magnitude of the difference. In this context, measurement at a range of distances from, or along, a track count as sites in the context of distance, tunnel depth and ground condition parameters.

The database used for either type of model should include a sufficient number of measurements at each measurement site of each train type on each track to quantify inter-train, inter-train-type and inter-track variability at that site.

9.3.3 Form of empirical models

The basic form of any model is given in 8.1. Empirical models require simplification of the underlying physics. The degree of acceptable simplification depends on

— the variability between the measurement and assessment sites, and

— the stage of assessment (see 8.2).

The fundamental simplification involved in empirical models is that the components can be decoupled. Cross-parameter elements should be added if there is significant interaction between two parameters, particularly at the detailed design stage where more accurate predictions are required.

As an example, the basic construction for an empirical model for ground-borne vibration, where it is appropriate to decouple model components, can be calculated as magnitude $A(f)$, e.g. acceleration in m/s^2 or velocity in m/s as shown in Equation (1):

$$A(f) = S(f) \cdot P(f) \cdot R(f) \quad (1)$$

where

$$S(f) = S_{\text{SRef}} \cdot S'_{\text{RSt}} \cdot S'_{\text{Rail}} \cdot S'_{\text{TF}} \cdot S'_{\text{SupIn}} \cdot S'_{\text{Speed}} \cdot \; \ldots$$

$$P(f) = P'_{\mathrm{SupIn}} \cdot P'_{\mathrm{PP}} \cdot \ \ldots$$

$$R(f) = R'_{\mathrm{G}} \cdot R'_{\mathrm{Struct}} \cdot \ \ldots$$

f is the frequency, in hertz;

superscript ’ denotes a magnitude ratio as a correction factor;

subscripts SRef, RSt, TR, SupIn, PP, G, Struct denote source reference, rolling stock, track form, supporting infrastructure, propagation path, ground and structure, respectively.

As an example, the basic construction for an empirical model for ground-borne noise where it is appropriate to decouple model components, expressed as level $L(f)$ at a required location in the required metric decibels (dB ref. 20 µPa), can be as shown in Equation (2):

$$L(f) = \tilde{S}(f) + \tilde{P}(f) + \tilde{R}(f) \tag{2}$$

where

$$\tilde{S}(f) = \tilde{S}_{\mathrm{SRef}} + \Delta\tilde{S}_{\mathrm{RSt}} + \Delta\tilde{S}_{\mathrm{Rail}} + \Delta\tilde{S}_{\mathrm{TF}} + \Delta\tilde{S}_{\mathrm{SupIn}} + \Delta\tilde{S}_{\mathrm{Speed}} + \ \ldots$$

$$\tilde{P}(f) = \Delta\tilde{P}_{\mathrm{SupIn}} + \Delta\tilde{P}_{\mathrm{PP}} + \ \ldots$$

$$\tilde{R}(f) = \Delta\tilde{R}_{\mathrm{G}} + \Delta\tilde{R}_{\mathrm{Struct}} + \Delta\tilde{R}_{\mathrm{Rad}} + \ \ldots$$

f is the frequency, in hertz;

~ signifies the metric is in decibels;

Δ denotes a level difference as a correction term;

subscripts are as for Equation (1), with Rad denoting radiation.

If the vibration is expressed in decibels, the reference quantities should be indicated. With single-site models, each component or parameter of Equations (1) and (2) should be derived from either theory or measurement.

9.4 Semi-empirical models

Semi-empirical models are a combination of the parametric models in 9.2 and empirical models in 9.3. In this approach, one or a number of empirical components or parameters are replaced either by analytical equivalents or by controlled measurements on the partly completed works (e.g. use of geoseismic vibration source in a completed tunnel without track as a means to identify the insertion gain required from the track to receiver). This approach is often adopted to extend an empirical model used for environmental assessment to make it appropriate for detailed design support. Elements that are generally modified are source parameters (e.g. tunnel, track and rolling stock design) and receiver parameters (e.g. foundation and building design).

Semi-empirical models enable the statistical confidence of empirical data to be combined with analytical tools to support detailed design development.

10 Development, calibration, validation and verification

The definition of the metric and associated physical conditions (e.g. occupancy of the room) used in measurements obtained to develop, calibrate and validate a model should be the same as the definition used for the metric in which the prediction model output is expressed.

It should be recognized that prediction of ground-borne vibration and/or ground-borne noise arising from rail systems is complicated and there are many unknowns and uncertainties associated with any analysis. The accuracy of a model therefore needs to be evaluated to give confidence in its application. As discussed in 8.2, the desired accuracy varies depending on the stage of development of the rail system. Generally the more advanced the development of the rail system, the greater the desired accuracy; i.e. the lower the acceptable error (see Figure 5). Knowledge of a model's accuracy is also an essential part of risk management during the design development of a rail system scheme.

NOTE Tentative guidance is provided in Annex C for information.

The general stages required to quantify accuracy are described in the following.

The accuracy of a model is evaluated by comparison with independent measured data (termed validation). Model accuracy may also be estimated by comparison, for a defined test case, against another validated model, and care should be taken to document differences in the assumptions and input conditions between the models. Input assumptions and input parameters used in validation should be documented and reported.

Model development and calibration should precede validation.

In the development stages, a model is modified, over a number of iterations, to improve the agreement between the model output and the measured data or test conditions. For very detailed and complex models that need to be very accurate, the development process may need to be applied to each component (i.e. source, propagation path and receiver) and/or to each main parameter (e.g. train speed, distance from the track). Where possible, the modifications made to the model parameter or component should be based on theoretical and/or empirical understanding of the underlying physical processes involved. The comparison could also be made to a geoseismic vibrator generating appropriate strain and frequency, after allowance for the difference between a point and a line source.

