RIVAS
Railway Induced Vibration Abatement Solutions
Collaborative project

Definition of appropriate procedures to predict exposure in buildings and estimate annoyance
Deliverable D1.6

Submission date: August 15, 2012

Project Coordinator:
Bernd Asmussen
International Union of Railways (UIC)
asmussen@uic.org

Title	**Procedures to predict exposure in buildings and estimate annoyance**
Domain	**WP 1.1**
Date	
Author/Authors	M. Villot, C. Guigou, P. Jean, N. Picard
Partner	CSTB, DB, RATP, SBB, Trafikverket, Cedex, BAM
Document Code	rivas_cstb_wp1_d1_6_v04_procedures_exposure_annoyance
Version	04
Status	Final version

Dissemination level:

Project co-funded by the European Commission within the Seventh Framework Programme		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission) Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Document history		
Revision	Date	Description
	July 01, 2012	First draft
1	July 20, 2012	Second draft
2	August 13, 2012	Final version
3	August 15, 2012	Final version (with minor corrections)

EXECUTIVE SUMMARY

Deliverable D1.6 aims at defining procedures to predict exposure in buildings and estimate annoyance. These procedures will be used at the end of the project to evaluate all the mitigation measures developed in RIVAS in common situations (deliverable D1.9) and to show their effects in typical configurations with vibration problems (hot spots) (deliverable D1.12).These procedures must be able to calculate exposure descriptors inside buildings for different emission / ground propagation / immission situations. Emission situations can be defined rather well from available ground vibrations data at 8m from the tracks. Tools (models, data) are therefore needed to estimate the four transfer functions TF1 from ground at 8m to ground at building location, TF2 from ground to building foundations, TF3 from foundation to floor and TF4 from floor vibration to ground borne noise.

TF1 can be known just by choosing building at reference distances from the tracks where ground measured data exist (8m or 16m for example). For estimating the transfer functions TF2-TF4, several models developed by RIVAS partners have been identified as well as data from particular sites in different countries. All these data have been collected, properly stored and analyzed / compared. Two types of data have been gathered: statistical data (mainly from SBB and DB empirical models), used as base curves, and data from well documented particular sites from Germany, Switzerland, France, Spain and Sweden, used to validate the statistical models. And since little information existed on ground and building foundation conditions, the CSTB numerical model has been used to estimate the effects of modifications in ground and building foundations on the corresponding transfer functions.

This analysis / cross validation has led to proposals for statistically predicting these three transfer functions TF2 to TF4; the proposed transfer functions are expressed as mean spectra, knowing that the associated standard deviation is of the order of 5 dB.

A MATLAB procedure has been developed to calculate the main descriptors identified in Deliverable D1.4 for different source/ground/building situations. The starting input is the ground velocity time signal at 8m. The above four transfer functions TF1 to TF4 expressed as 1/3 octave amplification or attenuation in dB are then applied to the input signal the same way as the frequency weighting, also expressed in dB; the mitigation measure performances expressed as 1/3 octave insertion loss in dB is also applied to the input signal in order to calculate descriptors after mitigation. Only a few descriptors calculated for a few emission / ground propagation / immission situations (to be chosen) will be used in D1.9 in order to clarify / simplify the result presentation. However, it seems that a minimum of four descriptors (max value and equivalent value for both vibration and ground borne noise) must be used to correctly evaluate the mitigation measures in D1.9.

Once the decrease in exposure associated with any mitigation measure has been estimated, the corresponding decrease in annoyance must be evaluated using proper exposure-response relationships. The most recent papers have been gathered to identify proper exposure-responses; more information might come later (particularly published results from the European project Cargovibes).

The results are the following:

For ***railway vibration***, at least a few exposure-response curves exist on both max values (velocity) and equivalent values (rms or VDV, both from acceleration). The two types of

curves (max and equivalent values) cannot be easily compared and are considered as complementary; it is proposed to use both of them.

For ***railway ground borne noise***, rare exposure-response curves exist. It is proposed to use the exposure-response relationships from the USA, expressed in terms of Lp_{ASmax}; unfortunately, no exposure-response relationships expressed in terms of Lp_{Aeq} exists for ground borne noise from railways, which would have added information on traffic effects.

This report has been circulated among RIVAS WP1.1 members and the main models/rules to estimate vibration and ground borne noise in buildings, as well as the descriptors and exposure-responses curves proposed in this report have been agreed upon. However, some details in the formulas proposed might be further discussed within RIVAS and modified when evaluating the mitigation measures at the end of the project (D1.9).

TABLE OF CONTENTS

INTRODUCTION

The aim of the RIVAS project is to develop mitigation measures at source, track, propagation path and vehicle [1]. The mitigation measure performances will be expressed as an insertion loss in 1/3 octave bands calculated from ground velocity levels measured at 8 m from the tracks, as defined in D1.2 [2a]. In order to evaluate the effects of these mitigation measures on people in buildings (Task of WP1.1), the mitigation measure performances must be translated in terms of attenuation of vibration and ground borne noise exposure in buildings and corresponding decrease in annoyance. The aim of this report (deliverable D1.6) is to define the procedures which will be used to estimate vibration and ground borne noise in buildings for typical situations, to calculate the corresponding exposure descriptors and to estimate the corresponding annoyance. These procedures will be used at the end of the project to evaluate all the mitigation measures developed in RIVAS in common situations (deliverable D1.9 [4]) and to show their effects in typical configurations with vibration problems (hot spots) (deliverable D1.12 [5]).

Since the work of this WP did not include any development of ground-building vibration models, any measuring campaign in buildings or any field survey (or lab study) on annoyance, existing models / data as well as existing exposure descriptors and exposure-annoyance relationships had to be identified and used.

This report is divided into four main parts: in Part 1, the existing models / data for estimating vibration and ground borne noise in buildings are identified and briefly described; in Part 2, the models / data are compared and cross-validated, and the best method for estimating vibration and ground borne noise in building is suggested. Concerning descriptors and annoyance, a review of existing standards, regulations, guidelines and related studies has already been made (see D1.4 [6]), where exposure descriptors for both vibration and ground borne noise as well as exposure-annoyance relationships have been identified and discussed. From these results, a MATLAB procedure for calculating the main existing exposure descriptors for any given situation (given emission, ground propagation and immission) has been developed; this procedure is described in Part 3, will be use to evaluate the mitigation measures in D1.9 and D1.12, and can be used for further comparisons between descriptors. Finally in Part 4, the (few) exposure-annoyance relationships identified in D1.4 are presented, compared when possible and their applicability checked.

1. EXISTING MODELS / DATA

1.1. General Aspects

All models / data of ground borne transmission path from source to building are decomposed into emission (E), propagation (P) and immission (I), as illustrated in Figure 1. **Emission** varies with the source and its surrounding ground conditions and leads to ground vibration levels (Lv1) at a certain distance from the tracks (often 8m, as used in RIVAS). **Propagation** corresponds to ground vibration propagating to the building location and leads to free field ground vibration levels (Lv2) at the same distance as the building (but without building) (1); the transfer function Lv2-Lv1 is denoted TF1 in this report. **Immission** corresponds to ground-building vibration interactions and is also decomposed into three steps: (i) ground to building foundation (transfer function TF2, usually an attenuation), leading to foundation vibration levels (Lv3), (ii) building foundation to floor (transfer function TF3, usually an amplification due to the floor first resonant vibration modes), leading to floor vibration levels (Lv4) and (iii) floor vibration to ground borne noise (transfer function TF4) , corresponding to sound radiated by vibrating structures and leading to sound pressure levels in the room (Lp). Table 1 summarizes the transfer functions used in this report.

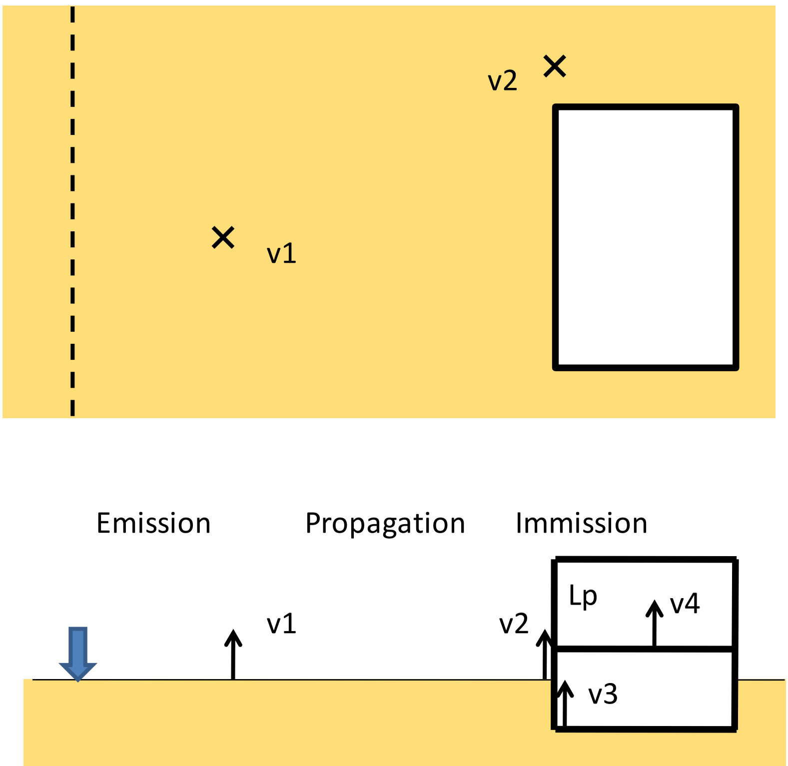

Figure 1.1: *Ground borne transmission path from source to building*

(1) For practical reasons, the measurement location is often next to the building (as indicated in figure 1.1) and not in real free field. The measurement location should not be in front of the building, in order to avoid any influence of ground standing waves.

Transfer function	*Notation*	*Output / input quantities*
Ground (8m) to building location	TF1	v2/v1
Ground (building location) to building foundation	TF2	v3/v2
Building foundation to building floor	TF3	v4/v3
Floor vibration to ground borne noise	TF4	p/v4

Table 1: *Transfer functions used (using notations from Figure 1.1)*

In some countries, this ground borne transmission path decomposition is defined in official documents such as the VDI 3837 document in Germany [7] and the FRA (Federal Railroad Administration) document in the USA where a detailed prediction method is proposed [8].

Several models developed by RIVAS partners have been identified (2), dealing with either the whole transmission path (EPI) or just part of it (PI or I):

- VIBRA-2 (also referred to as UIC RENVIB model in the RIVAS DoW) developed by SBB is a purely empirical model treating the whole transmission path (EPI)
- BAM prognosis tool developed by BAM is a semi empirical model also treating the whole transmission path (EPI)
- MEFISSTO is a numerical model developed by CSTB treating only ground propagation and immission (PI) from measured ground vibration levels used as input data
- DB has well documented empirical data for immission and has developed statistical models for estimating the transfer function from building foundation to floors as well as the transfer function from floor vibration to ground borne noise

These models, available for comparison / validation, are briefly presented in this chapter, the presentation being focussed on immission. All the models presented give frequency dependent (1/3 octave) results.

The FRA detailed model already mentioned proposes approximations for the different transfer functions and will be used in the comparisons presented in the next chapter.

1.2. SBB model

The SBB VIBRA-2 model is a purely empirical model based on measured data and described by the following (classical) equation:

$$v_j = v_{0,j}.(G/G_0)^h.F_t.F_s.F_b.(r_0/r)^m.F_a.F_d \quad (1)$$

(2) Other models developed by non RIVAS partners exist: for example an empirical model similar to SBB model has been developed in Norway [20]. Nevertheless, only models developed by RIVAS partners have been considered because of their full availability for analysis and comparison.

where v_j is the building floor velocity at mid span for train type j

$v_{0,j}$ is the ground velocity at 8m from the tracks for train type j

G the train speed (G_0 a reference speed) and h a frequency dependent exponent

F_t a factor taking into account the track situation (ground surface, embankment...)

F_s a factor for particular track situations (switches ...)

F_b a factor taking into account the track sub ground

r the distance from track to building (r_0 the 8m reference distance) and m a frequency dependent exponent taking into account both geometrical spreading and ground material damping

F_a the transfer factor from free field ground velocity at distance r to building foundation velocity

F_d the transfer factor from building foundation velocity to building floor velocity at mid span

All these parameters are frequency dependent (1/3 octave).

This full (EPI) model can be used to predict absolute building floor velocity level.

Concerning the transfer factor from ground to building foundations (TF2), SBB has communicated the transfer spectra measured at different sites, from which an average spectrum and corresponding standard deviation have been calculated. Two categories of buildings have been considered separately: houses and multifamily buildings; more detailed categories on ground or building foundation could not be obtained, since no information was available on the ground and building foundation conditions. Figure 1.2 gives as an example the transfer spectra in dB for multifamily buildings in Switzerland expressed as mean value ± one standard deviation (60 % of the measured spectra are within the limits given). A dB scale is used in order to better show the small values of this factor (0 dB corresponds to a factor of 1).

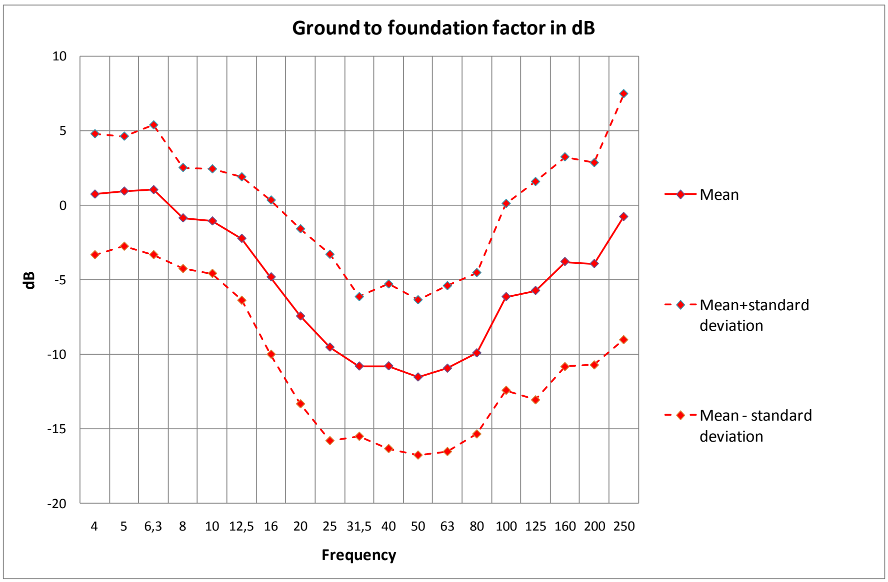

Figure 1.2*: Free field ground to building foundation vibration statistical transfer function in dB (mean value ± standard deviation); SBB data for multifamily buildings*

Concerning the transfer factor from building foundations to building floor at mid span (TF3), two categories of floor (concrete and wood) are considered and for each category, sub categories corresponding to different frequency ranges of floor first resonant vibration modes are proposed. For each sub categories, SBB has communicated the measured transfer spectra from which an average spectrum and corresponding standard deviation have been calculated. Figure 1.3 gives as an example the transfer spectra in dB for all the concrete floor subcategories expressed as mean value and mean value + one standard deviation (60 % of the concrete floors measured have a response equal or smaller than this limit).

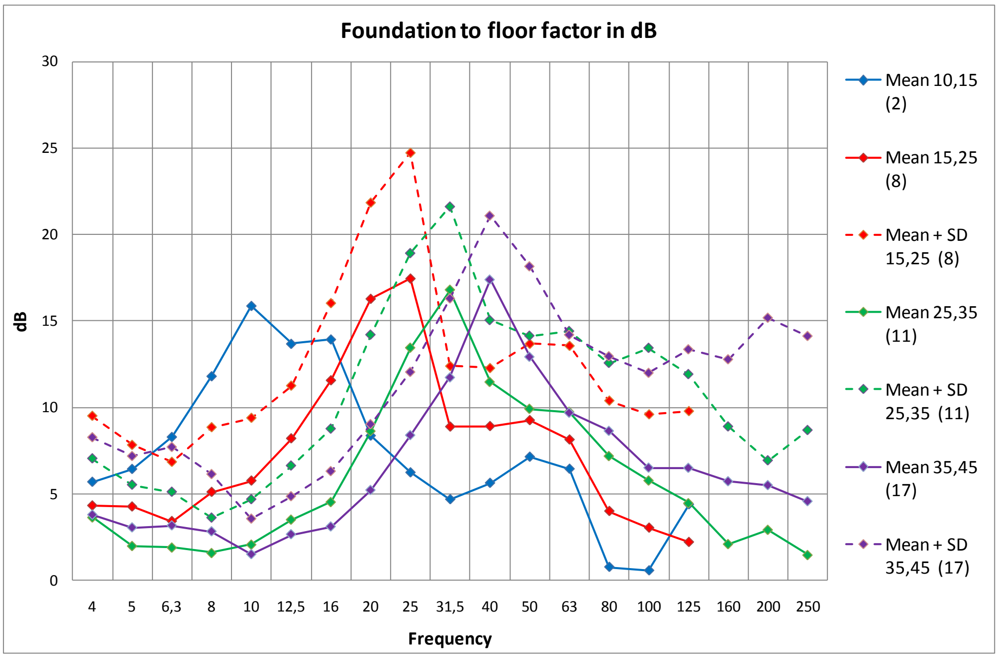

***Figure 1.3**: Building foundation to floor vibration statistical transfer function in dB (mean value and mean value + standard deviation) for 4 ranges of floor resonant frequencies: 10-15, 15-25, 25-35 and 35-45 Hz; the number of samples is given in parenthesis; SBB data for concrete floors*

Concerning the transfer factor from building floor at mid span to ground borne noise (TF4) , two categories of floor (concrete and wood) are also considered and for each category, SBB has communicated the measured transfer spectra from which an average spectrum and corresponding standard deviation have been calculated. Figure 1.4 gives as an example the transfer spectra in dB for concrete floors expressed as mean value and mean value ± one standard deviation (60 % of the concrete floors measured are within these limits); the reference for sound level is 2.10^{-5} Pa and for velocity level $5\ 10^{-8}$ m/s. The applicability of this statistical sound radiation model is discussed in section 2.4.

The SBB model is a good basis to get statistical estimations of immission vibration transfer functions, assuming that data from other countries, measured in similar situations, also fit into this model; this is checked in chapter 2.

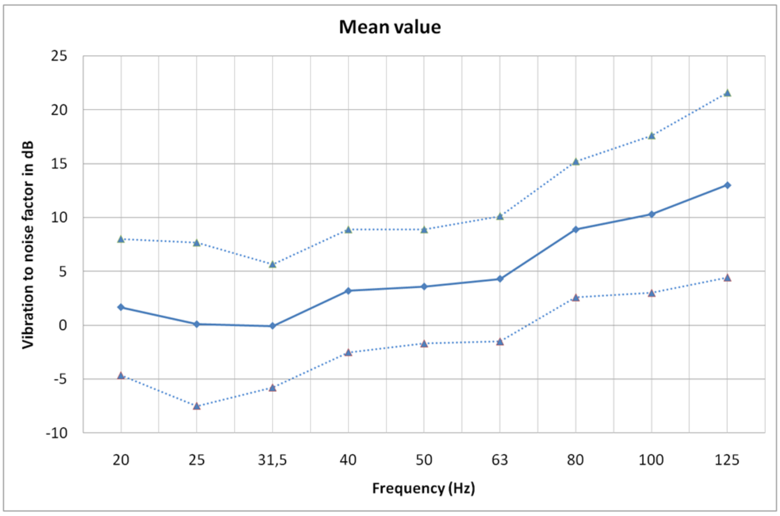

***Figure 1.4**: Building floor vibration (at mid span) to ground borne noise statistical transfer function (mean value ± standard deviation); SBB data for concrete floors*

1.3. BAM model

The BAM prognosis tool is a semi empirical model dealing with vibration emission, propagation and immission as represented in Figure 1.5. All the data / parameters are frequency dependent (1/3 octave).