Improvement of a prediction model at a specific site could be assisted by comparison with measurements at that site (e.g. from existing rail systems, or the use of down hole sources, or a geoseismic vibrator) allowing for appropriate corrections between the indicative sources and the actual rail system. Once the model has been developed as far as possible, calibration of the model output can be made; i.e. a calibration function is, or functions are, evaluated to ensure agreement between the model output and measured data. The form of the calibration function(s) used should be documented and reported.

The final stage of evaluating a model's accuracy is the validation. This is where the output of a model is compared with an independent set of measurements for an operational rail system. It should not be compared with the measurement case used in the calibration process. The accuracy and uncertainty should be documented as identified by a validation process (guidance is given in Annex C).

Models are generally implemented via a computer program (spreadsheet or a program written specifically in a programming language). The correctness of the implementation should be verified before the program is applied to a rail system project. Verification usually takes the form of test cases, where the output is calculated by hand and is then compared with the output from the computer implementation. It also includes testing the stability of the program, by trying from minimum to maximum values for all the input variables.

Annex A
(informative)

Checklist of issues relevant to modelling and measurement

A.1 General

This annex provides a checklist of issues relevant to modelling and measurement that should be reviewed when predicting ground-borne vibration and/or resulting ground-borne noise, or when undertaking measurements. The parameters will have varying degrees of significance and some will not be relevant to a particular prediction situation. It is therefore a matter for expert engineering judgement as to their relative significance or relevance to a given situation.

They are listed under the principle headings of source, propagation path and receiver. They are not listed in any significant order.

The component parameters listed may either be constant or a function of frequency, strain, load, temperature, etc. It may be possible to ascribe confidence limits to these parameters, either from a statistical evaluation or by engineering judgment.

A.2 Source

A.2.1 Route alignment

a) Horizontal, vertical

b) At grade, cuttings, embankments

c) Elevated

d) In tunnel

A.2.2 Rolling stock

a) Vehicle length

b) Wheel profile

c) Wheel diameter

d) Wheel roughness, wheel faults

e) Wheel dampers

f) Resilient wheels

  — rim mass

  — dynamic stiffness

g) Unsprung mass

  — wheels

  — axles

  — other (brake discs, axle hung motor, gearboxes, etc.)

h) Primary suspension

— stiffness

— damping (viscous, hysteretic, Coulomb)

i) Sprung mass

— bogie frame

— traction components

— frame-hung motors or gearboxes

j) Secondary suspension

— stiffness (bogie fraction, traction components)

— damping

k) Body mass (all mass above secondary suspension)

l) Total mass per axle (= unsprung mass + sprung mass + body mass): empty or full

m) Axle load (static/dynamic)

n) Moments of inertia and flexure of wheel/axle set

o) Number of axles and axle spacing

p) Flexural modes of body

A.2.3 Rail

a) Alignment (track geometry: line and level)

b) Rail gauge

c) Rail roughness (condition, irregularities), various types

d) Rail section, rail steel

e) Switches, crossings, joints, welds

f) Periodicity of load (parametric excitation) due to varying track support stiffness and axle spacing (function of vehicle speed)

g) Lateral loads [cant deficiency, oscillating wheel rail forces due to tight curves (e.g. manifest as wheel squeal), flange contact, contact patch]

h) Contact patch stiffness (vertical)

i) Lubrication (friction modifiers)

A.2.4 Track form

a) Load capacity of rail fastening (clips, insulator, clamping system)

b) Continuously supported rail

c) Embedded rail

d) Sleepers

e) Periodicity of support

f) Ballast (glued ballast)

g) Booted blocks, sleepers

h) Pads and resilient bearings (resilient fasteners or resilient base plates or under sleepers)

i) Ballast mats

j) Static/dynamic/acoustic stiffness of resilient elements

k) Concrete slab

l) Floating track slab

m) Current collection (power track)

A.2.5 Supporting infrastructure

A.2.5.1 At grade

In cutting, on an embankment (soil or expanded polystyrene), ground beams, piles, ground stabilization (lime-cement, grouting, soil nails, mesh), bituminous surfacing, concrete slab, sub-grade (soft spots), ground conditions.

A.2.5.2 Elevated structure

a) Construction material: steel (welded, bolted, riveted), concrete (*in situ*, precast), composite (steel/concrete), timber

b) Deck mobility (complex)

c) Frequencies, damping

d) Soil-structure interaction (foundation type, soil conditions)

e) Changes (e.g. removal of ballast under track replacement)

NOTE Structure-radiated noise that can have a significant environmental impact is excluded.

A.2.5.3 Tunnel

a) Type and location

b) Depth

c) Shape

d) Lining, relining

e) Track foundation (invert)

f) Immediate soil and structures, grout

g) Voids

h) Rattle from loose fixings in tunnel

A.2.6 Construction tolerance

a) Stiffness variation of resilient elements

b) Construction tolerance on support spacing

c) Time effects, long-term E-values (Young's modulus)

d) Cracking

A.2.7 Operational

a) Train speed

b) Mixture of traffic or service pattern

A.2.8 Operational maintenance

a) Track geometry (e.g. rail line and level)

b) Wheel trueing

c) Wheel and rail grinding

d) Roughness

- corrugation
- degradation

e) Wheel slip/slide protection

f) Ballast and track slab condition

g) Track maintenance factors

A.3 Propagation path

A.3.1 Ground (soil, rock)

a) Geological profile (stratification, layer inclination and distinction of layer interfaces)

b) Topography

- ground surface

- buildings (shape, size and location)
- ditches

c) Water tables

d) Soil dynamic properties at small strains (drained and undrained)

- shear modulus
- Poisson ratio
- density
- shear (v_s), compression (v_p) wave velocities
- loss factor (type and viscous or hysteretic)

e) Inhomogeneties in the path

- man-made (pipes, roads, other tunnels, ground anchors, piles, deep foundations, pre- or post-ground treatment)
- natural (faults, fissuring, voids, layering, anisotropies, inclusions, two-phase propagation, free surface)
- mitigation, interventions (e.g. screen walls)

f) Season (frozen ground or soil properties, moisture content)

A.3.2 Wave field

a) Wavetype, wavetype conversion, reflections and diffraction

b) Angle of incidence

c) Near field

d) Far field

e) Axis (resultant, or longitudinal, transversal, vertical)

f) Radiation distribution

g) Geometric damping

A.4 Receiver

A.4.1 Structures

a) Metric to predict

b) Foundation type (raft, piles, base isolation, etc.; materials of foundation, and response to different wavetypes)

c) Geometry of foundation

d) Local soil dynamic properties

e) Effect of local ground treatment

f) Formation level (distance, axis)

g) Soil-structure interaction

h) Building type

- concrete
- brick
- timber
- steel

i) Building condition

j) Floor type (geometry and materials, suspended, ground bearing)

- stiffness, mass, damping
- live loading

k) Eigen frequencies of structure and damping

l) Predicted parameters of vibration with reference to structures, occupants, sensitive equipment

m) Location of prediction in structure

n) Empty or full buildings (mass)

o) Background vibration levels (e.g. services equipment, road traffic, footfall)

p) Visual/audible cues to vibration

q) Swimming pools (underwater noise)

A.4.2 Ground-borne noise

a) Ground-borne noise: Distinction between airborne, ground-borne, bone conduction on pillow

b) Metric to predict

c) Position in building

d) Position in room

e) Radiation efficiency

f) Room acoustics

- reverberation time (empty or full)
- room size and liveliness of room elements
- background noise

g) Rattle of contents (high frequency).

Annex B
(informative)

Mitigation of ground-borne vibration and ground-borne noise

B.1 Introduction

Ground-borne noise and/or vibration can be mitigated, as follows.

a) At source: Principally, this is via (in order of effect)

- alignment (horizontal and vertical),
- track design,
- rail quality and its maintenance,
- train/vehicle design and its maintenance,
- train speed (for speeds below approximately 100 km/h),
- design of supporting infrastructure (e.g. formation, elevated structure or tunnel).

NOTE 1 Ground-borne noise can arise from tunnelled sections of rail systems (or some surface sections where there is significant mitigation of direct airborne noise which can highlight the ground-borne noise component).

NOTE 2 Control of structure-radiated noise from an elevated structure is a separate but linked matter.

b) By limiting the propagation (e.g. trenches or concrete walls between a source and receiver).

c) At the receiving building: For new buildings, this is generally via base isolation or by isolating spaces within buildings (box-in-box structures), which are more effective at dealing with ground-borne noise. A reduction of vibration can also be achieved by, for example, providing damping to, or changing the design of, floor constructions. It is generally unreasonable or impracticable to retrofit vibration mitigation to existing buildings.

Mitigation at source is the most effective means of vibration mitigation. However, all of the available forms of mitigation are linked to fundamentals of rail system design and operation. The provision and design of any mitigation needs to be consistent with the safety, operational, maintenance, reliability and economic fundamentals of the rail system.

The constraints that these railway fundamentals impose on the design of mitigation at source are outlined in B.2. The nature and form of constraints differ among rail schemes (e.g. light-railway tram compared to high-speed trains) and operators. It is therefore essential that ground-borne noise and/or vibration mitigation be included as an integral part of the rail system design, and that the design is led by the appropriate engineers based on the overall rail system needs.

B.2 Mitigation at source

B.2.1 Existing rail systems

The means of reducing ground-borne vibration and/or ground-borne noise generated by operational rail systems are generally limited. This is because the alignment is fixed and mitigation options such as using a different, more resilient track system or adding stiffness and mass to the foundation (e.g. adding a concrete slab or lime piles under the track to control low-frequency vibration) require lengthy stopping of the train service to undertake such works. This has very substantial implications for passengers and business and may therefore only be considered as part of major renovation programmes.

The forms of ground-borne noise and/or vibration control that can be generally applied to operational lines are therefore limited to those that can be implemented through maintenance, particularly maintenance that ensures a smooth running surface of rail and train wheels. The principal options, and the limitations on their use, are as follows.

a) Rail grinding: minimize the rail roughness at wavelengths associated with ground-borne vibration and/or ground-borne noise at the operational speed of the system under consideration. Limitations arise through the need to maintain traction and braking forces. Consistent reduction of noise and vibration levels can only be achieved by regular preventive grinding or polishing or linking the requirement for grinding to acoustic criteria.

b) Joint removal: This is principally achieved by welding rail joints. Limitations are imposed by the need to manage thermal rail expansion and the difficulties (in terms of health and safety) associated with welding inside tunnels.

c) Switches and crossings maintenance: Regular re-adjustment of built-up switch and crossing components to minimize rail movement.

d) Wheel truing and grinding. The matters raised under rail grinding also apply here.

e) Rail alignment: for high-speed trains, improvements to the accuracy of rail line and level can reduce low frequency vibration.

NOTE 1 Grinding associated with minimization of rail wear and optimization of passenger comfort will not necessarily provide benefits at all of the wavelengths of interest to ground-borne vibration and/or ground-borne noise. Furthermore, there are less data available about typical in-service roughness amplitudes at these wavelength as, historically, roughness measurements have focused on longer wavelengths (wear and passenger comfort) or shorter wavelengths (associated with airborne noise).