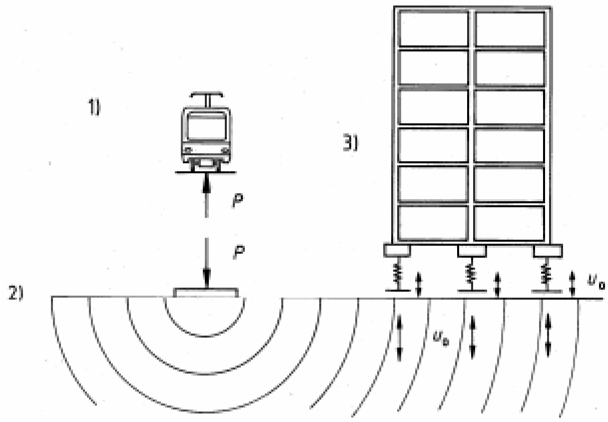

***Figure 1.5**: Schematic diagram of the BAM prognosis tool: 1) emission, 2) propagation, 3) immission*

For emission, a multi-body model for the vehicle and a beam-on-support model for the tracks, including the ground stiffness, are used. Measured ground vibration spectra can also be used as input, from which excitation forces can be back-calculated.

Transmission through ground is modelled as a transfer function of homogeneous half space; more complicated layered grounds can be modelled or approximated by a homogeneous half space with adjusted frequency dependent material properties. A very recent paper [10] shows rather successful comparisons between calculated and measured ground vibration spectra at different distances from the tracks for different ground conditions, including layered grounds. Moreover, the same paper presents calculated results where the moving static train load is also considered in the model, in a case of a fast train (200 km/h) on a layered ground. The moving load leads to very low frequency ground vibration (below 8 Hz), which decays very rapidly with distance (decaying near field) as shown in Figure 1.6; calculated and measured results agree reasonably well.

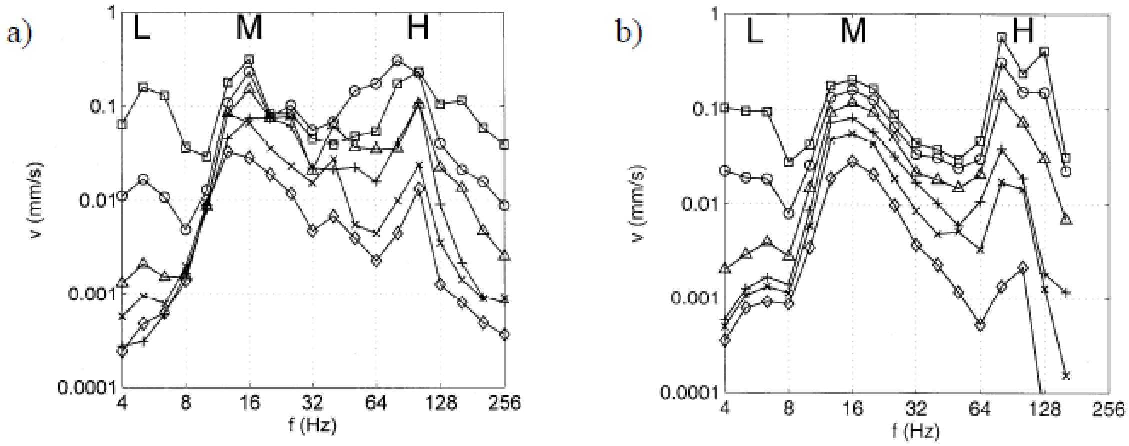

Figure 1.6*: BAM prognosis tool: Ground vibration from a fast train (200 km/h) at distances between 2.5 and 50m on a two layered ground (cs1=270m/s; cs2= 1000m/s); a) measurements and b) prediction*

Immission is estimated from a numerical (building) wall floor model with ground taken into account as spring-damper elements. The immission module is fitted to experimental data and theoretical knowledge by tuning the different parameters. Parametric studies have been performed [9] to see the influence of parameters, such as the ground stiffness (shear wave velocity), the ratio of the building foundation area to the total area of the building, the mass density of the building and the resonance frequency of the floors, as shown in Figure 1.7.

More detailed information on this model is given in [9].

This full (EPI) model could be used to predict absolute building floor velocity level, but has not been validated yet.

Information on this model and associated data has only been gathered through published results; the effects of changes in ground and building parameters are compared to other models in chapter 2.

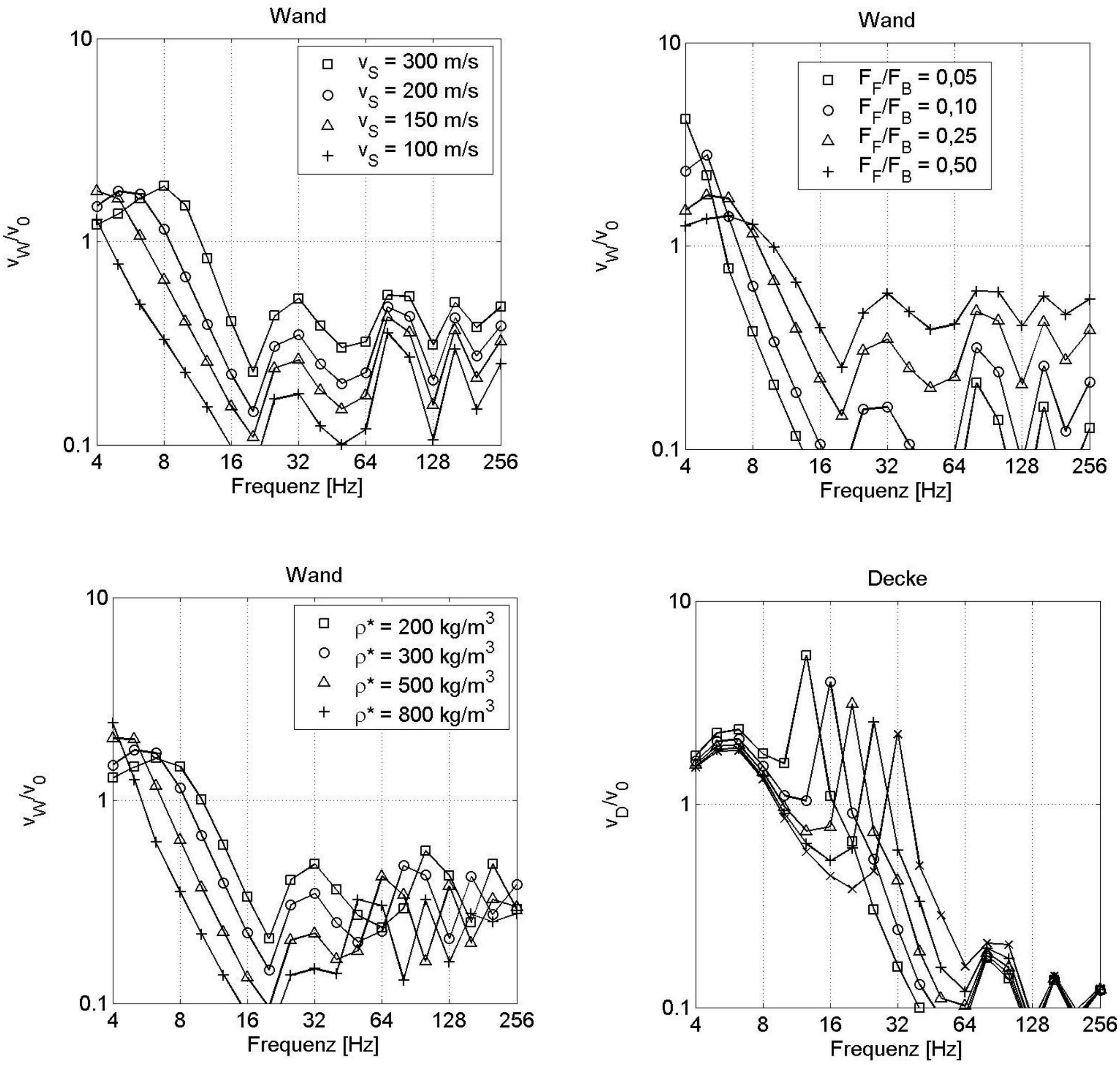

Figure 1.7*: BAM prognosis tool: ground to building transfer functions for a 6-storey concrete building; variation of the ground stiffness (upper left), the foundation (ratio of foundation to building area) (upper right), mass density of the building (lower left) and resonance frequency of floors (lower right).*

1.4. CSTB model

CSTB has developed a BEM FEM vibration interaction model called MEFISSTO. With the FEM (Finite Element Method) the entire domain considered is meshed whereas with the BEM (Boundary Element Method) only the domain boundaries are meshed. The basic configuration consists of a half space ground (BEM approach) and a building (FEM) with building elements either underground or above ground. The 2D example given in Figure 1.8 shows a half space ground in contact with a building.

Continuity of displacement and stress is assumed at common boundaries between domains. FEM and BEM calculations are performed in narrow frequency bands, but all the frequency spectra given are expressed in a more robust way in 1/3 octave bands.

For train excitation, MEFISSTO 2D ½ is used, where a 2D geometry, infinite in the third direction (parallel to the train tracks), is represented; such configuration allows point excitations anywhere in the 3D space, with reasonable computing time (as opposed to 3D); train excitation can then be represented by an uncorrelated line force (see Figure 1.9).

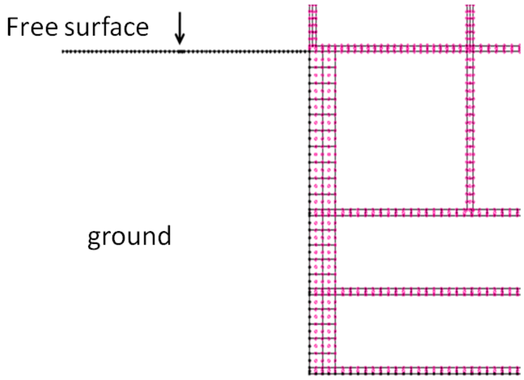

***Figure 1.8:** Typical BEM/FEM 2D meshing; ground contour in black and building FEM meshing in red; excitation force on ground surface; only a portion of the building is shown*

Both excitation forces and ground parameters must be calibrated: the source is calibrated from ground vibration measured at a certain distance from the tracks and the ground is calibrated from ground vibration measured at different distances from the tracks (with trains as a source). The vibration spectra measured at different distances are compared to the spectra calculated by MEFISSTO for three half space ground types: rather "normal" (shear velocity of 200 m/s), stiffer or softer than normal (shear velocities respectively twice as high or twice as low); the best fitted ground type is then retained. These ground types are in accordance with the French ground classification for seismic events [14] (3).

Building foundations are also modelled using MEFISSTO 2D ½ in order to get proper ground vibration attenuation with distance and proper ground to foundation vibration transfer functions (see Figure 1.9). The transfer functions from foundation to floor are estimated in 2D or in 3D, often using purely structural FEM models (see example given in chapter 2).

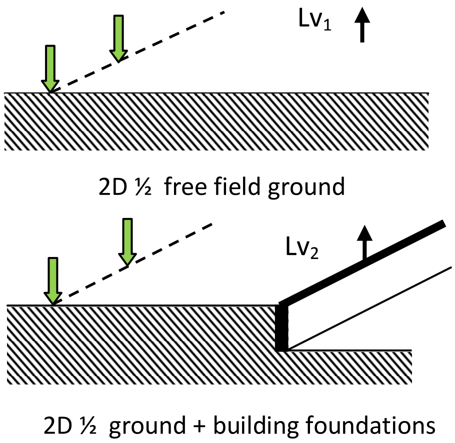

***Figure 1.9:** Typical 2D ½ ground and ground-foundation configurations modelled by MEFISSTO; excitation: uncorrelated line force*

(3) This national (French) classification is derived from the more general Eurocode 8 classification.

A more detailed description of MEFISSTO as well as its validation applied to railway vibration can be found in [12]; the validation has been performed in the frame of the French VIBSOLFRET project [13].

Ground borne noise (room space average sound level) is estimated in a separate module from the floor space average velocity level according to the building acoustics theory. The following frequency dependent transfer function is used, based on an energy approach:

$$Lp_{av} - Lv_{av} = 10 \lg\sigma + 10\lg (4S/A) \quad (2)$$

where σ is the radiation efficiency of the floor, S its surface area and A the absorption area of the room; the reference for sound level is 2.10^{-5} Pa and for velocity level $5\ 10^{-8}$ m/s. A 3 dB constant is often added assuming both floor and ceiling are the main ground borne source in the room. This relation is discussed in section 2.4.

The MEFISSTO model has been used in RIVAS for estimating the effects of changes in ground parameters and for a better understanding of the building response (foundation and floor vibration as well as noise radiated); see chapter 2.

1.5. DB model

DB has not developed any empirical model comparable to VIBRA-2 but has gathered and analyzed a lot of vibration measurements inside building and was able to propose statistical transfer functions from foundation to floors from measurements in about 800 standard buildings investigated [15]. Like in the SBB model, two categories of floor (concrete and wood) are considered. However the sub categories corresponding to the floor first resonant vibration modes are a bit different from SBB and correspond to resonant modes at each 1/3 octave band from 8 Hz to 80 Hz (11 sub categories); each result is expressed as an idealized average floor frequency response. Figure 1.10 gives as an example the transfer spectra in dB for all the concrete floor subcategories expressed as idealized mean spectra.

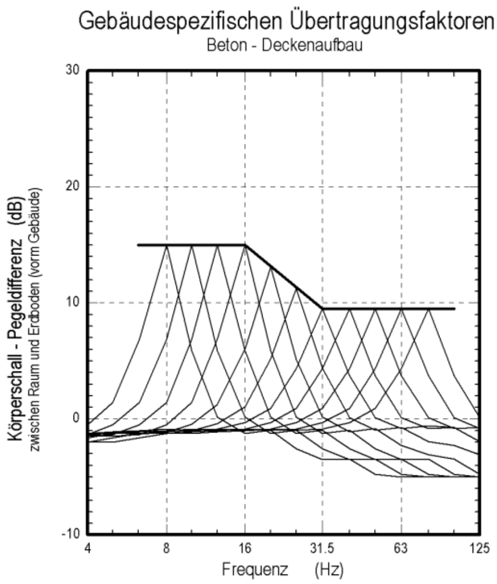

Figure 1.10*: Building foundation to floor vibration statistical idealized average transfer functions (amplification in dB) for floors with resonant frequencies from 1/3 octave 8 to 80 Hz; DB data for concrete floors*

Concerning the transfer function TF4 from building floor at mid span to ground borne noise due to at-grade railway traffic, DB uses statistical transfer functions expressed as frequency dependent regression curves for each 1/3 octave from 25 to 80 Hz and obtained from field measurements of both floor velocity at mid span and noise in the room. The results are based on sound levels measured within a limited frequency range (up to 100 Hz) in order to eliminate unwanted airborne noise and get higher correlation coefficient [16]; two categories of floor (concrete and wood) are also considered. Table 2 gives as an example the regression curves obtained for concrete floors; the unusual relationships used are supposed to correctly relate the total ground borne noise radiated by all the building elements (floor, ceiling and walls) in the room, to the floor velocity only.

The DB statistical model giving statistical estimations of the foundation to floor transfer functions is compared to the SBB model in chapter 2. The applicability of the DB statistical sound radiation model is discussed in section 2.4.

Frequency (Hz)	***Regression curves (Lp in dB, ref.2 10^{-5} Pa; Lv in dB ref. 5 10^{-8} m/s)***
25	Lp = 32.4 + 0.418 . Lv
31.5	Lp = 28.0 + 0.501 . Lv
40	Lp = 28.8 + 0.506 . Lv
50	Lp = 25.3 + 0.557 . Lv
63	Lp = 22.6 + 0.595 . Lv
80	Lp = 23.7 + 0.597 . Lv

Table 2: *Floor velocity to ground borne noise regression curves; DB data for concrete floors*

2. COMPARISON / VALIDATION OF MODELS /DATA

2.1. General Aspects

The aim of the procedure to be developed is to calculate descriptors inside buildings for different emission / ground transmission / immission situations. Emission situations can be defined with rather good precision on trains, tracks and ground conditions from ground vibration at 8m from the tracks; existing data as well as all the experiments within RIVAS (performed at 8m) can and will contribute to define reference emission situations. Moreover, the ground transfer function TF1 from 8m to the building location can be exactly known just by choosing the building location at reference distances from the tracks where measured ground data exist (8m or 16m for example). Therefore, only the immission transfer functions TF2 to TF4 defined in Table 1 have to be estimated correctly in order to get proper building floor velocity and associated ground borne noise from ground vibration at 8m from the tracks. This chapter is focussed on statistically estimating these three transfer functions using the SBB and DB empirical statistical models as basis. In order to compare and validate these models, many measured data have been gathered and stored in Excel files (data storage performed by RATP and CSTB); a brief description of these data is given in section 2.2.

As a result, the full validation of the only two models dealing with the whole transmission path from source to building (VIBRA-2/RENVIB and BAM models) and leading to absolute values of the building floor vibration is not necessary; nevertheless, among all the data gathered, absolute floor vibration spectra are available, from which the owner of these two models (SBB and BAM) can later validate their model.

2.2. Gathering data

Concerning statistical data, only data from Switzerland and Germany were available: (i) all the measured transfer functions used in the SBB empirical model have been communicated so that mean values and standard deviation can be calculated and used (see chapter 1); (ii) statistical results from DB, expressed as idealized mean transfer function (foundation to floor vibration) or as regression curves (floor vibration to ground borne noise) have been used.

Data measured in particular sites in known conditions have also been gathered from different partners in order to check the applicability of the above statistical models to various situations; around 20 sites have been filed:

- 8 sites from DB, well documented (except ground conditions) with data on ground, building foundation and floor

- 10 sites from SBB (sites from the SBB empirical model) well documented (except ground and foundation conditions) with data on ground, building foundation and floor,

- 2 sites from ADIF, well documented with data on building foundation and floor

- 1 site from CSTB, well documented with data on ground, building foundation and floor

- 1 site from RATP, well documented (except ground conditions) with data on building floor

- 1 site from TV well documented with data on ground, building foundation and floor; this “Furet site” (Sweden) has its ground conditions described in Deliverable 4.1, section 2.5 [3].

2.3. Ground to building foundation vibration transfer function (TF2)

SBB statistical models

Statistical data from the SBB model have already been presented in chapter 1. Two categories of buildings are considered separately: houses and multifamily small building. Comparing the results (mean value and standard deviation) obtained for these two categories (Figure 2.1) shows a transfer function for multifamily small buildings only a few dB (2-3 dB) lower than for houses.