NOTE 2 Joints at switches and crossings can be minimized by installing swing-nose switches. For street running systems, flange-riding switches can eliminate joint noise and reduce vibration to a limited extent.

In extreme cases, it may be possible to consider temporary speed restrictions over short lengths of line, whilst other longer-term mitigation is effected. However, control of speed is generally an ineffective means of controlling ground-borne vibration and/or noise and, because of the non-linear relationship with speed, levels of ground-borne vibration/noise may actually be increased. The local benefit of any ground-borne vibration and/or noise reduction needs to be weighed against the potential delays and hence disturbance of rail passengers (see also B.2.2.4).

B.2.2 New rail systems

B.2.2.1 Alignment

Aligning a new rail system away from sensitive receivers is effective mitigation.

The ability to achieve this is limited. Maximum curvature (horizontal and vertical), maximum rates of change of curvature (horizontal and vertical) and vertical gradient are necessarily constrained to protect key matters such as passenger comfort and rate of wear to train and track components.

The extent of these constraints varies among types of rail system. The constraints on alignment increase with increasing speed of operation.

B.2.2.2 Track design

Use of continuous welded rail (CWR) removes the impulsivity in the noise and vibration associated with jointed track and therefore provides noise and vibration benefits.

Over and above the selection of the rail type and maintenance of its running surface, mitigation of ground-borne noise and/or vibration is achieved by increasing the vertical dynamic resilience of the track and ultimately by the provision of increased mass over any resilience provided. Notwithstanding noise and vibration issues, resilience is required in the permanent way to safeguard passenger comfort and reduce wear and tear on the train and track components. However, too much resilience can adversely affect the same key issues.

It is important to note that track systems do not include significant absorptive or dissipative elements (except ballast). Different track designs merely “move” the vibration energy to different elements of the train-track-supporting structure system. Care therefore needs to be exercised to ensure that in designing a track to mitigate, for example, a ground-borne noise issue, the design does not give rise instead to a ground-borne vibration and/or ground-borne noise or passenger comfort issue, as well as introducing unacceptable reliability, availability, maintainability and safety (RAMS) implications.

This is particularly an issue for surface sections of rail systems where (except behind substantial noise barriers or deep cuttings) perceptible vibration is generally the main issue. In such cases, the provision of track systems with more resilient rail support are unlikely to provide material reduction of wayside vibration unless such track systems are combined with changes to the design of the formation that provide for a more rigid formation (e.g. ground slab, piled slab, lime piles or ground treatment below the track).

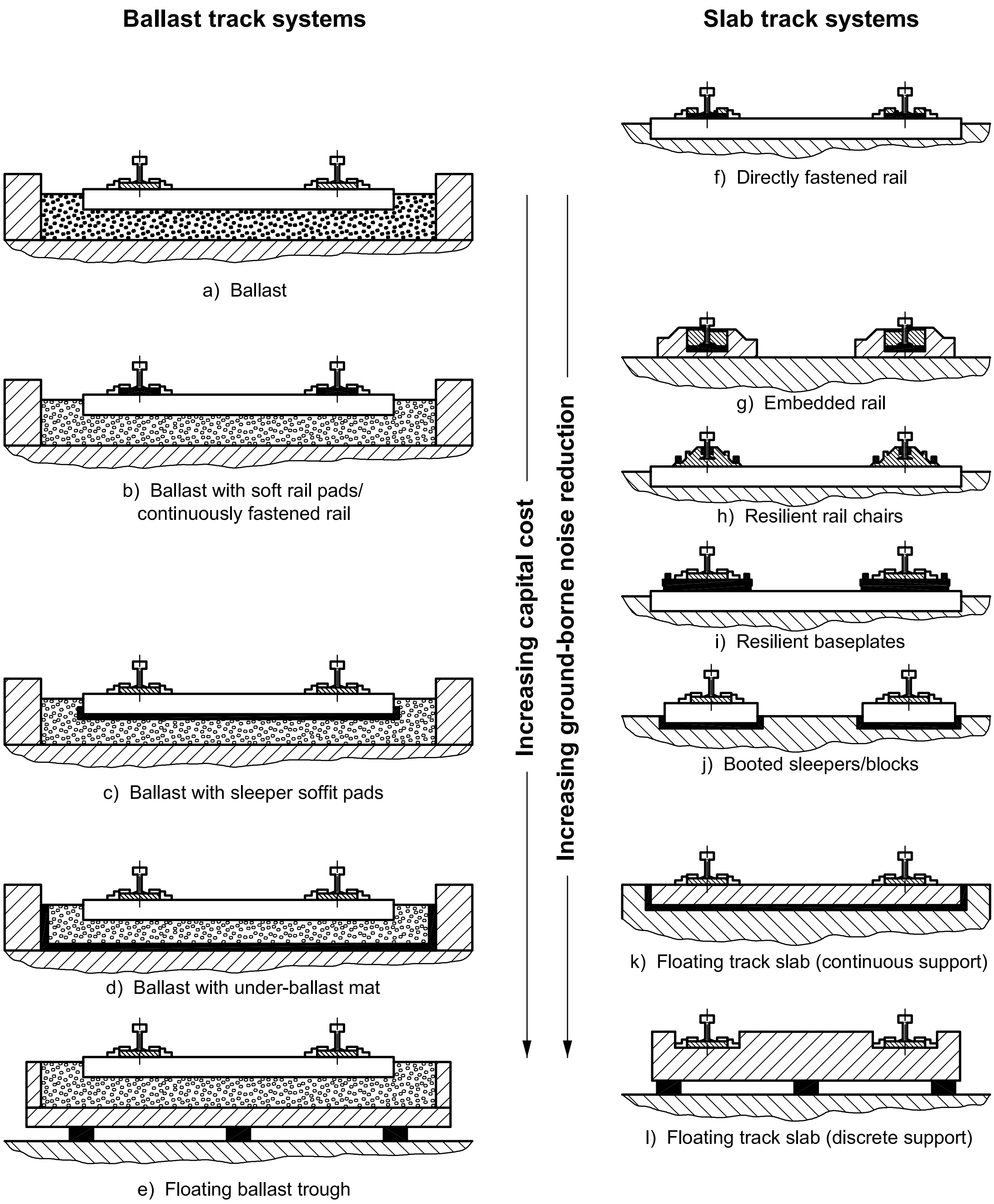
The generic types of ballast and non-ballast track forms may be categorized in terms of their ground-borne noise or vibration reduction as shown in Figure B.1. This figure also presents the principal features of the layout of these different generic designs and the location of the principal resilient component(s) in each case.

To control ground-borne vibration from surface sections, some consideration should be given to the use of glued or cemented ballast in combination with resilient rail pads, as a more cost-effective solution to ground slabs or substantial ground treatment (e.g. concrete or lime piles, ground treatment).

It should be noted that each generic form of track can have a wide range of ground-borne noise and/or vibration performance. For example, a poorly designed or installed floating slab track can perform only as well as directly fastened rail. However, the converse is not true: it is not possible to design or install a directly fastened rail to perform as well as a well designed, high-performance booted sleeper/block system or floating track slab. The performances of the generic systems, when well designed, can therefore be ordered as shown in Figure B.1. Poor design can reduce or remove any vibration reduction benefit.

From a ground-borne vibration and/or ground-borne noise perspective, the performance of individual generic track forms presented in Figure B.1 cannot be added together to provide increased reduction of ground-borne vibration and/or ground-borne noise. For example, if a resilient base plate reduces overall ground-borne vibration and/or ground-borne noise levels by 10 dB and a floating slab track reduces levels by 20 dB then providing the resilient base plates over the floating slab track will not reduce levels by 30 dB. In fact, in this case, it is possible for the combined performance to be less than that for the floating slab track on its own. There are, however, situations where generic systems are added together for other reasons. For example, whilst the provision of resilient base plates over a floating slab track may adversely effect the reduction of ground-borne vibration and/or ground-borne noise, it will reduce the level of vibration occurring on the floating track slab and thus the airborne noise radiated by it. This can be an important issue when airborne noise needs to be controlled as well as ground-borne vibration. However, the ultimate ground-borne noise and vibration performance is reduced in this instance.

Whilst track forms provide an effective method for mitigating ground-borne vibration and/or ground-borne noise, this is not their prime function. Foremost, the track form is provided to support and guide the rolling stock to provide a safe, comfortable and cost effective revenue service for the rail system. To this end, the design of a track form should be considered with respect to the principles of reliability, availability, maintainability and safety, as well as cost and the need to permit operation of a range of rolling stock. In some situations, these constraints can adversely constrain the ground-borne vibration and/or ground-borne noise reduction that can be achieved by a track form.



NOTE 1 Main resilient elements are shown in black.

NOTE 2 The slab track systems g), h), i), j) could be designed to be as effective as each other in terms of ground-borne noise with little cost difference.

Figure B.1 — Generic track form layouts (schematic)

Key aspects for a track form are:

a) safety, including for example

- rail stress and roll,
- rail clamping force and longitudinal rail restraint,
- static and dynamic rail deflections and differential deflection (e.g. rail stress),
- rates of change of static and dynamic deflection along the length of tracks,
- fastening system stress and attenuation of impact loading (fatigue loading of track components);

b) capital cost, including for example

- complexity of track form,
- specially designed components,
- time and man-power for installation;

c) whole-life cost (including maintenance)

- component lifetimes,
- access to components with shorter lifetimes;

d) passenger comfort

- static and dynamic rail deflections,
- effect of track form dynamics on ride quality and on-train vibration;

e) reliability;

f) rail system availability (i.e. loss of revenue service because of high track maintenance);

g) rail roughness and corrugation growth characteristics.

Reliability, availability, maintainability and safety (RAMS) criteria, including constraints on matters such as those set out above, are set by rail operators and permanent-way designers and will differ between rail systems. Safety is the over-riding issue and hence track systems must be proven in-service or through tests before they will be considered for an operational rail system.

The characteristics of the permanent way that ensure compliance with the reliability, availability, maintainability and safety criteria for a rail system may oppose the characteristics required to provide reduction of ground-borne vibration and/or ground-borne noise. It is therefore essential that the development of any track form intended to provide ground-borne vibration and/or ground-borne noise reduction is an integrated design led by permanent-way design engineers.

B.2.2.3 Train/vehicle design

Unlike airborne noise, there are relatively few characteristics of train design that are key to ground-borne vibration and/or ground-borne noise. The key parameters are:

a) primary and secondary suspension (the softer the better and no friction dampers);

b) unsprung mass (this needs to be optimized taking account of the track that the trains will operate over);

c) overall mass (the smaller the better);

d) wheel tyre roughness (should be reduced);

e) use of resilient wheels [these generally improve the vibration isolation performance of resilient rail support systems (e.g. resilient base plates), but can adversely effect the isolation performance of floating slab track systems].

As with track design, all of these above parameters are critical to the reliability, availability, maintainability and safety performance and costs of the rail system. Mitigation can therefore only be provided as part of the integrated design development of the train and the mitigation may be necessarily compromised by the operational requirements of the rail system. There are advantages (in terms of control of ground-borne noise and vibration) in integrating the train and track designs.

B.2.2.4 Train speed

Train speed is fundamental to the business case for, and the transportation benefits provided by, a rail scheme. Furthermore, train speed variation is not generally an effective means of vibration mitigation. Train speed variation should not be considered as a general means of ground-borne noise and/or vibration reduction.