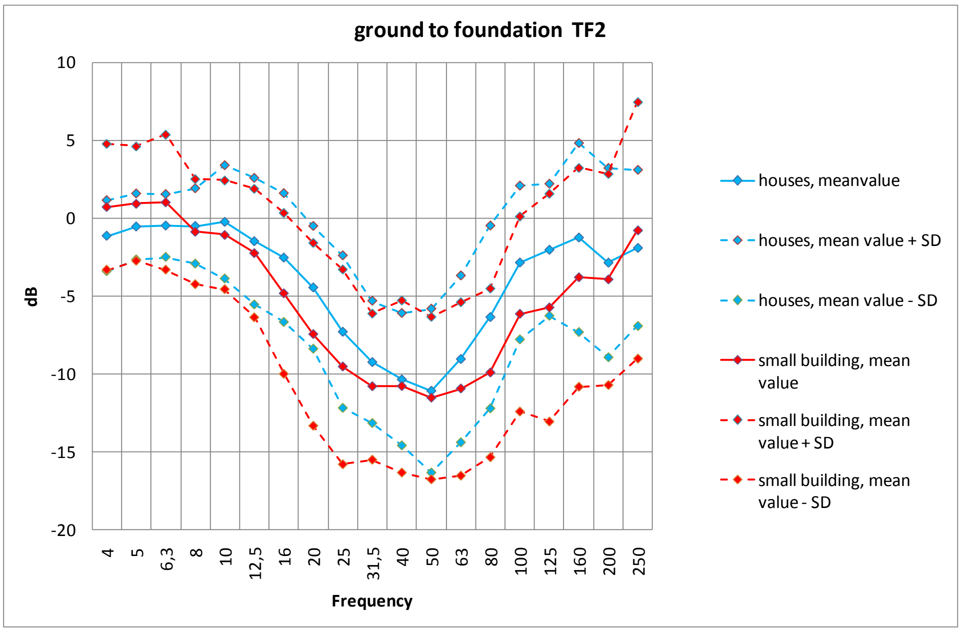

***Figure 2.1**: Ground to foundation vibration statistical transfer function in dB (mean value ± standard deviation); SBB data for houses and multifamily small buildings*

More detailed categories on ground or building foundation cannot be obtained, since no information is available on the ground and building foundation conditions. In order to get more knowledge, the SBB statistical spectra for small buildings has been used as base curves and compared to other sources of information.

It should be noted that most of the sites correspond to ground vibration spectra (8m from the tracks) with energy located in the range 10-100 Hz (see example in Figure 2.2). However the Swedish site from TV is particular with a lot of energy located at around 5 Hz as shown in Figure 2.3; this case, typical for softer grounds, is treated in a separate paragraph.

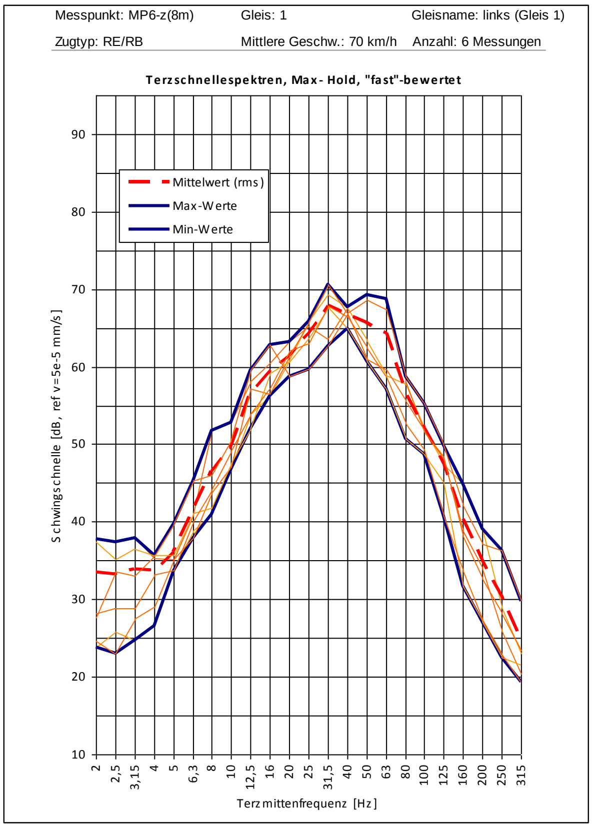

Figure 2.2*: Typical ground vibration velocity spectra measured at 8m from the tracks (Germany); dB ref. 5. 10^{-8}m/s.*

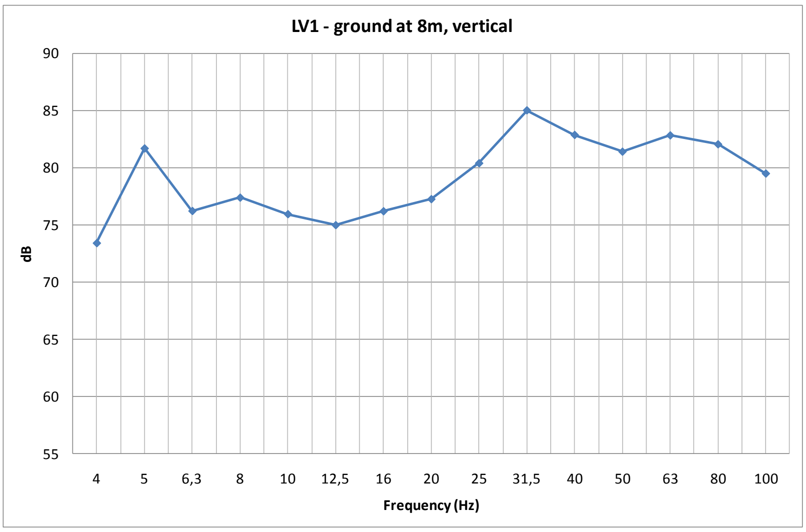

Figure 2.3*: Furet Site (Sweden) from TV: Ground vibration velocity spectra measured at 8m from the tracks; dB ref. 5. 10^{-8}m/s.*

.

First, the well documented (except on ground conditions) sites from DB have been used and compared to the above SBB base curves as shown in Figure 2.4. Most of the DB sites are small house/building with one level basement and the corresponding curves roughly fit within the SBB 60% confidence limits (except at frequencies above 100 Hz where velocity levels are usually very low, thus likely leading to transfer functions with greater uncertainties); the spreading of the DB transfer functions probably comes from different ground conditions and maybe different wall thicknesses.

In order to see the influence of the ground conditions and the building foundation types on these ground to foundation transfer functions, the CSTB MEFISSTO software has been used. Figure 2.5 shows the calculated transfer function in the case of a "normal" half space ground (not too stiff or too soft, with shear wave velocity of the order of 200 m/s) and three types of building foundations: shallow footing (house), one level basement (1-2 stories) and deeper underground levels (taller building). The calculated results show that the deeper (and thicker) the foundation, the greater the (ground to foundation) attenuation.

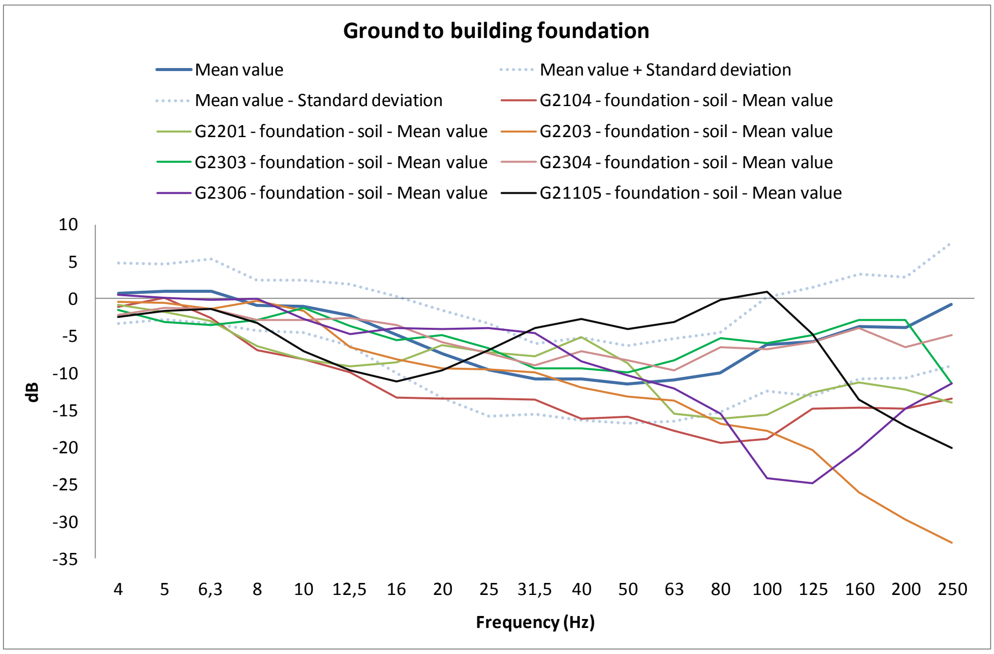

***Figure 2.4**: Ground to foundation transfer function in dB; DB data for particular sites compared to SBB statistical data (mean value ± standard deviation); mainly multifamily small buildings*

Figure 2.6 shows the transfer function calculated by MEFISSTO in the common case of a small building basement calculated for three types of half space ground: "normal" (shear velocity of the order of 200 m/s), harder (shear velocity twice as high) and softer (shear velocity twice as low). A decrease in (ground to foundation) attenuation of the order of 6-7 dB (factor of 2) is obtained by doubling the ground shear wave velocity; the same results have been obtained using the BAM model (see Figure 1.7, upper left). It should be noted that none of the calculated results show a decrease of attenuation at higher frequencies (above 100 Hz) as many of the measured results do; but the precision at higher frequencies is not that important since the absolute vibration levels are very low.

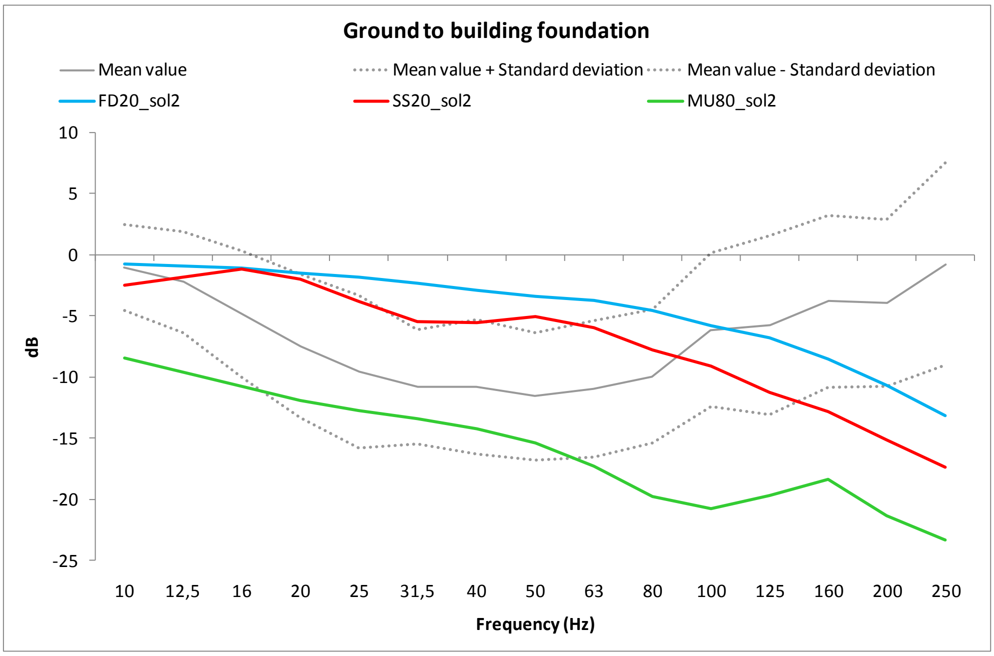

Figure 2.5: *Ground to foundation transfer function in dB; data calculated for normal ground (CSTB model), compared to SBB statistical data (mean value ± standard deviation); shallow footing (blue), basement (red), deeper underground levels (green)*

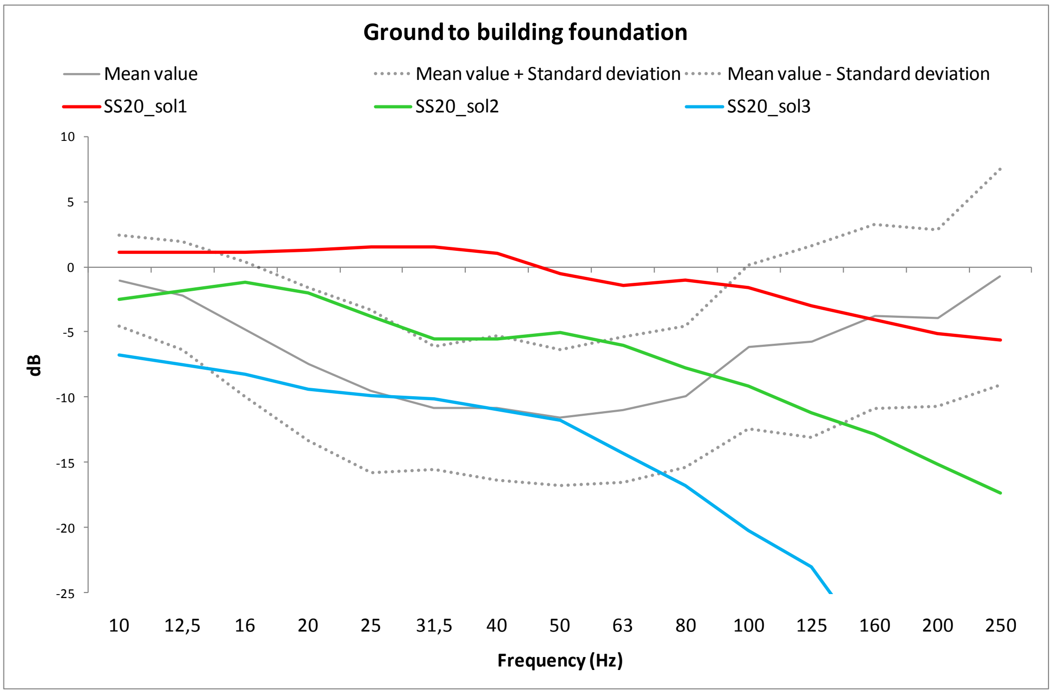

Figure 2.6: *Ground to foundation transfer function in dB; data calculated for common small building basement (CSTB model), compared to SBB statistical data (mean value ± standard deviation); normal ground (green), softer ground (blue), stiffer ground (blue)*

The French site is interesting because the old SNCF office building tested has unusually thick (40 cm) concrete walls and also thick (40 cm) concrete foundations, including a one level basement on footing; the building was located very close to the tracks (6m); the ground is “normal”. Figure 2.7 shows that the corresponding ground to foundation attenuation is unusually great; it can also be seen that the transfer function does not depend on the excitation (passenger or freight). Of course, more data would be necessary to confirm this result.

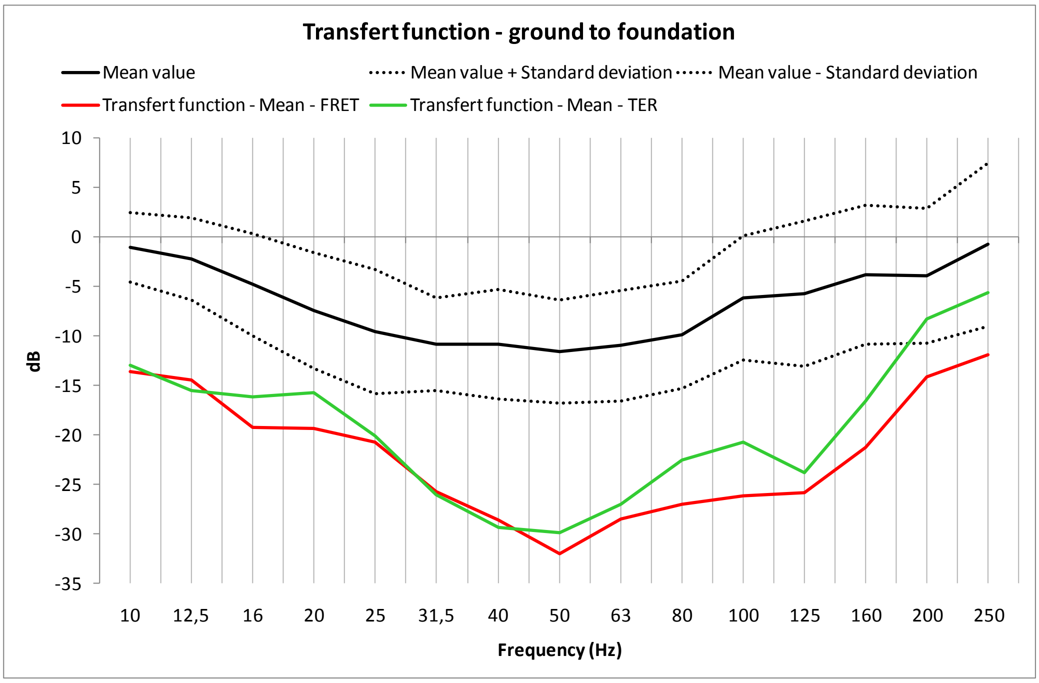

***Figure 2.7**: Ground to foundation transfer function in dB; French data for an old office building with very thick concrete walls and foundations, compared to SBB statistical data (mean value ± standard deviation); mean transfer function calculated separately for passenger (green) and freight (red) trains*

BAM has published [11] the results of field measurements in 8 sites where the ground to foundation transfer functions have been calculated; Figure 2.8 gives the results with a dB scale superimposed on the original linear scale, showing that the mean spectrum is very close to the SBB mean spectrum.

Finally, it is interesting to compare the SBB base curves to the approximated transfer functions proposed in the American detailed prediction model (FRA document, [8]), as shown in Figure 2.9; according to the FRA, the bigger the building, the greater the (ground to foundation) attenuation, thus leading to values for big buildings of the order of the SBB 60% confidence lower limit. The ground conditions are not considered in the FRA document.