B.3 Mitigation by impeding propagation

Trenches dug between a source and receiver generally perform poorly. This is because of the long wavelengths associated with ground-borne noise, and vibration at the frequencies of interest diffract round trenches (sides and base). There are practical limitations in constructing deep trenches with adequate perimeter length.

Concrete walls or other intervening barriers may be made deeper than trenches so that they break the “line of sight” between source and receiver, provided they are also of adequate perimeter length. These have some benefit but only close to the walls, again as a consequence of the long wavelengths involved and hence diffraction around the edges of the barrier.

B.4 Mitigation by the receiver

a) Rearrangement of spatial plan (e.g. locate building far from source, switch location of car parks and landscaping into nearby areas).

b) Reconsider use of site (commercial may be less sensitive than residential).

c) Avoid floor resonance with dominant peaks in ground vibration spectrum (de-tune).

d) Solid ground bearing slabs may be preferential to suspended slabs (e.g. bungalows in place of two storey dwellings).

e) Unavoidable resonances targeted at frequencies of least human sensitivity, usually require high frequency (bandwidth may be broad, increasing risk of tuning with source).

f) Low natural frequency floors may avoid tuning with source (also narrower bandwidth), but increased risk of footfall induced vibration (see ISO 10137).

g) A floor may be constructed on isolators off a sub-floor (floating floor).

h) Isolate sensitive areas (box-within-box).

i) Isolate individual items of sensitive equipment.

j) A dynamic system added to the primary system (dynamic vibration absorber), to neutralize motion (at a specific frequency, where de-tuning cannot be achieved).

k) Select structural form for optimum damping (e.g. concrete in preference to steel).

l) Constrained layer floor damping treatments.

m) Building foundations taken into strata with less vibration, decouple from soil near surface (appropriate where source is a rail system at grade).

n) Vibration-sensitive equipment on foundation bearing deep in soil, and decoupled from building or soil near surface (appropriate where source is a rail system at grade).

o) Vibration-sensitive equipment on ground rather than suspended floors (to avoid floor resonance, although a low frequency floor could provide passive isolation to higher frequencies).

p) Base isolation (mostly effective at reducing ground-borne noise).

q) Deploy traditional structural materials in a way that achieves rigid body mount frequency comparable to that obtained with base isolation.

r) Increase path length of vibration to increase damping (e.g. suspend floors from tops of columns rather than supported from columns directly off the ground).

s) Irregular construction patterns and discontinuities in the construction.

t) Heavier forms of construction.

u) Increase background noise levels to mask intrusive noise (with care to avoid adverse affect on speech intelligibility and maintain a spectral balance).

v) Active vibration control using electromechanical or hydraulic actuators (unlikely to be a viable option in all but under special circumstances).

Annex C
(informative)

Process and tools for development, calibration, validation and verification

C.1 Introduction

Developing, calibrating and validating a model and verifying its implementation are vital steps in quantifying and improving the model's accuracy. However, there are no International Standards currently in place that provide guidelines on these processes. This annex gives a set of processes and tools that may be used or which may assist in the development of other processes for these key activities.

The metric should be defined completely so that prediction and measurement are undertaken under known and identical conditions.

A model should be implemented to the situations for which it was developed (i.e. it should be fit for purpose). For example, a model that only treats the ground as a half space would not be capable of modelling a layered half space and, similarly, a scoping model could not be expected to have good validation. See Clauses 8 and 9 for stages and types of model.

C.2 Explanation of the elements for quantifying the model accuracy

The quantification process can be simplified, as shown in Figure C.1.

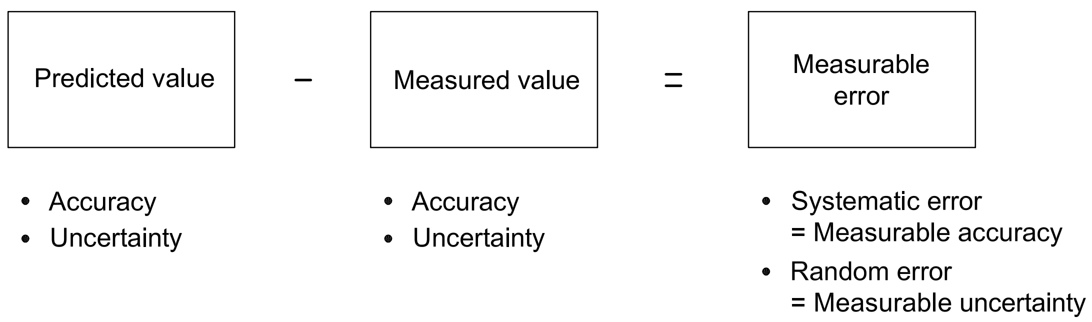


Figure C.1 — Quantification process

The accuracy is the correctness (or exactness) of either the predicted value (i.e. correctness of the model algorithms) or measured value (i.e. correctness of the measurement equipment) against the true value. The true value is seldom known, which is why the measurable accuracy is defined against measured data.

The uncertainty of the predicted value defines the variability in the output value associated with variability in the input parameters. The uncertainty of the measured value defines the variability in the measured value associated with variability in the measurement conditions (e.g. inter-train variability, geological variability).

The measurable error is the difference between a predicted value and the measured value. Measurable error has two components (see ISO 3534-1 and GUM for details):

— systematic error (the measurable accuracy of the model) and

— random error (the measurable uncertainty associated with predicted and measured values).

For illustration of the two types of measurable error, see Figure C.2.

Key

1 true value

Figure C.2 — The two types of measurable error

C.3 Population of prediction and measurement data set

C.3.1 General

As part of model development and calibration, a data set of prediction and measurement pairs should be created. The data set population should ideally be sufficient to achieve the following, although in practice there are practical limitations (e.g. cost and time):

— it should cover the range of values (or as close as reasonably possible) for each parameter (e.g. train speed, distance, ground type) associated with the predictions to be made;

— it should provide a statistically robust representation of the uncertainty in the predicted and measured values. This requires model sensitivity analysis and multiple measurements.

C.3.2 Sensitivity analysis

Sensitivity analysis measures the impact on prediction outcomes of changing one or more key input parameters about which there is uncertainty.

EXAMPLE Pessimistic, expected and optimistic value might be chosen for an uncertain variable. Then an analysis could be performed to see how the output of the model changes as each of the chosen values is considered in turn (with all other parameters held the same).

The use of risk assessment tools and techniques such as Monte-Carlo analysis can assist in evaluating the random component of the measurable error.

C.3.3 Measurement variability

The measured values will demonstrate variability as a consequence of changes in measurement conditions. Multiple measurements should ideally be undertaken to quantify this effect, considering, for example,

— inter-train variability: measurements obtained from revenue service (at least five trains and, depending upon dispersion of results, more of each train type on a given line should be recorded), and

— inter-line variability: measurements obtained from revenue service (at least five trains and, depending upon dispersion of results, more of each type should be recorded on each line).

Where reasonably practicable, inter-location variability should also be examined. Measurements, at one distance from the line, should be repeated at least twice at different locations that are on the same side at the same perpendicular distance from the railway, and separated by not less than 10 m but not more than 100 m from one another.

C.4 Development and calibration tools

The development and calibration of a model is most effectively undertaken at parameter level (e.g. speed, distance from railway) using trend analysis on the "fit" between predicted and measured values.

One form of this analysis is presented in Figure C.3. Best-fit regression analysis (not necessary linear regression) between the predicted and measured data forms the basis of the analysis. The objectives of the development stage are to modify the model (at parameter level) to provide

— a linear relationship between predicted and measured values,

— a unity gradient for the linear regression line,

— a zero y-axis offset, and

— as small a standard deviation for the distribution of data around the best-fit line as possible.

Once the development process has been applied to each main parameter, it can then be applied to the whole model.

Once the development process has been completed, the model should be calibrated. The calibration process derives (where required) calibration functions or values that ensure unity gradient and zero y-axis offset for the best-fit regression line(s). Calibration should ideally be undertaken at a parameter or component level rather than on the whole model.

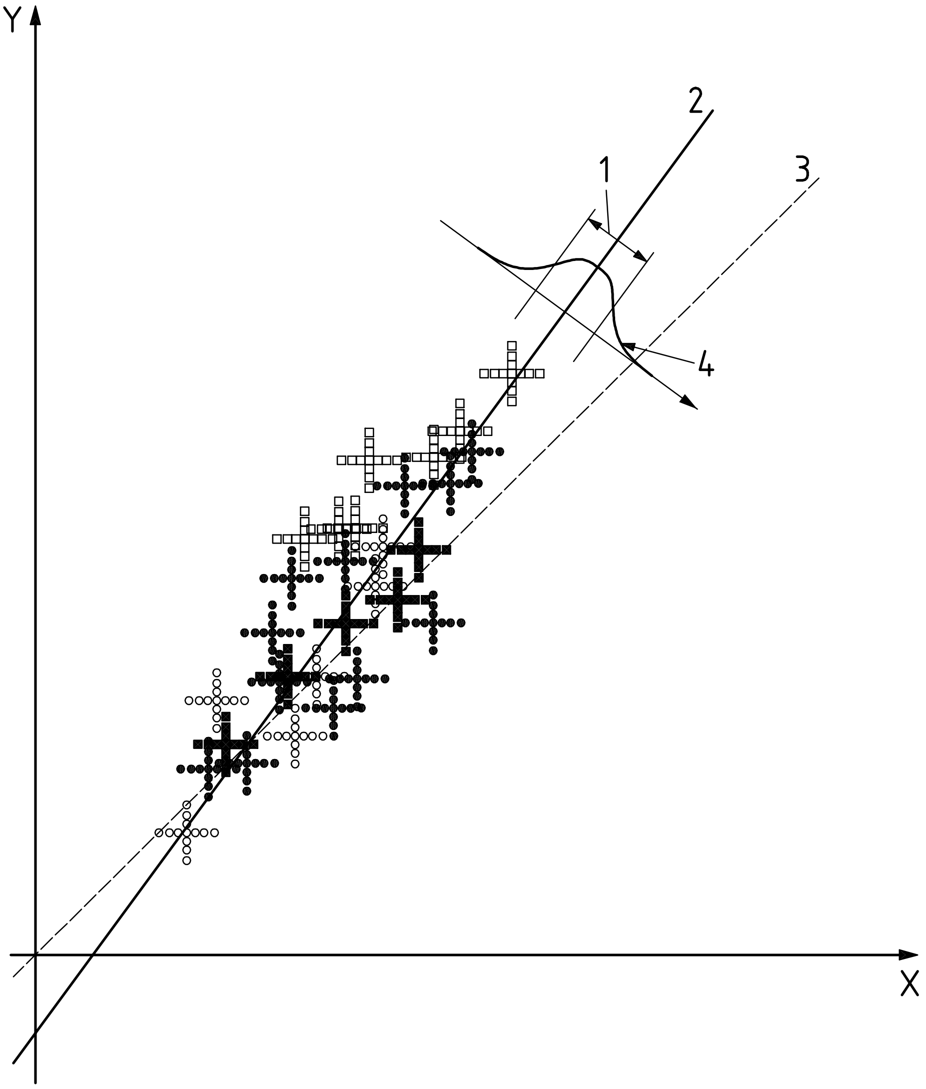
C.5 Validation tools

The validation data set should be different from that used for the development and calibration populated from prediction and measurement pairs.