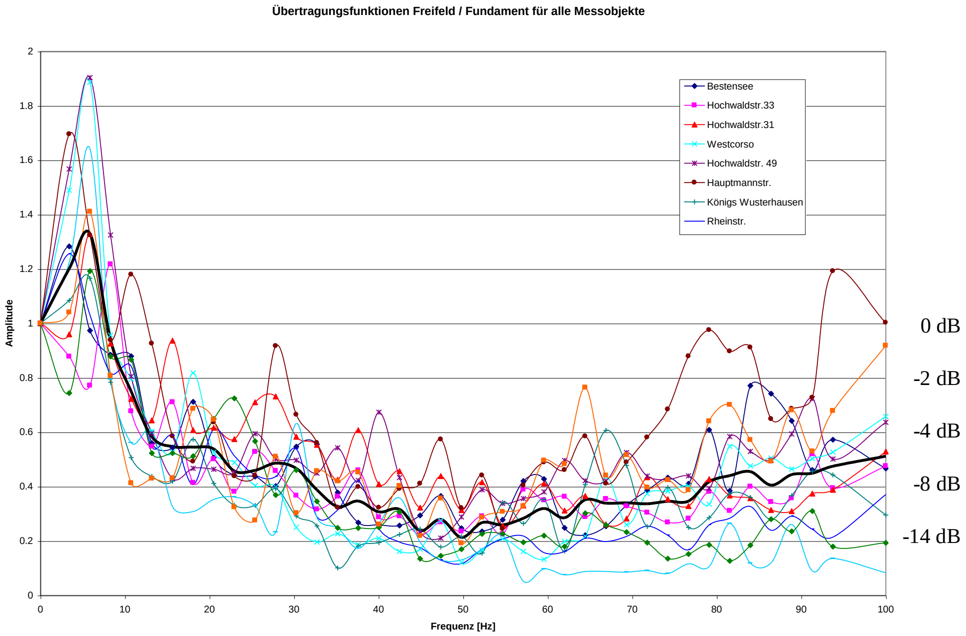

Figure 2.8*: Ground to foundation transfer function; dB scale superimposed on a linear scale; results from a BAM publication [29]*

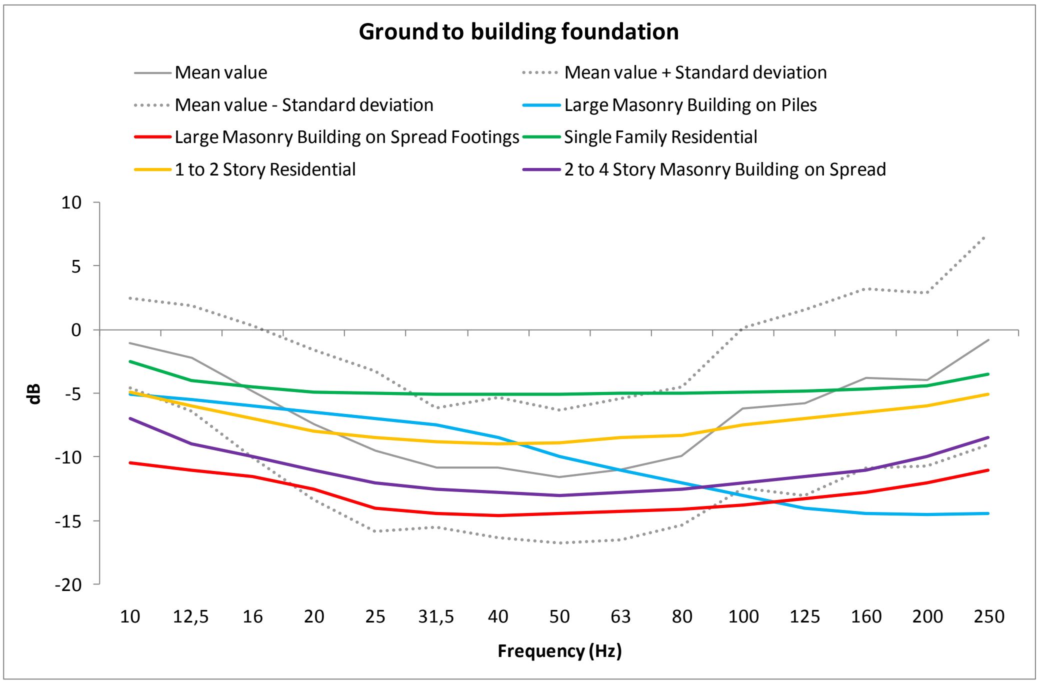

Figure 2.9*: Ground to foundation transfer function in dB; FRA approximations for different building types compared to SBB statistical data (mean value ± standard deviation).*

Swedish TV "Furet"site

The following data have been communicated: ground velocity (3 axes) measured at 8m from the tracks, building foundation velocity (vertical) and building floor velocity (3 axes); the measured results (vertical velocity) are given in figure 2.10. The building is a multi-storey building with basement and concrete floors, located at 16m from the tracks.

The ground conditions, evaluated in the frame of RIVAS, correspond to the ground parameters given in Table 3.

Layer	h [m]	C_s [m/s]	C_p [m/s]	β_s [-]	β_p [-]	ρ [kg/m^3]
1	2	154	375*	0.025	0.025	1800
2	10	119	290*	0.025	0.025	1850
3	∞	200	490*	0.025	0.025	1710

***Table 3**: Ground parameters for the "Furet" Swedish site: layer thickness h, shear velocity Cs, loss factor β, density ρ*

As already said, the ground vibration spectra measured at 8m (Figure 2.3) is particular with energy located at very low frequencies (around 5 Hz) and at mid frequencies (below 100 Hz).

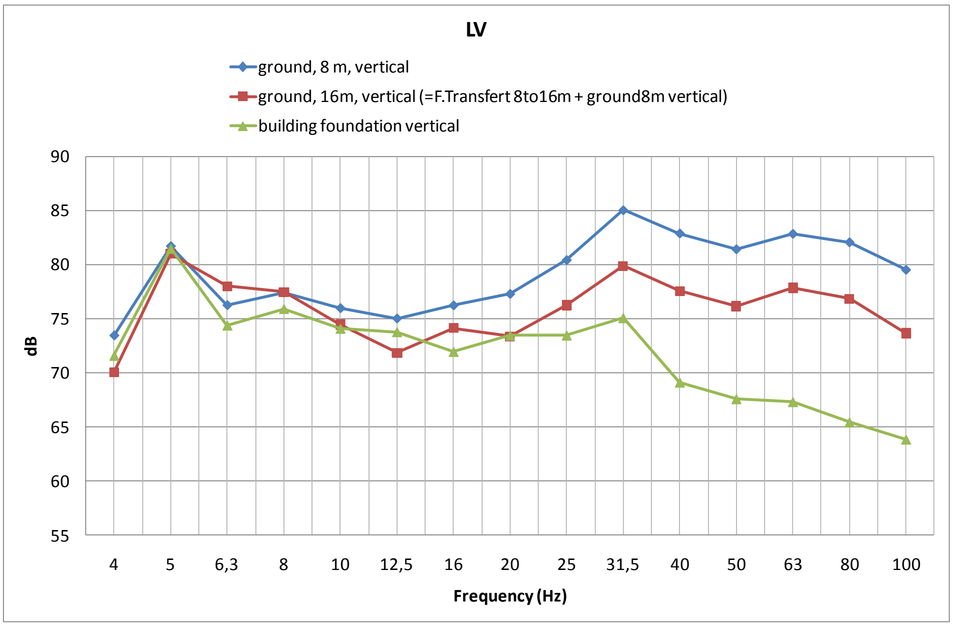

***Figure 2.10**: Furet Site (Sweden) from TV: Ground vibration velocity spectra measured at 8m (in blue); measured building foundation velocity (in green); ground velocity calculated (CSTB MEFISSTO software) at 16m (in red) ; dB ref. 5. 10^{-8}m/s.*

According to [10] and as shown in Figure 1.6, the ***low frequency*** part is likely to be generated by a train ground interaction involving the moving load mechanism and should rapidly decay with distance, <u>but is still quite strong at 8m though</u>. Unfortunately, no proper model (BAM tool), capable of simulating such complex wave field, has been applied to this case; so the ground attenuation from 8 to 16m remains unknown for the low frequencies. It is therefore difficult to explain why the foundation vibration level is nearly the same as the ground level at 8 m: it could be due to either a ground decaying near field compensated by a strong building ground resonance or a smaller ground attenuation compensated by a smaller building ground resonance.

The ground propagation from 8 to 16m (TF1) can be properly estimated at ***mid frequencies*** (from 10 Hz) using the CSTB MEFISSTO software applied to this 3 layer ground with a uncorrelated line source as shown in Figure 1.9. The calculated ground velocity at 16m is given in Figure 2.10 (red curve); the values below 10 Hz are not correct as explained above.

The corresponding ground to foundation transfer function TF2 can now be estimated (at least above 10 Hz); the results are given in Figure 2.11, surprisingly showing a rather small attenuation, which fits within the SBB 60% confidence interval, in spite of the rather soft ground at this site. Once again, more data would be necessary to confirm this result.

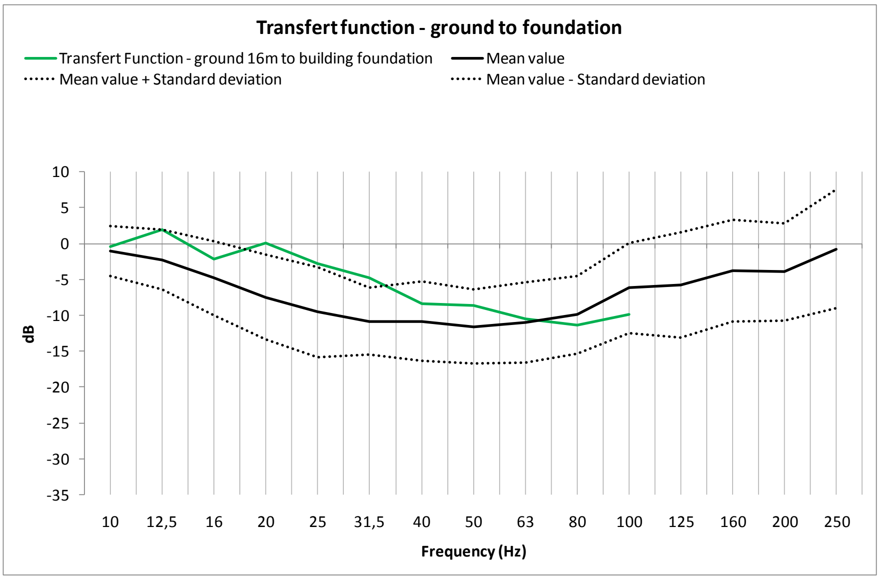

Figure 2.11*: Ground to foundation transfer function in dB; "Furet" site result compared to SBB statistical data (mean value ± standard deviation)*

Conclusions

The following (rough) rules could be used to estimate the ground to foundation transfer functions, knowing that whatever curve is used, the associated standard deviation is of the order 5 dB: (i) the SBB mean statistical ground to foundation attenuations for houses and small buildings could be used in the case of normal ground; (ii) if the ground is softer or harder (factor of 2 on the shear wave velocity), the SBB 60% confidence limits (respectively min. or max.) could be used as mean value; (iii) if the building is taller, the 60% confidence min. limit could be used as mean value.

2.4. Building foundation to floor vibration transfer function (TF3)

Statistical models

Statistical data from the SBB model have already been presented in chapter 1. Two categories of floor (concrete and wood) are considered and for each category, sub categories corresponding to different frequency ranges of floor first resonant vibration modes are proposed. The corresponding transfer functions in dB for concrete has already be given (see

Figure 1.3); for wood floors the results are given in Figure 2.12. The mean resonant amplifications for concrete floors seem quite stable (around 15 dB) whatever the floor resonant frequencies are. For wood floors, the mean resonant amplifications decrease with increasing floor resonant frequencies.

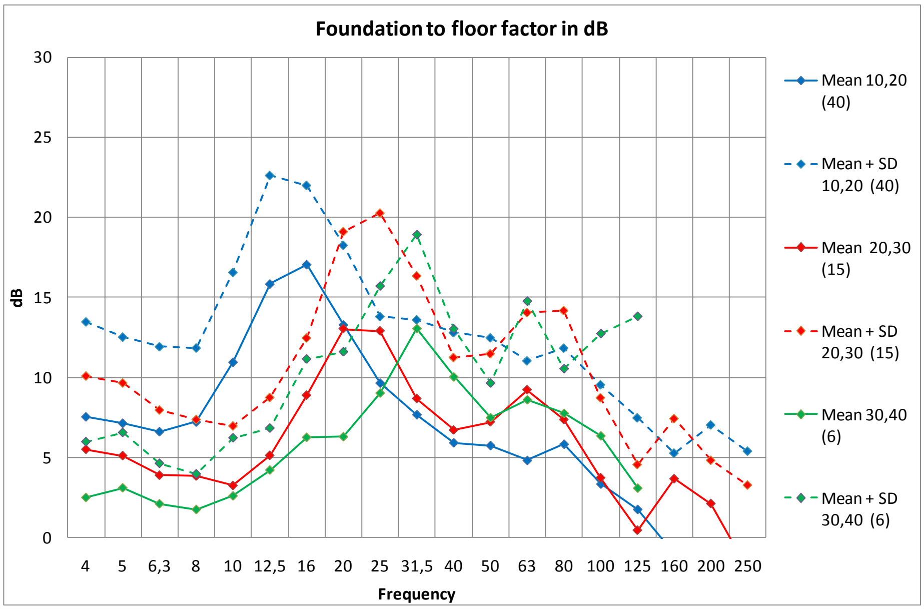

Figure 2.12*: Building foundation to floor statistical transfer function in dB (mean value and mean value + standard deviation) for 3 ranges of floor resonant frequencies: 10-20, 20-30 and 30-40 Hz; the number of samples is given in parenthesis; SBB data for wood floors*

The DB statistical data for concrete floors (Figure 1.10) show the same order of amplifications as the SBB data, except at higher frequencies (above 31.5 Hz), where smaller amplifications (around 10 dB) are obtained. For wood floors, the curves are similar to SBB with a decrease in amplification with increasing resonant frequencies (Figure 2.13).

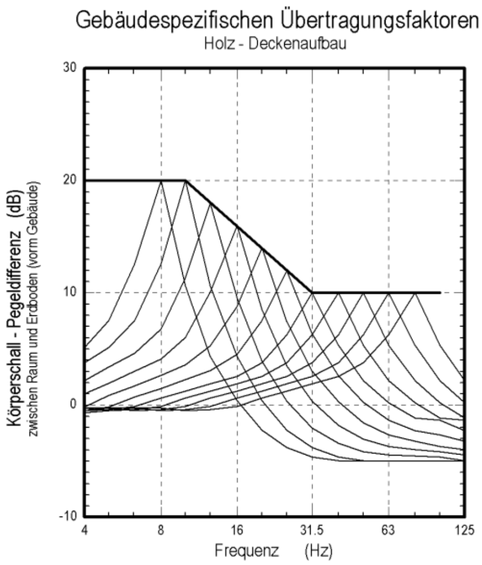

Figure 2.13*: Foundation to floor statistical idealized average transfer functions in dB for floors with resonant frequencies from 1/3 octave 8 to 80 Hz; DB data for wood floors*

In order to get more knowledge, the SBB statistical data have been used as base curves and compared to other sources of information.

Comparison with other data

First, the sites from DB have been used and compared to the above SBB base curves as shown in Figure 2.14a and b for concrete floors. The corresponding amplifications fit quite well within the SBB 60% confidence limits.

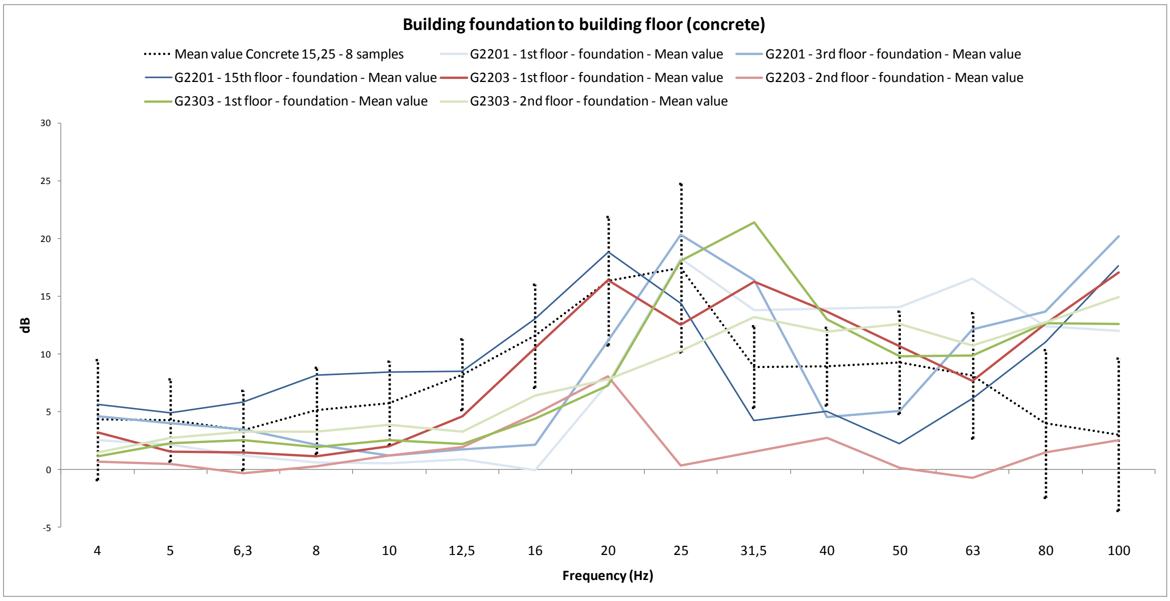

***Figure 2.14a**: Foundation to building floor; data from DB sites compared to SBB statistical 15-25 data category; concrete floors*

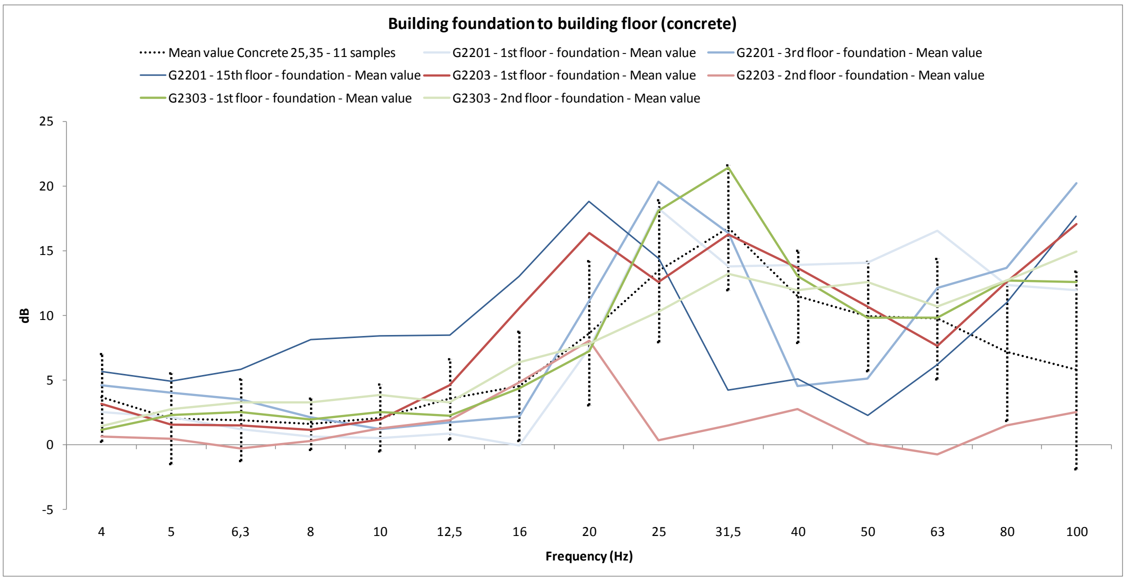

***Figure 2.14b**: Foundation to building floor; data from DB sites compared to SBB statistical 25-35 data category; concrete floors*

For wood floors, Figure 2.15a and b show that the corresponding amplifications fit quite well within the SBB 60% confidence limits (though some are slightly above).

Most of the DB site concrete floor resonances are at or above 20 Hz as most of the DB site wood floor resonances are at or below 20 Hz with high amplifications (20 dB or more).

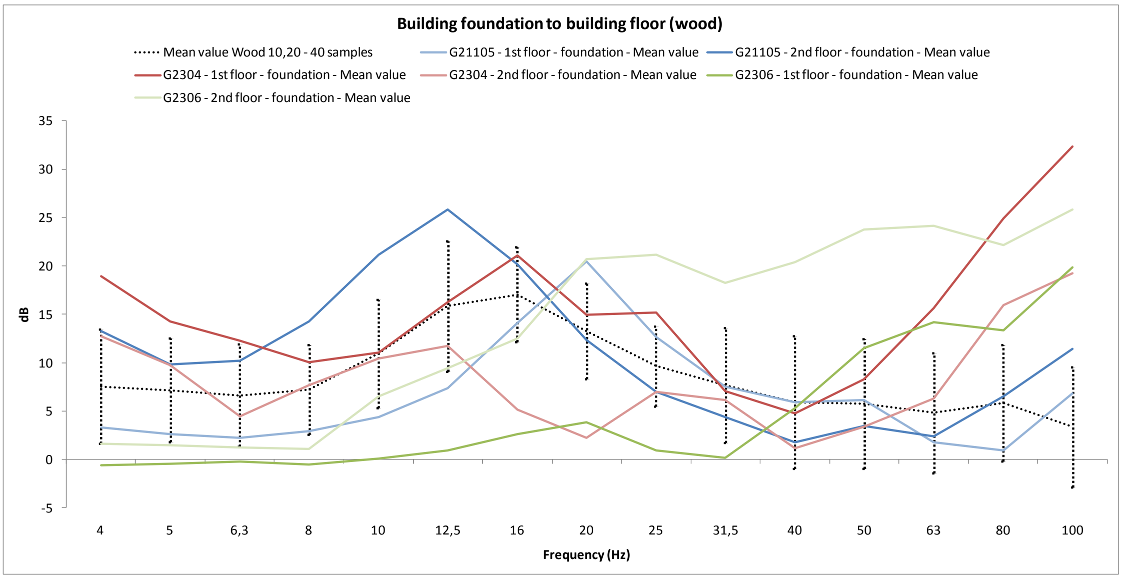

***Figure 2.15a**: Foundation to building floor; data from DB sites compared to SBB statistical 10-20 data category; wood floors*

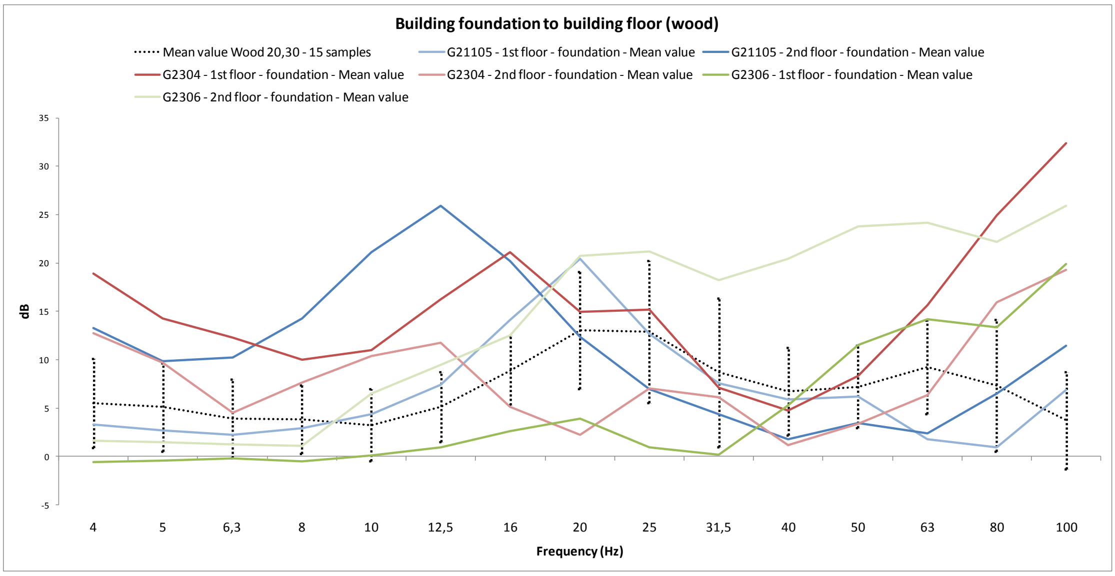

***Figure 2.15b**: Foundation to building floor; data from DB sites compared to SBB statistical 20-30 data category; wood floors*

Data from ADIF sites have been communicated on foundation to floor amplifications for typical Spanish (heavy) apartment buildings: usually (hollow) block and beam thick floors with brick walls. The corresponding amplification is compared to the SBB statistical data in Figure 2.16; the floor resonances frequencies are spread over a large frequency range (12 to 63 Hz) and show a decrease in amplification from 25 dB (12-16 Hz) to 10 dB (63 Hz) very similar to wood floors. Of course, more data would be necessary to confirm this result.

Data from the French site already mentioned (20 cm concrete floors with span of the order of 5-6 m) have been compared to the SBB statistical data as shown in Figure 2.17; the amplifications fit well within the SBB 60 % confidence limits.

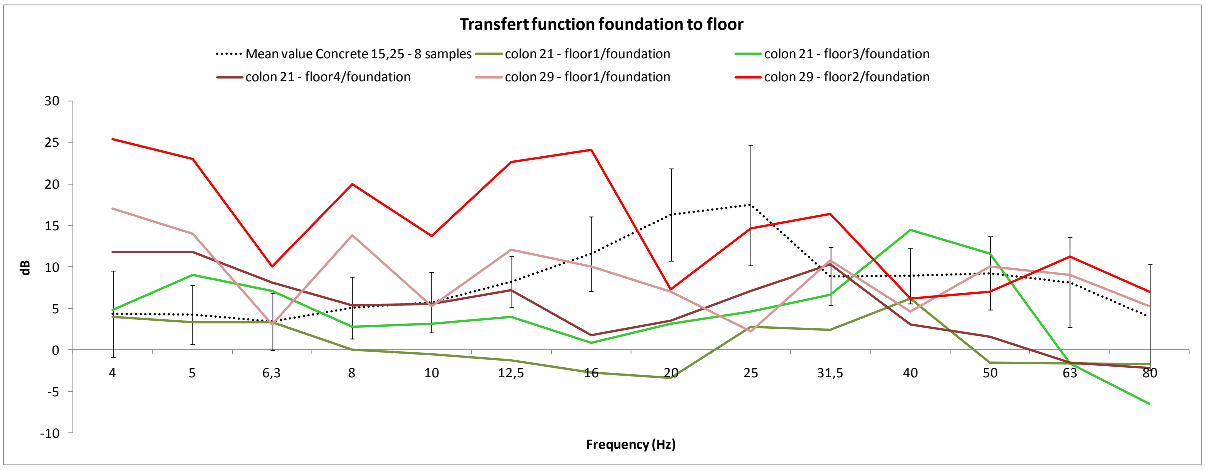

Figure 2.16: *Foundation to building floor; data from ADIF sites compared to SBB statistical 15-25 data concrete floor category; hollow block and beam floors*

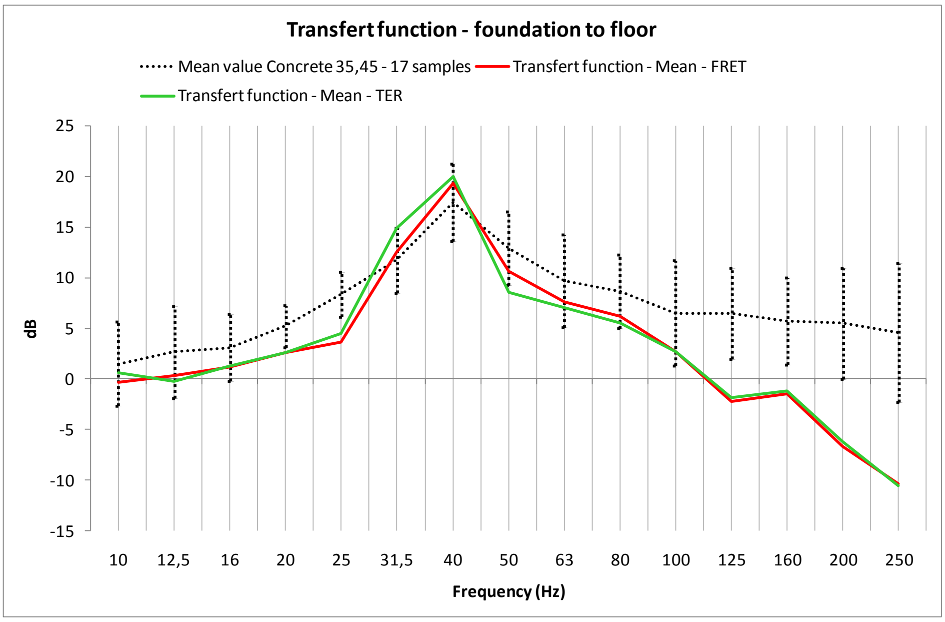

Figure 2.17: *Foundation to building floor; data from CSTB (French) site compared to SBB statistical 35-45 data concrete floor category; concrete floor*

It should be noted that the BAM report on field measurements [11] mentioned in section 2.3 presents results expressed as ground to floor transfer functions (TF2+TF3) on a linear scale showing floor amplifications of the order of the results presented in this section.

Finally data from the Swedish “Furet” site already mentioned (concrete floors) have been compared to the SBB statistical data as shown in Figure 2.18; small amplifications (5dB) at mid frequencies are surprisingly observed (compare to the usual 10-15 dB for concrete floors).

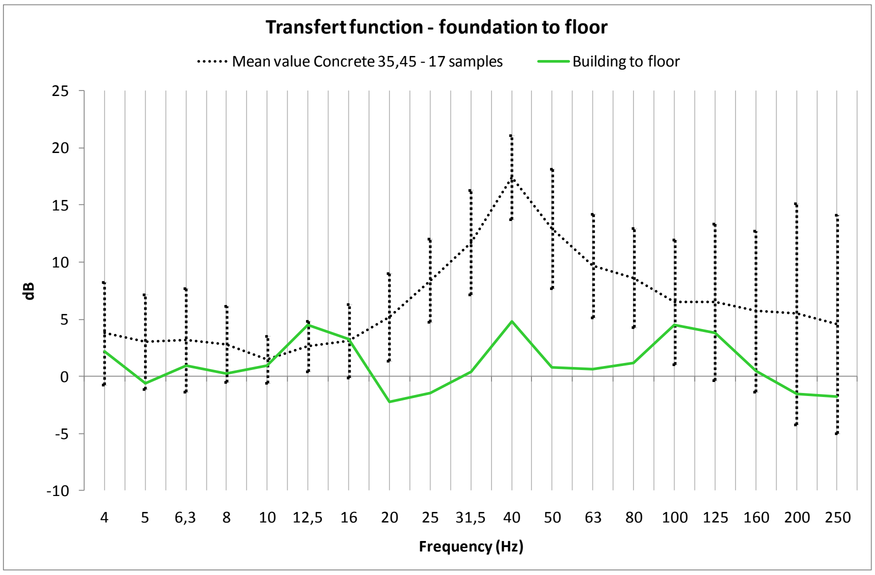

***Figure 2.18**: Foundation to building floor; data from Swedish "Furet" site compared to SBB statistical 35-45 data concrete floor category; concrete floor*

Conclusions

The SBB statistical data for foundation to floor amplification can be used: for concrete floors the same amplification of the order of 15 dB over the whole frequency range can be retained as a mean value; for wood floors a decrease in amplification (with increasing resonant frequencies) can be retained, from 20 dB (12-16 Hz) to 10 dB (63 Hz) as a mean value; the same variation as for wood can be used for Spanish hollow block and beam floors. However, this section shows that the measured data are often higher than the mean value and a statistical max (mean + one standard deviation) should probably be used to make sure data are on the safe side. Simple models exist in structural dynamics to estimate building floor first resonant frequencies: formulas for isotropic (concrete) or orthotropic (wood) floors can be found in text books; the main parameters are the floor thickness and material, and the floor dimensions. At low frequencies, the boundary conditions are often assumed to be simply supported.

2.5. Floor vibration to ground borne noise transfer function (TF4)

Statistical models

Statistical data from the SBB model have already been presented in chapter 1; the transfer spectra in dB for concrete floors expressed as mean value and mean value ± one standard deviation (60 % of the concrete floors measured are within these limits) is given in Figure 1.4; the reference for sound level is 2.10^{-5} Pa and for velocity level $5\ 10^{-8}$ m/s. The statistical transfer spectra in dB for wood floors show values of the same order as for concrete floors.

The statistical data from DB are expressed in terms of regression curves as shown in Table 2 for concrete floors; very similar regression curves are also proposed for wood floors [15]. In order to check the corresponding floor vibration to ground borne noise transfer function, which depends on the absolute floor velocity levels, a example of floor response with first resonance near 30 Hz and an absolute vibration level of the order of 70 dB (ref. 5 10^{-8} m/s) was chosen; the floor vibration to ground borne noise transfer function obtained is very flat, close to 0dB and within the SBB 60% confidence interval as shown in Figure 2.19.

Two remarks can be made on these statistical (empirical) data: (i) the noise measured might be a mixture of ground borne noise and airborne noise transmitted through the façade, which would lead to overestimating the transfer factor; (ii) noise is measured using one microphone in the centre of the room, which at low frequencies leads to underestimating the space average sound level in the room (close to walls or in corners, sound levels are several dB higher, as mentioned in ISO 14837-1 [17]) and therefore to underestimating the transfer factor. ***For these two reasons, ground borne noise is preferably calculated from floor velocity*** as explained below.

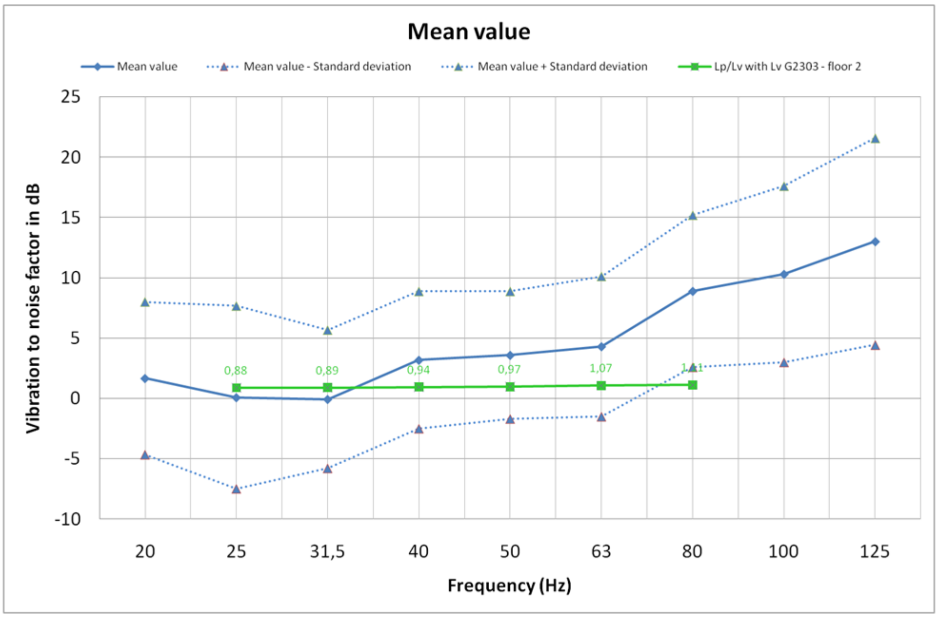

Figure 2.19: *Floor vibration (at mid span) to ground borne noise statistical transfer function (mean value ± standard deviation); SBB data for concrete floors compared to DB data calculated using DB regression curves)*

Building acoustics approach

As already mentioned in section 1.4 and according to the building acoustics theory, the following well known frequency dependent transfer function is often used, based on a simplified energy approach:

$$Lp_{av} - Lv_{av} = 10 \lg\sigma + 10\lg (4S/A) \qquad (2)$$

where σ is the radiation efficiency of the floor, S its surface area and A the absorption area of the room. The formula relates the space average floor velocity level to the space average sound level in the room; both sound pressure levels and velocity levels are in dB ref. 2.10^{-5} Pa and 5.10^{-8} m/s respectively. A 3 dB constant is often added, assuming both floor and ceiling are the main ground borne source in the room.

Figure 2.20 gives typical radiation efficiencies expressed in dB, showing that heavy ***concrete structures*** radiate well (radiation efficiency close 0 dB), even at low frequencies. Statistics from results calculated using a more precise modal approach taking into account the coupling between the floor vibrational resonances and the room acoustic resonances would also lead to radiation efficiencies close to 0 dB at low frequencies [18]. Consequently, equation (2) for concrete floors can be simplified as

$$Lp_{av} - Lv_{av} = 7 \qquad (3)$$

assuming the room is normally furnished. Moreover, with velocity levels expressed in dB ref. 1 inch/s, equation (3) becomes $Lp_{av} \approx Lv_{av}$, which is the frequency dependent formula used in the American FRA detailed prediction method [8]; Lp in dB(A) is then simply obtained from A-weighted floor velocity levels (as shown in Figure 4.8 in Chapter 4).

Figure 2.20 also shows that ***lightweight floors*** (bare 22mm OSB on solid wood joists) radiate less in average at low frequencies; in first approximation, a radiation efficiency of - 10 dB can be retained for lightweight floors over a 25-100 Hz frequency range. This result seems in contradiction with the SBB and DB statistical data showing similar factors for wood and concrete floors; but the Swiss and German wood floors are probably loaded, much heavier than this simple bare OSB floor and closer to concrete floors.