The simplest form of validation is to evaluate the arithmetic mean and the standard deviation of the measurable error distribution created by subtracting the measured value from the predicted value for each case considered in the data set. The mean value and the standard deviation of the measurable error distribution give the systematic (accuracy) and random (uncertainty) components, respectively.

This simple approach provides no indication of any trends in the fit between predicted and measured values (e.g. the systematic error may be a function of predicted value). This information can be particularly important when predictions are extrapolations of the data set used to develop the model.

Trends in the fit between predicted and measured values can be established using validation tools similar to those used to undertake development and calibration (see C.4). Figure C.4 shows how regression analysis may be used to yield the systematic error and random error components as a function of level.



Key

X measured
Y predicted
1 ± 1 standard deviation
2 best fit regression line
3 accurate model
4 statistical distribution around best fit regression line, from which follows the standard deviation

Data of this example

Gradient: 1,3
Standard deviation: 2,5
Offset: –2,7
Number of observations: 250

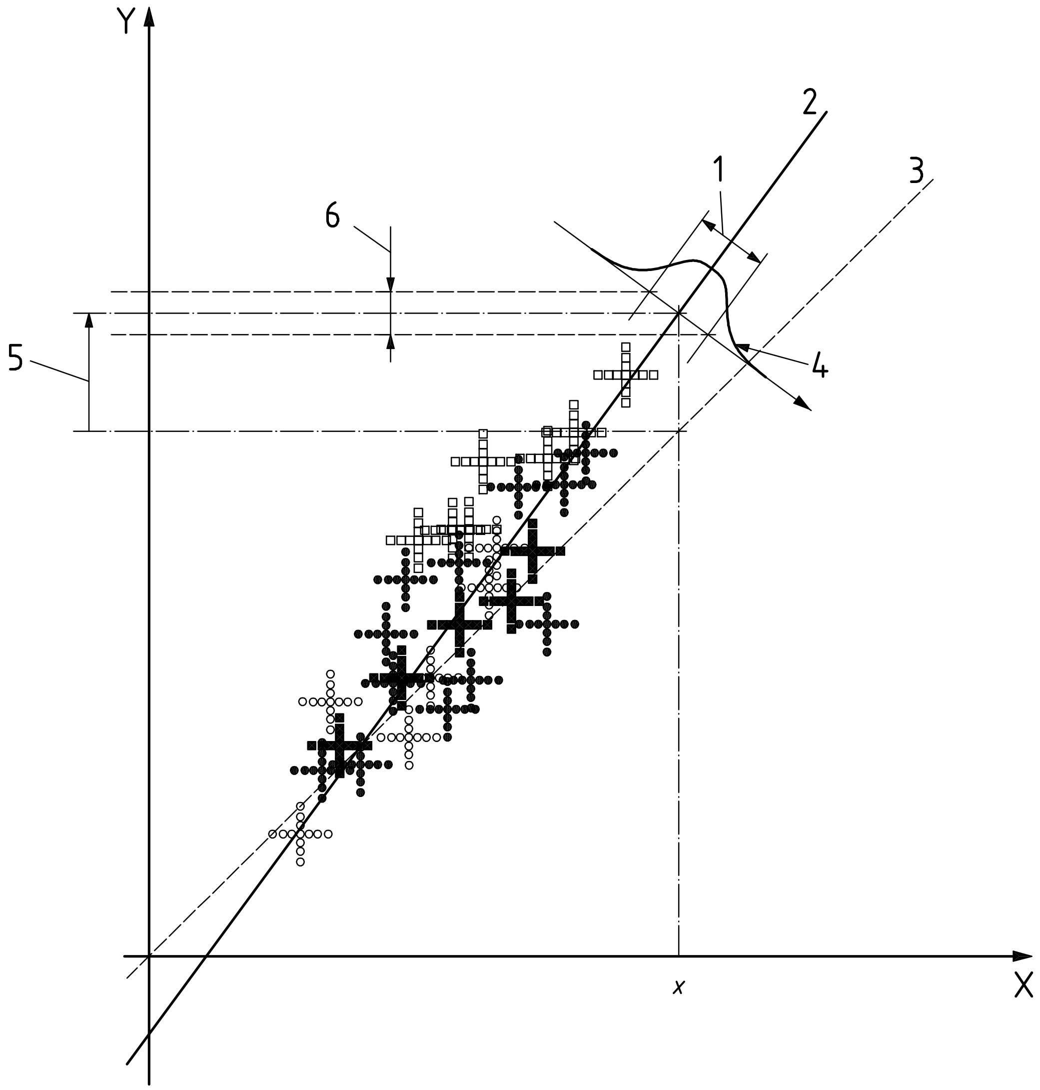
Prediction and measurement pair

Sensitivity tests

○ Site 1
● Site 2
□ Site 3
■ Site *N*

Measurement variability

Figure C.3 — Example of development and calibration tools



Key

X measured

Y predicted

1 ± 1 standard deviation

2 best fit regression line

3 accurate model

4 statistical distribution around best fit regression line, from which follows the standard deviation

5 systematic error at x: y_1

6 random error at x: $\pm y_2$

Data of this example

Gradient: 1,1

Standard deviation: 2,1

Offset: –2,0

Number of observations: 75

Prediction and measurement pair

Sensitivity tests

○ Site 1

● Site 2

□ Site 3

■ Site *N*

Measurement variability

NOTE For an ideal model, the systematic error $y_1 = 0$ and the random error $y_2 = 0$.

Figure C.4 — Example of validation tools

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