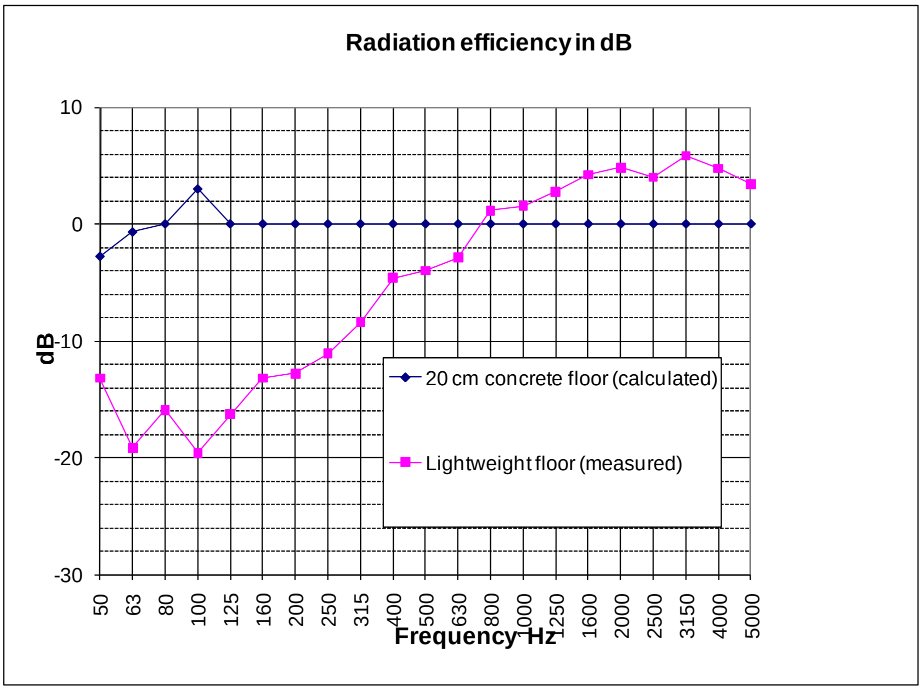

***Figure 2.20**: Typical radiation efficiencies: heavyweight (20 cm concrete) floor (in black) and lightweight (22mm OSB on solid wood joists) floor (in pink)*

Now the very simple equation (3) relates the space average floor velocity level to the space average sound level in the room; but what is measured is the floor velocity at mid span: are these two velocity levels close to each other? To answer this question, a numerical simulation using the FEM NASTRAN software has been performed by CSTB on the simplified concrete building shown in Figure 2.21; the walls and floor at the bottom are supposed to be in contact with ground (higher loss factor). Three typical French floor / wall thicknesses are used, combined with corresponding floor spans as shown in Table 4, thus leading to 9 configurations. 1/3 octave results are given in Figure 2.22 in terms of foundation to floor velocity (at mid span) transfer function in dB (upper curves) and in terms of difference in dB between floor velocity at mid span and floor space average velocity (lower curves).

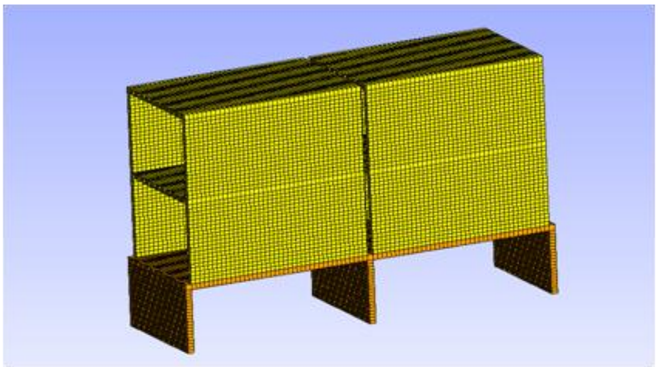

Figure 2.21*: Simulated building (FEM NASTRAN Software)*

Wall/floor thicknesses (cm)	***Floor spans (m)***	***Colours (Figure 2.21)***
15	4 (± 20%)	blue
18	6 (± 20%)	red
20	6 (± 20%)	green

Table 4*: Simulated building dimensions*

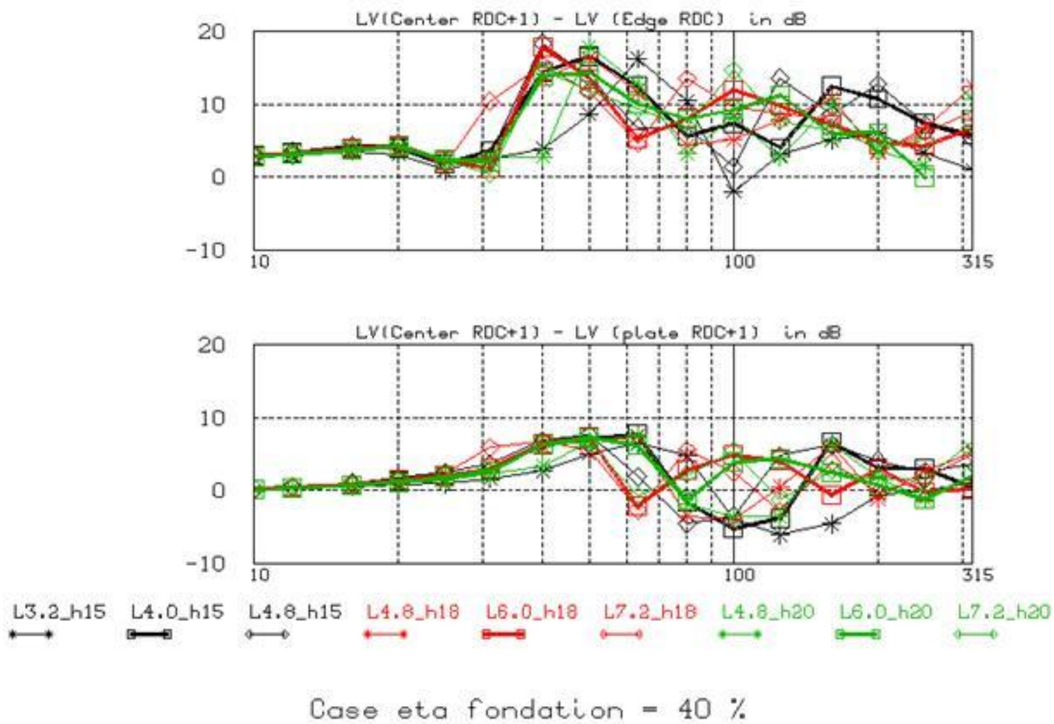

Figure 2.21*: Calculated results (NASTRAN Software): Foundation to floor velocity (at mid span) factor in dB (upper curves); difference in dB between floor velocity at mid span and space average floor velocity (lower curves).*

The calculated foundation to floor (mid span) factors (upper curves) are very similar to the measured results presented in section 2.4 (amplifications close to 15 dB in the 30-63 Hz range), thus showing that the model is well calibrated. The lower curves show that near floor first resonant frequencies, the velocity at mid span over estimates the space average velocity (by around 5 dB) as at higher frequencies the difference is within a ± 5 dB interval.

Consequently, assuming the sound level measured in the middle of the room (Lp_{meas}) a few dB lower (say 3 dB) than the space average sound level, the floor vibration level at mid span (Lv_{meas}) a few dB higher (say 3 dB) than the space average floor vibration level, and taking into account that both floor and ceiling radiate noise (+ 3 dB), equation (3) leads to $Lp_{meas.} \approx Lv_{meas} + 4$ dB, which is close (within 3 dB) to the statistical result obtained by DB and close to the SBB mean value as shown in Figure 2.19.

Conclusion

Since ground borne measurements are problematic (possible mixture of ground borne and airborne noise, as well as erroneous measurement at low frequencies using one microphone in the middle of the room), ground borne noise is preferably calculated from the floor space average velocity, using the building acoustics relationship (equation (3)). However, since only the floor velocity at mid span is measured, a correction shall be made assuming the floor velocity at mid span is a few dB higher than the floor space average velocity. In the case of lightweight wood floors and in first approximation, a transfer function 10 dB lower than for concrete could be retained.

2.6 Proposal for predictions

The following (rough) rules are proposed to statistically calculate the mean value of the three transfer functions TF2-TF4 needed in the procedure estimating vibration and ground borne noise exposure in buildings from ground vibration. The associated standard deviation is of the order 5 dB (statistical max/min could be used to make sure data are on the safe side). The transfer function ***TF1 from 8m to the building location*** can be exactly known just by choosing the building location at reference distances from the tracks where measured ground data exist (8m or 16m for example) and does not really need to be estimate here.

TF2 (ground to building foundation): (i) the SBB mean statistical ground to foundation attenuations for houses and small buildings can be used as mean value in the case of normal ground; (ii) if the ground is softer or harder (factor of 2 on the shear wave velocity), the SBB 60% confidence limits (respectively min. or max.) can be used as mean value; (iii) if the building is taller, the 60% confidence min. limit could be used as mean value.

TF3 (building foundation to floor): (i) the SBB statistical mean data for foundation to floor amplification can be used for concrete floors with the same amplification of the order of 15 dB over the whole frequency range; a average floor resonance frequency of 31.5 Hz can be used in the procedure; (ii) for wood floors a decrease in amplification (with increasing resonant frequencies) can be used, from 20 dB (12-16 Hz) to 10 dB (63 Hz); a average floor resonance frequency of 16 Hz can be used in the procedure.

TF4 (floor vibration to ground borne noise): (i) for concrete floors, room space average sound level and floor vibration at mid span could be related using $Lp_{av} \approx Lv_{meas} + 7$ dB, which takes into account that both floor and ceiling radiate noise; (ii) for lightweight wood floors, $Lp_{av} \approx Lv_{meas}$ -3 dB can be used as first approximation; heavier (loaded) older wood floors likely behave like concrete floors .

3. PROCEDURE TO ESTIMATE DESCRIPTORS IN BUILDINGS

3.1. General Aspects

First, only railway induced vibration and ground borne noise are considered here; railway airborne noise transmitted through the building façade is supposed to be sufficiently attenuated by the façade using acoustically good windows and air inlets, thus leading to airborne noise levels inside the building of the order of the back ground noise accepted as limits by the national building acoustics regulations (which could also be an objective for ground borne noise limits).

The aim of this procedure is to calculate descriptors inside buildings for different emission / ground transmission / immission situations. Emission situations are defined with rather good precision on trains, tracks and ground conditions from ground vibration at 8m from the tracks; existing ground vibration signals (including the ones measured within RIVAS) can be used to simulate typical traffics. Mitigation performances will be also defined within RIVAS as ground velocity insertion loss at 8m from the tracks. However, and because the measuring conditions of the mitigation measure performances can be different from the reference conditions defined within RIVAS, the mitigation performances will be recalculated for a reference situation including parameters for the excitation, the train, the track and the soil, measured according to protocols defined in deliverable D1.2 annex [2b]; this reference situation will be used whenever possible in D1.9.

Concerning descriptors, a review of existing standards, regulations, guidelines and related studies has already been made (see D1.4 [6]), where exposure descriptors for both vibration and ground borne noise have been identified and discussed. The calculation procedure has been developed in such a way that different descriptor types (the main types identified in D1.4) can be calculated for different source/ground/building situations. This procedure will be used later in the evaluation of the mitigation measures efficiency (D1.9), using only a few proper descriptors and a few source/ground/building configurations (both to be chosen later), in order to simplify /clarify the result presentation. The ground building configurations retained will be characterized by a set of transfer functions TF1-TF4 estimated according to the proposal presented in section 2.6 and used as input data.

In this chapter, the main descriptor types identified for both vibration and ground borne noise are briefly presented and then the calculation procedure is described, followed by an example of application.

3.2. Main descriptor types

According to D1.4 conclusions, consistent metrics (log-scale levels) should be used for both ***vibration and ground borne noise***, whether measured or estimated, unless their descriptors badly correlate subjective annoyance. Two types of indicators seem equally meaningful: maximum values (of running r.m.s. quantities) and traffic-oriented equivalent (rms or VDV) values; the former are more related to sleep disturbance; the latter are more related to annoyance. ***This already leads to four descriptors*** (two for vibration and two for ground borne noise)

Concerning ***vibration*** in particular, several international and national standards as well as guidelines propose a great variety of descriptors, defined by three different mathematical operators (the already mentioned rms equivalent values, maximum of running rms values and vibration dose values), based on two different physical quantities (velocity or acceleration), using single number values calculated from three different frequency weightings (no weighting, ISO *Wm/KB* and British W_b/W_d) and expressed in different units. The findings of recent lab studies lead to use acceleration rather than velocity, and flat weighting spectra for acceleration instead of the present flat weighting spectra for velocity; however, no field survey is available to prove that these newly proposed descriptors correlate well subjective annoyance.

Concerning ***ground borne noise*** in particular, fewer standards and guidelines (than for vibration) exist, but several documents deal with indoor low frequency noise in general. Fewer descriptors are proposed; all are expressed as A-weighted SPL in dB(A). It should be noted that C-weighting is also used in order to identify low frequency noise by the difference between the C-weighted and A-weighted values; a difference greater than 15 to 20 dB indicates low frequency noise, for which some countries recommend more severe limits (expressed in dB(A)) than for broadband noise.

Some standards or regulations express limits in terms of 1/3 octave spectra instead of single number values: this is the case for vibration in ISO 2631-2:1989 where frequency dependent base curves are used in association with multiplying factors to define acceptable vibration levels in buildings; this is also the case for low frequency noise in several national regulations where frequency dependent limits are used. The procedure developed here allows calculating such frequency dependent values.

Table 5 below summarizes the main parameters in the descriptor calculation.

Parameters	***units***	***notations***	***examples***
Acceleration / velocity	$m.s^{-2}$ / $m.s^{-1}$ or $mm.s^{-2}$ / $mm.s^{-1}$	*a / v*	-
Time constant (running rms)	s	τ	τ = 0.125s (Fast) τ = 1s (Slow)
Frequency weighting	dB	*W*	ISO W_m British W_b/W_d
Mathematical operator	Max. of running rms / rms (equivalent) / vibration dose value		
Train passage duration (exposure period)	s	*T* *(exposure period te)*	-
Traffic (rms (equivalent) / vibration dose value)	Train passages during assessment period		
Assessment period	s	*tr*	-

***Table 5**: Main parameters in descriptor calculation*

All the above mentioned descriptor types have been implemented in the procedure developed.

3.3. MATLAB procedure to calculate descriptors

General aspects

The calculation procedure developed starts at ground level (ground vibration velocity at 8m) and uses as input data the transfer functions TF1- TF4 defined in section 1.1 and calculated according to the proposal defined in section 2.6 for a given ground building configuration. These transfer functions are expressed as 1/3 octave amplification (or attenuation) spectra in dB and are applied to the input signal (ground vibration at 8m) at the same level as the frequency weighting needed for calculating descriptors. The mitigation measure performances, expressed as an insertion loss in 1/3 octave bands, can also be applied to the input signal at this level in order to calculate descriptor values after mitigation.

Procedure main steps

The procedure can be decomposed into four different steps:

(i) ***Starting input***: the starting input is the ground vibration velocity time signal (at 8m from the tracks) during train passage

(ii) ***Time domain 1/3 octave filtering***

The input time signal is filtered in time domain, over the frequency range from 4 Hz to 250 Hz (according to D1.2), thus leading to nineteen 1/3 octave time signals.

Any 1/3 octave frequency weighting or transfer function can be inserted at this level:

- frequency weighting
- ground propagation to building location (TF1, expressed as velocity ratio)
- ground at building location to foundation (TF2, expressed as velocity ratio)
- foundation to floor (TF3, expressed as velocity ratio)
- floor vibration to ground borne noise (TF4, velocity to sound pressure ratio)
- insertion loss associated with mitigation measure performances (IL_v)

For descriptors based on acceleration signals, the derivative of the velocity input signal is calculated and filtered by acceleration based 1/3 octave transfer functions approximated by those based on velocity (4).

(iii) ***Primary descriptors calculation*** (from velocity or acceleration)

Primary descriptors (corresponding to one train passage) are first calculated with the following steps:

- ***running rms*** (during train passage)
    - calculation of time dependent rms signal $s_{i,rms}(t) = \left[\frac{1}{\tau} \int_{t-\tau}^{t} s_i^2(t)\,dt \right]^{1/2}$ with time constant τ (ith 1/3 octave)
    - frequency weighting *W* of each 1/3 octave
    - 1/3 octave summation leading to $s_{w,rms}(t)$
    - identification of max value $s_{w,max}$

(4) Same uncertainty as with derivative performed in frequency domain from1/3 octave spectra.

- ***rms over train passage T***
  - calculation of rms value: $s_{i,rms} = \left[\frac{1}{T} \int_0^T s_i^2(t)dt \right]^{1/2}$ (ith 1/3 octave)
  - frequency weighting *W* of each 1/3 octave
  - 1/3 octave summation leading to $s_{w,rms}$
- ***VDV over train passage T***
  - frequency weighting *W* of each 1/3 octave
  - 1/3 octave summation leading to $s_w(t)$
  - calculation of Vibration Dose Value $VDV = \left[\int_0^T s_w^4(t)\,dt \right]^{1/4}$

(iv) ***Traffic descriptors calculation***

Traffic descriptors (corresponding to several train passages during a given assessment period) are calculated using the following formulas:

- ***Max values***
  - max value (*N* passages *j*) : max ($s_{w,max,j}$)
  - statistical max (*N* passages *j*) : $s_{w,\max,95} = \overline{s_{w,\max,j}} + n.\sigma$

  (for example, *n* =1.8 to get a 95% confidence level)
  - max average (*N* passages *j* of train type *k*): $\overline{s_{w,\max,k}} = (\frac{1}{N})\left[\sum_j^N s_{w,\max,j}^2 \right]^{1/2}$

- ***Equivalent values***
  - equivalent value: $s_{w,eq} = (1/tr)\left[\sum_j^P s_{w,rms,j}^2.te_j \right]^{1/2}$

  (*P* passages *j* of exposure period te_j during assessment period *tr*)
- ***VDV values***
  - *VDV* value: $VDV = \left[\sum_j^P VDV_j^4 \right]^{1/4}$ (*P* passages *j* during assessment period *tr*)

Remark: the same calculations is performed for noise, VDV excluded, by replacing the vibration *W* weighting by the noise A or C weighting; C weighting is used in several countries to identify low frequency noise from the difference between C-weighted and A-weighted sound levels (high difference for low frequency noise).

Example of descriptor calculation

The track-ground configuration tested in the VIBSOLFRET project (ref. [13]) has been used as an example: ground vibration levels were measured at 9m and 17m (as well as other distances) from the tracks (instead of 8m and 16m respectively as in RIVAS); the ground behaviour is similar to a half space “normal” ground (shear wave velocity of the order of 200 m/s) (ref. [12]). The velocity time signals recorded at 9m during different passenger and freight train passages are used as input signals. The traffic is supposed to be composed of 5 train passages (either 5 passenger trains or 5 freight trains) during the night in order to calculate the corresponding night traffic descriptors.

The building is supposed to be located at 17m from the tracks so that the TF1 transfer function (ground propagation from 9m to building location) can be calculated from the measured ground data. The building is supposed to be a small concrete apartment building with concrete floors. The ground to foundation transfer function TF2 is supposed to be similar to the mean spectrum given in Figure 1.2 (SBB statistical data) and the foundation to floor transfer function TF3 similar to the mean spectrum given in Figure 1.3 (SBB statistical data) and corresponding to the floor category having its first resonant modes in the range 25-35 Hz; combining these two transfer functions leads to the ground to floor TF2+TF3 transfer function required in the procedure.

Finally, the concrete floors are supposed to radiate ground borne noise with a unit radiation efficiency in a normally furnished room (reverberation time of the order of 0.5s) as explained in section 2.5, thus following the (frequency dependent) relationship $Lp_{av} = Lv_{meas} + 7$ given in section 2.6, where Lp_{av} is the room space average sound level in dB (ref. 2.10^{-5} Pa) and Lv_{meas} the floor velocity level measured at mid span in dB (ref. 5.10^{-8} m/s).

The following descriptors have been calculated:

(i) primary descriptors (over train passages): $v_{w,S,max}$ (Slow) like in Sweden, $a_{w,S,max}$ (Slow) like in Austria, $v_{w,F,max}$ (Fast) similar to KB, $a_{i,rms}$ (ith 1/3 octave) like in ISO 2631, Lp_{ASmax} like in the USA, Lp_{AFmax} like in Norway.

(ii) traffic oriented descriptors: $a_{w,rms,night}$ like in Austria, VDV_{night} like in the UK, and $Lp_{Aeq,night}$ like in Switzerland.

The descriptors obtained are given in Table 6 for passenger trains and Table 7 for freight trains and two examples of acceleration spectra $a_{i,rms}$ are given in Figure 3.1 (for passenger train T3 and freight train F3).

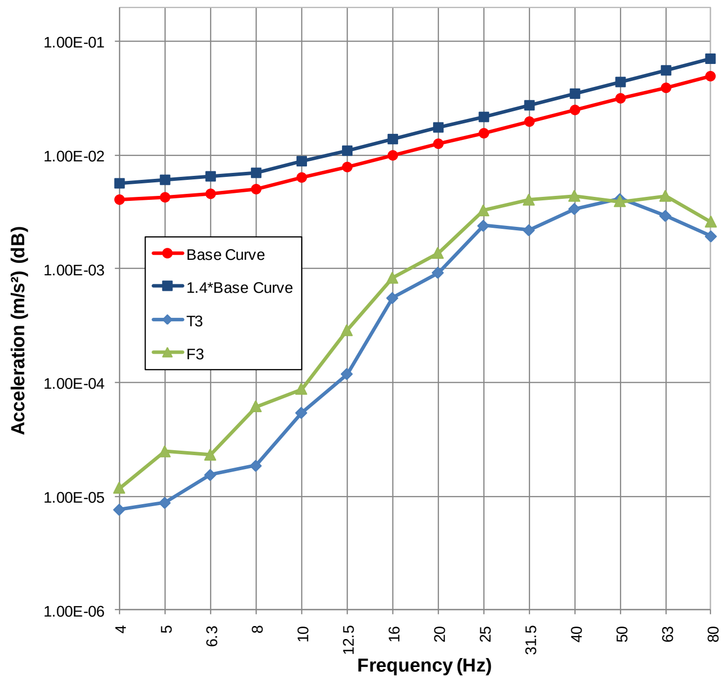

***Figure 3.1**: W_m-weighted acceleration $a_{i,rms}$ compared to ISO 2631 base curves*

T1	$v_{w,max\text{-}Fast}$ = 0.0818 mm/s $v_{w,max\text{-}Slow}$ = 0.0642 mm/s $a_{w,max\text{-}Slow}$ = 2.32 mm/s² Lp_{ASmax} = 33.9 dB Lp_{AFmax} = 36.4 dB
T2	$v_{w,max\text{-}Fast}$ = 0.0988 mm/s $v_{w,max\text{-}Slow}$ = 0.0789 mm/s $a_{w,max\text{-}Slow}$ = 2.90 mm/s² Lp_{ASmax} = 39.4 dB Lp_{AFmax} = 42.6 dB
T3	$v_{w,max\text{-}Fast}$ = 0.0753 mm/s $v_{w,max\text{-}Slow}$ = 0.0635 mm/s $a_{w,max\text{-}Slow}$ = 2.28 mm/s² Lp_{ASmax} = 35.2 dB Lp_{AFmax} = 37.9 dB
T4	$v_{w,max\text{-}Fast}$ = 0.113 mm/s $v_{w,max\text{-}Slow}$ = 0.0732 mm/s $a_{w,max\text{-}Slow}$ = 2.62 mm/s² Lp_{ASmax} = 37.9 dB Lp_{AFmax} = 42.3 dB
T5	$v_{w,max\text{-}Fast}$ = 0.0619 mm/s $v_{w,max\text{-}Slow}$ = 0.0478 mm/s $a_{w,max\text{-}Slow}$ = 1.75 mm/s² Lp_{ASmax} = 33.7 dB Lp_{AFmax} = 37.2 dB
Night 22h to 6h	$a_{w,rms,night}$ = 0.0694 mm/s² VDV_{night} = 0.0133 m/s$^{1.75}$ $Lp_{Aeq,night}$ = 4.7 dB

***Table 6**: Descriptors for passenger trains*

In this building at 17m from the tracks, the descriptors values for vibration are all below the different limits for subjective annoyance; however, ground borne noise might be problematic, with Lp_{ASmax} levels sometimes greater than 35 dB(A) for passenger trains and always greater than 35 dB(A) (and sometimes close to 40 dB(A)) for freight trains.

F1	$v_{w,max\text{-}Fast}$ = 0.142 mm/s $v_{w,max\text{-}Slow}$ = 0114 mm/s $a_{w,max\text{-}Slow}$ = 4.18 mm/s² Lp_{ASmax} = 38.6 dB Lp_{AFmax} = 40.5 dB
F2	$v_{w,max\text{-}Fast}$ = 0.1235 mm/s $v_{w,max\text{-}Slow}$ = 0.0929 mm/s $a_{w,max\text{-}Slow}$ = 3.34 mm/s² Lp_{ASmax} = 40.4 dB Lp_{AFmax} = 45.6 dB
F3	$v_{w,max\text{-}Fast}$ = 0.1275 mm/s $v_{w,max\text{-}Slow}$ = 0.0918 mm/s $a_{w,max\text{-}Slow}$ = 3.27 mm/s² Lp_{ASmax} = 38.7 dB Lp_{AFmax} = 42.9 dB
F4	$v_{w,max\text{-}Fast}$ = 0.1475 mm/s $v_{w,max\text{-}Slow}$ = 0.109 mm/s $a_{w,max\text{-}Slow}$ = 3.89 mm/s² Lp_{ASmax} = 39.3 dB Lp_{AFmax} = 42.4 dB
F5	$v_{w,max\text{-}Fast}$ = 0.118 mm/s $v_{w,max\text{-}Slow}$ = 0.0935 mm/s $a_{w,max\text{-}Slow}$ = 3.33 mm/s² Lp_{ASmax} = 39.7 dB Lp_{AFmax} = 43.5 dB
Night 22h à 6h	$a_{w,rms,night}$ = 0.136 mm/s² VDV_{night} = 0.0235 m/s$^{1.75}$ $Lp_{Aeq,night}$ = 10.2 dB

Table 7*: Descriptors for freight trains*

4. EXPOSURE-ANNOYANCE RELATIONSHIP

4.1. General Aspects

The RIVAS Description of Work (DoW) defines the aim of WP1.1 as translating all the results of mitigation measures developed in WP2 to WP5 in terms of attenuation of vibration exposure in buildings and decrease in annoyance for typical situations; the results will be collected in Deliverable D1.9 at the end of the project. So, in a first step the decrease of a (proper) descriptor value, calculated before and after mitigation, must be estimated using the procedure presented in chapter 3; in a second step, the decrease in annoyance expressed in terms of decrease of percentage of people annoyed at a certain degree must be estimated from the known decrease of the descriptor value; a proper exposure-annoyance relationship is therefore required, for both vibration and ground borne noise since both of them are considered. Unfortunately, only a few exposure-annoyance relationships are available. This chapter mainly describes these existing exposure-annoyance relationships and checks their applicability in the RIVAS project.

There is another aspect which is not considered in this report: the resulting exposure level (after mitigation) should be compared to accepted limit criteria in order to check if the mitigation measure applied has solved the problem or not; this aspect will be addressed in deliverable D1.12 where typical situations with vibration problems (hotspots) will be evaluated. Here again, proper descriptors and proper limit criteria must be identified and used; this task has not been performed yet. However, proper limits should ideally be derived from a clear cut-off annoyance level resulting from exposure-response relationships; the existing exposure-response relationships presented in section 4.2 and 4.3 below already give some information on limit criteria.

4.2. Vibration

Deliverable D1.4 cites five countries which have performed large scale field surveys on vibration annoyance: Norway, the USA, Sweden, Germany and the UK; the outcomes of these field surveys are summarized below; more detailed information can be found in D1.4.

Norway

In Norway, a field survey *(Klaeboe et al. 2003 [19])* on vibration in dwellings was undertaken in 1997 and 1998. The surveyed areas were selected so that indoor sound levels should be low ($L_{\mathrm{Aeq,24h}} < 30$ dB). Annoyance from vibration was reported from about 700 respondents on a categorical scale. Since there was no significant difference between the vibration sources, unique exposure-response relationships were estimated for various degrees of annoyance (Figure 4.1); the descriptor used is the statistical 95-percentile max of running rms (time constant Slow) W_m-weighted velocity (floor at mid span). The results show that 5 % of the respondents were highly annoyed at a vibration level of 0.1 mm/s, but the proportion amounted to 30 % at a level of 4 mm/s. In the comfort classes used in Norwegian standard NS 8176, the max value recommended for new residential buildings (Class C) is at a level of 0.3 mm/s (15% of the respondents are moderately or highly annoyed at this level) .

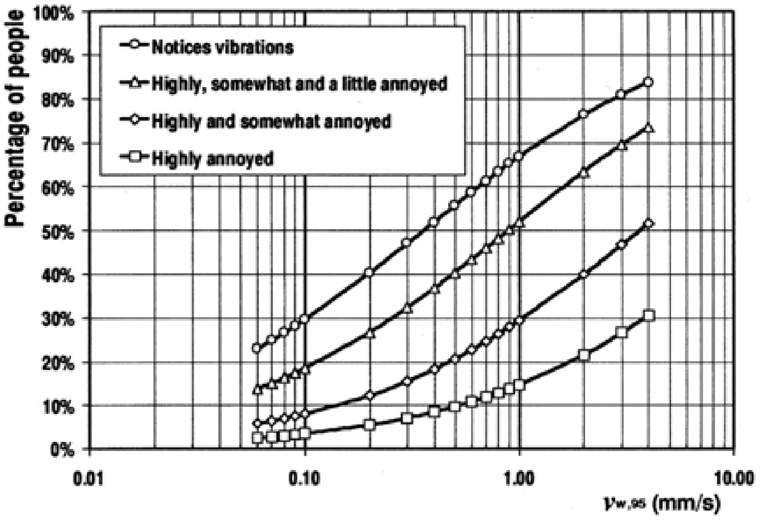

***Figure 4.1**: Exposure-response relationships for different degrees of annoyance (Klaeboe et al. 2003)*

USA

In the USA, a field survey on vibration in dwellings was undertaken in 2009 in five North American cities *(Zapfe et al.2009 [21])*. Annoyance from vibration mainly due to rail transit systems (more than 70 events per day) was reported from about 1300 respondents. Exposure-response relationships were developed with confidence intervals as shown in Figure 4.2; the descriptor used is a max of running rms (time constant Slow) unweighted velocity expressed in VdB ref. 10^{-6} inch/s. 72 VdB (0.10 mm/s) is the FTA limit in dwellings for “frequent” events and corresponds to a probability of high annoyance from 5 to 10% and a probability of moderate or high annoyance from 10 to 20%, both close but a bit higher than the above Norwegian results. 82 VdB (about 0.3 mm/s) would lead to a probability of moderate or high annoyance from 20 to 40 %, higher than the above Norwegian results (15%).

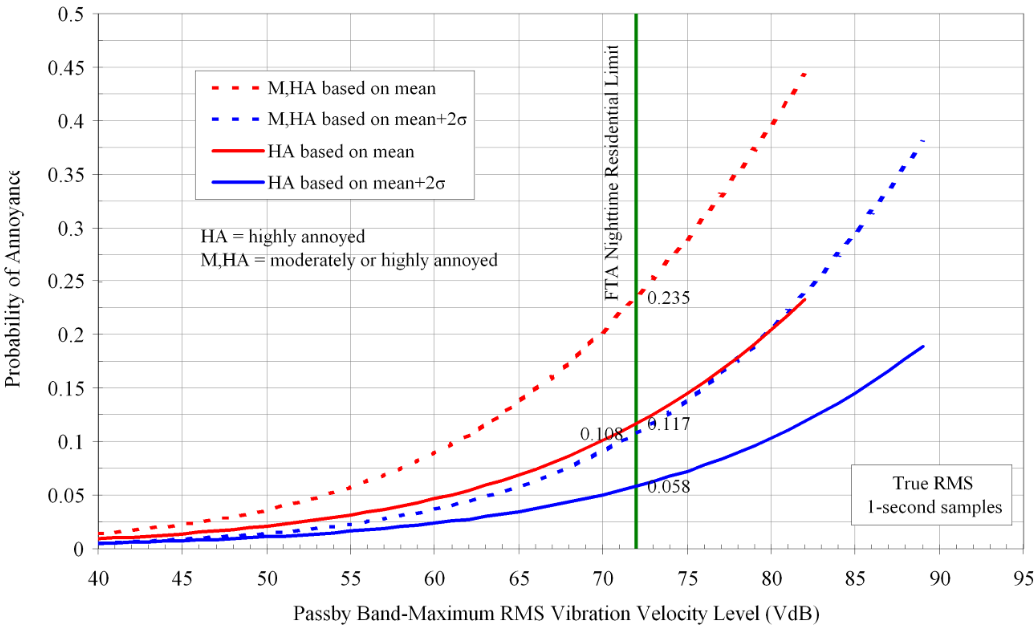

***Figure 4.2**: Exposure-response relationships (vibration) for different degrees of annoyance (Zapfe et al.2009)*

Sweden

In Sweden, the TVANE project aimed at studying the effects of noise and vibration from railway traffic in dwellings from 2006 to 2011 *(Öhrström et al. 2011 [22])*. Among the areas tested, Kungsbacka is particularly interesting with strong ground vibration (noise should be a secondary parameter) and where annoyance was expressed as a function of indoor velocity as shown in Figure 4.3, from 218 houses tested; the descriptor used is the same as in Norway (max of running rms (time constant Slow) W_m-weighted velocity) but with no statistics. The probability of high annoyance is close to 17% at levels between 0.20 and 0.29 mm/s showing that for the site tested, limits should be set below 0.2mm/s, as in the USA.

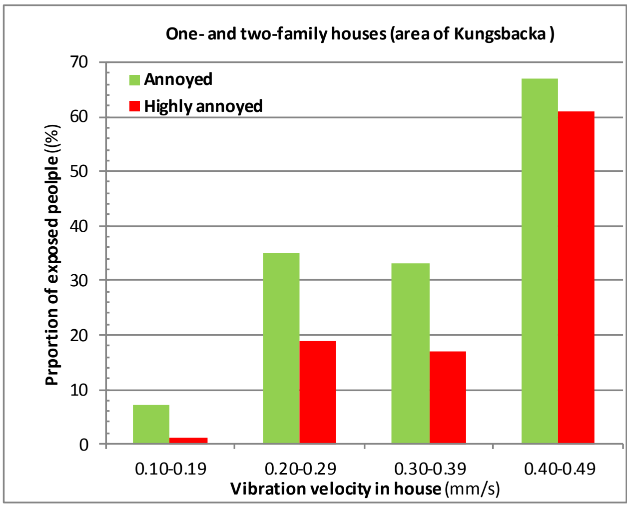

Figure 4.3*: Annoyance of residents in houses from railway vibration (Öhrström et al. 2011)*

Remark: The three exposure-response set of curves presented from Norway, the USA and Sweden are similar, using very close descriptors, but also different, the main difference being in the curve slopes: the proportion of people annoyed rises sharply when the vibration level reaches 0.4mm/s in the American and Swedish survey results and much less in the Norwegian survey results. This difference could be due to different traffic densities (heavy traffic in the USA) and/or different frequency contents in the floor signals.

Germany

A field study performed in Germany where noise and vibration data were measured [24] was combined with a field survey and the results analyzed in terms of combined effect of railway noise and vibration (*K. Zeichart,* [23]). The results were not directly expressed as exposure-response relationships and will not be presented in this report; however, exposure-response relationships could probably be obtained with further analysis of the data.

UK

In the UK, a large scale survey on railway vibration has been recently carried out. The report has not been published (by DEFRA) yet; the whole report should be available before the end of RIVAS. However, results on annoyance have already been published in several recent papers: (*Peris et al. 2011* [25]), (*Woodcock et al. 2011* [26]), (*Peris et al. 2012* [27]) and (*Woodcock et al. 2012* [28]). The data relate to measurements of and response to railway vibration collected in the North-West of England and the Midlands area during 2009 and 2010. Three types of results are obtained:

(i) First the exposure-response curves obtained with confidence intervals from 931 responses associated with vertical vibration data in buildings are given in [27] and [28] and shown in Figure 4.4; the descriptor used is the acceleration based VDV with W_b-weighted (according to BS 6472-1:2008) over a period of 24 hr.

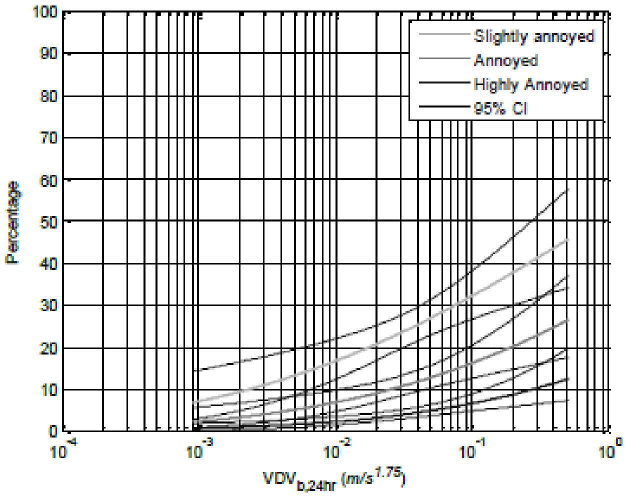

Figure 4.4: *Exposure-response curves for overall day vertical vibration in building; proportion of people reporting different degrees of annoyance with 95% confidence intervals (Woodcock et al. 2012)*

(ii) More precise results are given in [27] with exposure calculated over the different periods of the day (day, evening and night) and expressed in terms of rms equivalent W_m-weighted (according to ISO 2631-1:1997) acceleration in m/s^2 (Figure 4.5). A single 24-h exposure is then calculated by combining the vibration exposures in the different periods using appropriate weightings; the overall annoyance (red curve in Figure 4.6) falls between evening and night curves.

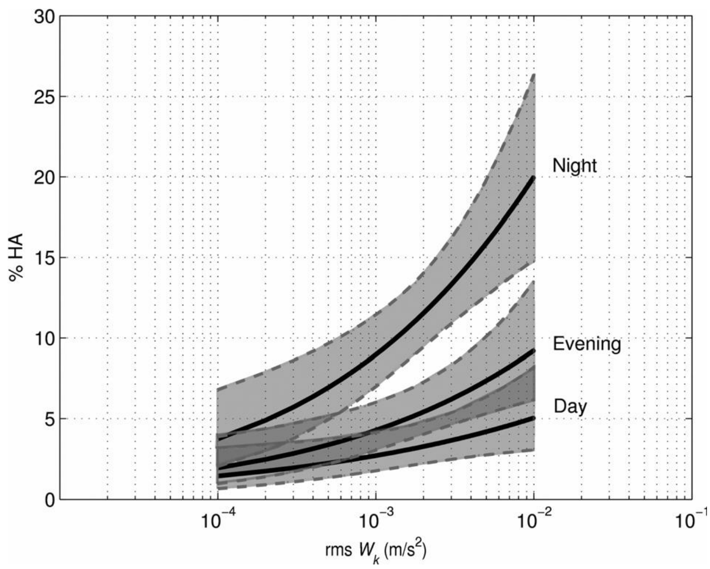

Figure 4.5: *Exposure-response curves for day, evening and night vertical vibration in building; proportion of people reporting high annoyance with 95% confidence intervals (Peris et al. 2012)*

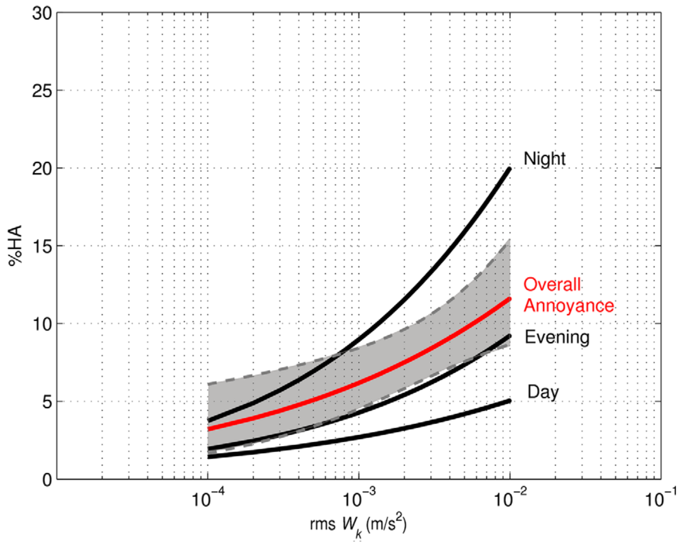

***Figure 4.6**: Exposure-response curve for 24h vertical vibration in building (in red); proportion of people reporting high annoyance with 95% confidence intervals (Peris et al. 2012)*

These results showing more annoyance for the same exposure at night are of great interest to assess night traffic. Very similar exposure-response curves are presented in [25] but expressed in terms of VDV.

(iii) A very recent publication (*Woodcock et al. 2012* [28]) goes even further by investigating differences in annoyance coming from the type of railway traffic (passenger and freight trains). The use of a recently developed algorithm to classify (separate) passenger and freight trains based upon recorded acceleration time histories, combined with the survey responses, has lead to the exposure response relationships given in Figure 4.7. The results show that for the same exposure, higher annoyance is obtained for freight trains and annoyance increases more rapidly with increasing exposure; these results should be regarded as preliminary, due to the uncertainty of the algorithm use (accuracy of the order of 80%).

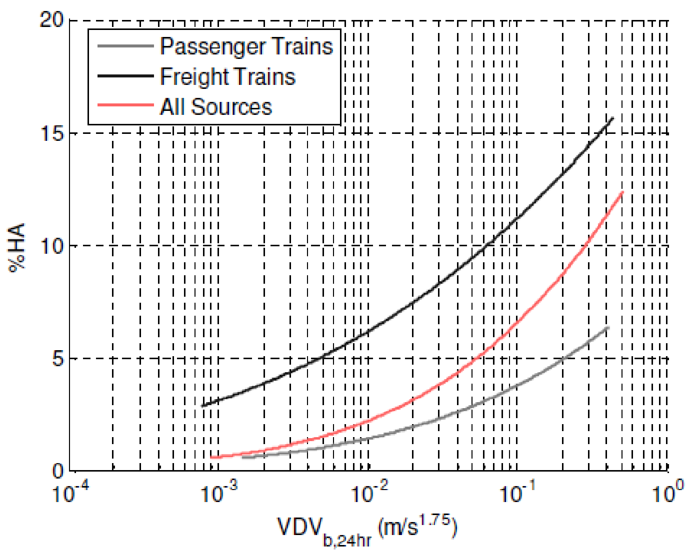

***Figure 4.7**: Preliminary exposure-response curve for 24h vertical vibration; proportion of people reporting high annoyance with 95% confidence intervals (Wooodcock et al. 2012)*

Conclusion

At least a few exposure-response curves exist for railway vibration on both max values (velocity) and equivalent values (rms or VDV, both from acceleration) and can be used to estimate the decrease in annoyance associated to the performances of the mitigation measure developed in RIVAS (if applied to similar situations as the field surveys). The curves expressed in max values (Norway, USA and Sweden) are similar but not the same, and correspond to situations not fully comparable (different countries, different traffics and probably different frequency contents); a second descriptor, based on rms equivalent values is missing and would have given some indication on the traffic density and the way it affects people. The curves expressed in rms (or VDV) values (UK) cannot be easily compared to the ones expressed in max values but are complementary. The detailed analysis performed in the UK leads to different exposure-response relationships depending on the period of the day (day, evening, night) and on the types of railway traffic (freight or passenger trains).

4.3. Ground borne noise

Field surveys on annoyance from structure-borne noise are rare; only two are reported in Deliverable D1.4: one in the USA and one in Norway.

USA

The field survey performed in the USA for vibration also considers ground borne noise. The A-weighted ground borne noise level is approximated by the A-weighted floor velocity (see section 2.5) expressed in VdB ref. 10^{-6} inch/s, thus leading to the exposure-response relationships given in Figure 4.8 with confidence intervals; the descriptor used corresponds to the sound level L_{pASmax} (A-weighed max of running rms with time constant Slow). 35 dB(A) is the FTA limit in dwellings for “frequent” events and corresponds to a probability of high annoyance from 3 to 7% and a probability of moderate or high annoyance from 8 to 15% . It should be noted that the FTA limit for vibration (72 VdB) would correspond to radiated ground borne noise levels in dB(A) about 10 dB higher (45 dB(A)) than the FTA limit for ground borne noise, thus showing the severity of the noise limit.

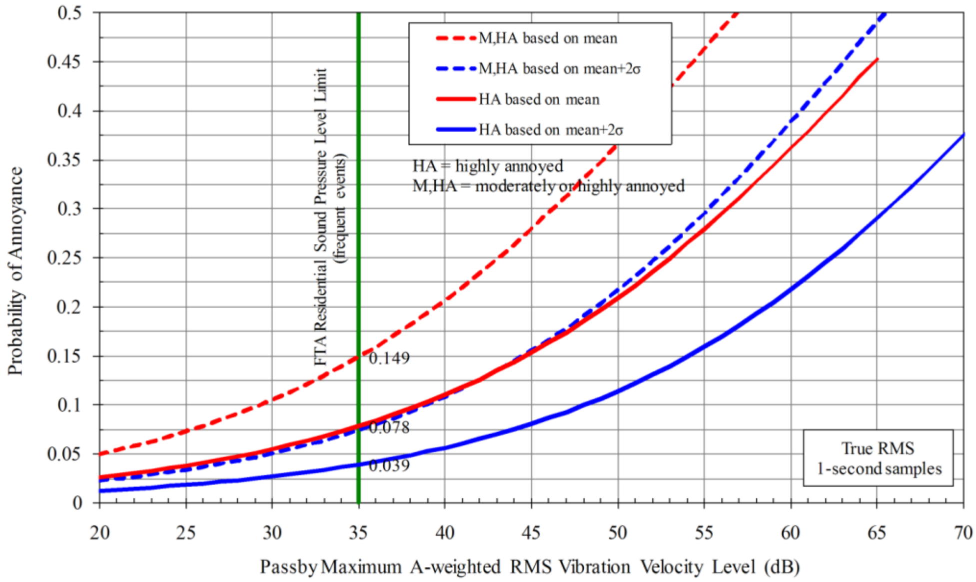

***Figure 4.8**: Exposure-response relationships (ground borne noise) for different degrees of annoyance (Zapfe et al.2009)*

Norway

In Norway, a field survey has been performed inside 313 dwellings exposed to ground borne noise from railway tunnels (*Aasvang et al. 2007 [29]*). Annoyance is expressed statistically as a function of structure borne levels in dB(A) with confidence intervals as shown in Figure 4.9; the descriptor used is the sound level L_{pAFmax} (A-weighed max of running rms with time constant Fast). 32 dB(A), limit value for sound class C dwellings in Norway corresponds to 20% of people annoyed in average (red curve) and 5% of people moderately or highly annoyed (black curve).

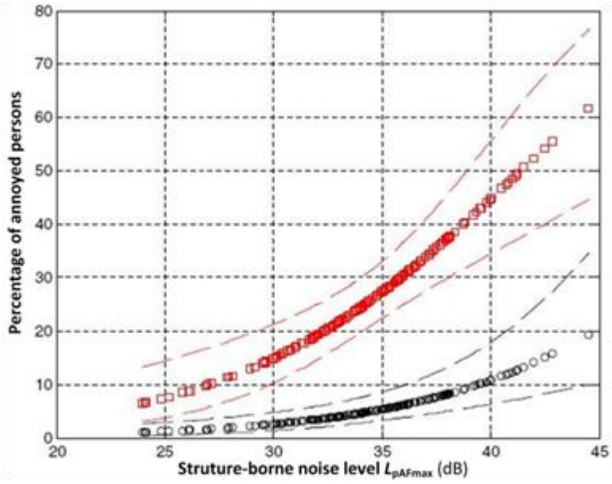

Figure 4.9*: Exposure-response relationships (ground borne noise) for different degrees of annoyance <u>during overall day</u> (Aasvang et al. 2007); dashed lines: 95% confidence interval*

Remark: The curves (and corresponding confidence intervals) obtained in the American and the Norwegian surveys and giving the proportion of people <u>moderately or highly annoyed</u> are very close (slope included) when taking into account the difference in the descriptors used: L_{pAFmax} (Fast time constant) for Norway should approximately be 3-4 dB greater than L_{pASmax} (Slow time constant) for the USA, according to ISO 14837-1[17].

Conclusion

The two existing exposure-response curves for ground borne noise are very similar, though obtained in different situations (only tunnel traffic in Norway, mixed tunnel and surface traffic in the USA). A second descriptor, based on equivalent noise level is missing and would give some indication on the traffic density and the way it affects people. No separate curves for different time of the day (as given in the UK for vibration) are given.

4.4. Proposal for RIVAS procedures

For ***vibration***, the two available exposure-response relationships expressed in terms of max velocity values (Norway and USA) can be used, the latter being likely more adapted for heavier traffic. The exposure-response relationships from the UK, expressed in terms of acceleration based rms / VDV, are complementary and will also be used; both overall day (24hr) and night descriptors will be used, calculated with mixed traffic.

For ***ground borne noise***, the exposure-response relationships expressed in terms of Lp_{ASmax} (USA) can be used. Unfortunately, no exposure-response relationships expressed in terms of Lp_{Aeq} exists for ground borne noise from railways.

5. Conclusions

Deliverable D1.6 aims at defining procedures to predict exposure in buildings and estimate annoyance. These procedures will be used at the end of the project to evaluate all the mitigation measures developed in RIVAS in common situations (deliverable D1.9) and to show their effects in typical configurations with vibration problems (hot spots) (deliverable D1.12).These procedures must be able to calculate exposure descriptors inside buildings for different emission / ground propagation / immission situations. Emission situations can be defined rather well from available ground vibrations data at 8m from the tracks. Tools (models, data) are therefore needed to estimate the four transfer functions TF1 from ground at 8m to ground at building location, TF2 from ground to building foundations, TF3 from foundation to floor and TF4 from floor vibration to ground borne noise.

TF1 can be known just by choosing building at reference distances from the tracks where ground measured data exist (8m or 16m for example). For estimating the transfer functions TF2-TF4, several models developed by RIVAS partners have been identified as well as data from particular sites in different countries. All these data have been collected, properly stored and analyzed / compared. Two types of data have been gathered: statistical data (mainly from SBB and DB empirical models), used as base curves, and data from well documented particular sites from Germany, Switzerland, France, Spain and Sweden, used to validate the statistical models. And since little information existed on ground and building foundation conditions, the CSTB numerical model has been used to estimate the effects of modifications in ground and building foundations on the corresponding transfer functions.

This analysis / cross validation has led to proposals for statistically predicting these three transfer functions TF2 to TF4; the proposed transfer functions are expressed as mean spectra, knowing that the associated standard deviation is of the order of 5 dB.

A MATLAB procedure has been developed to calculate the main descriptors identified in Deliverable D1.4 for different source/ground/building situations. The starting input is the ground velocity time signal at 8m. The above four transfer functions TF1 to TF4 expressed as 1/3 octave amplification or attenuation in dB are then applied to the input signal the same way as the frequency weighting, also expressed in dB; the mitigation measure performances expressed as 1/3 octave insertion loss in dB is also applied to the input signal in order to calculate descriptors after mitigation. Only a few descriptors calculated for a few emission / ground propagation / immission situations (to be chosen) will be used in D1.9 in order to clarify / simplify the result presentation. However, it seems that a minimum of four descriptors (max value and equivalent value for both vibration and ground borne noise) must be used to correctly evaluate the mitigation measures in D1.9.

Once the decrease in exposure associated with any mitigation measure has been estimated, the corresponding decrease in annoyance must be evaluated using proper exposure-response relationships. The most recent papers have been gathered to identify proper exposure-responses; more information might come later (particularly published results from the European project Cargovibes).

The results are the following:

For ***railway vibration***, at least a few exposure-response curves exist on both max values (velocity) and equivalent values (rms or VDV, both from acceleration). The two types of curves (max and equivalent values) cannot be easily compared and are considered as complementary; it is proposed to use both of them.

For ***railway ground borne noise***, rare exposure-response curves exist. It is proposed to use the exposure-response relationships from the USA, expressed in terms of Lp_{ASmax}; unfortunately, no exposure-response relationships expressed in terms of Lp_{Aeq} exists for ground borne noise from railways, which would have added information on traffic effects.

This report has been circulated among RIVAS WP1.1 members and the main models/rules to estimate vibration and ground borne noise in buildings, as well as the descriptors and exposure-responses curves proposed in this report have been agreed upon. However, some details in the formulas proposed might be further discussed within RIVAS and modified when evaluating the mitigation measures at the end of the project (D1.9).

REFERENCES

[1] RIVAS, Description of Work, 2010

[2a] RIVAS, Del 1.2, Protocol for measuring parameters influencing the insertion loss in the project RIVAS for WP2, 3, 4, 5 (published)

[2b] RIVAS, Del 1.2, Annex, Measurement protocol for parameters influencing mitigation effects (published)

[3] RIVAS Del.4.1, Report defining scope and constraints of numerical parametric study (published/restricted)

[4] RIVAS, Del 1.9, Report giving the decrease of exposure and annoyance associated with each mitigation measures (to be published at the end of RIVAS)

[5] RIVAS, Del 1.12, Vibration reduction for reference cases (to be published at the end of RIVAS)

[6] RIVAS, Del 1.4, Review of existing standards, regulations and guidelines, as well as field and laboratory studies concerning human exposure to vibration (published)

[7] VDI 3837, Ground borne vibration in the vicinity of at-grade rail systems; spectral prediction method. (2006)

[8] US Department of Transportation, Federal Railroad Administration, High-speed ground transportation noise and vibration impact assessment (1998)

[9] L. Auersch and W. Rücker, "A user-friendly prediction tool for railway induced ground vibration: Emission – Transmission – Immission", 9th IWRN Proceedings, Munich 2007

[10] Lutz Auersch, "Train induced vibration of inhomogeneous soils – a prediction based on measured and calculated point-load solutions", ICSV19 Congress, Vilnius Lithuania, July 2012, Proceedings

[11] C. Meinhardt et al.: "Messbericht zu durchgeführten Messungen an Ein- und Mehrfamilienhäusern in Wildau, Zeesen, Königs Wusterhausen, Zeuthen und Eichwalde ", BAM, Berlin, 2004

[12] M. Villot, P. Ropars, P. Jean, E. Bongini, F. Poisson, "Modelling the influence of structural modifications on the response of a building to railway vibration", Noise Control Eng. J. **59** (6) Nov. Dec. 2011

[13] Project VIBSOLFRET: 'Comparison between freight and passenger trains in terms of environmental vibration'; Work performed in 2009-2010 by SNCF, CSTB and SATEBA; work financially supported by the French Agency ADEME (Agency for Environment and Energy Management).

[14] N. F. Norme, P0613, Règles de construction parasismique, Règles PS applicables aux bâtiments, PS92, Eyrolles, seconde édition 1998 (Building code for buildings exposed to earthquake risks).

[15] DB, OBERMEYER, Erschütterungstechnischen Untersuchungen zur Ermittlung der gebäudespezifischen Übertragungsfaktoren, A. Said (2003)

[16] A.Said, H. P. Grütz, R. Garburg, "Ermittlung des sekundâren luftschalls aus dem Schienenverkehr", Zeitschrift für Lärmbekämpfung, 53 (2006) Nr.1-Januar

[17] ISO 14837-1:2005, Mechanical vibration- Ground borne noise and vibration arising from rail systems. Part 1: General guidance.

[18] Pierre Ropars, « Modélisation des vibrations d'origine ferroviaire transmises aux bâtiments par le sol », ("Modeling railway vibration transmitted to buildings through ground"), PhD dissertation, Université Paris Est, Ecole doctorale SIE, December 2011

[19] Klæboe R., Turunen-Rise I.H., Hårvik L., Madshus C. (2003a): Vibration in dwellings from road and rail traffic – Part II: exposure-effect relationships based on ordinal logic and logistic regression models. *Applied Acoustics,* 64, 89-109.

[20] C. Madshus, B. Bessason and L. Harvik, "Prediction model for low frequency vibration from high speed railways on soft ground", *Journal of Sound and Vibration* (1996) **193**(1), 195-203.

[21] Zapfe J.A., Saurenman H., Fidell S. (2009): *Groundborne Noise and Vibration in Buildings Caused by Rail Transit*. Final report for Transit Cooperative Research Program (TCRP) D-12.

[22] Öhrström E., Gidlöf-Gunarsson A., Ögren M., Jerson T. (2011): *Effekter av buller och vibrationer från tåg- och vägtrafik – tågbonus, skillnader och samverkan mellan tåg- och vägtrafik*. Slutrapport Forksningprogrammet TVANE, Rapport nr 1:2011.

[23] K. Zeichart, "Kombinatorische Wirkungen von Bahnlärm und Bahnerschütterungen", Zeitschrift für Lärmbekämpfung -1998

[24] K. Zeichart *et al*. "Erschütterungen durch Eisenbahnverkehr und ihre Wirkungen auf Anwohner", Teil 1-2, Zeitschrift für Lärmbekämpfung -1994

[25] E. Peris *et al*. "Community reaction to railway vibration at different times of the day", 10^{th} International Congress on Noise as a Public Health Problem (ICBEN) 2011, London UK, Proceedings

[26] J. Woodcock *et al*. "Human response to vibration in residential environments: Establishing exposure-response relationships", 10^{th} International Congress on Noise as a Public Health Problem (ICBEN) 2011, London UK, Proceedings

[27] E. Peris *et al*., "Annoyance due to railway vibration at different times of the day", J. Acoust. Soc. Am. **131**(2), Express Letters, February 2012

[28] J. Woodcock *et al*., "Human response to vibration from passenger and freight railway traffic in residential environments", ICSV19 Congress, Vilnius Lithuania, July 2012, Proceedings

[29] Aasvang G.M., Engdahl B., Rothschild K. (2007): Annoyance and self-reported sleep disturbances due to structurally radiated noise from railway tunnels. *Applied Acoustics,* 68, 970-981, and Corrigendum 69 (2008), 285.