Vibration and ground borne noise exposure in buildings and associated annoyance

Michel VILLOT, CSTB France
(Responsible for RIVAS WP1.1: Assessment of human exposure)
Results from CSTB work by Simon Bailhache, Catherine Guigou and Philippe Jean

Vibration and ground borne noise exposure in buildings and associated annoyance

RIVAS WP1.1: Assessment of human exposure

Goal: **Evaluate the effect of the mitigation measures develop in RIVAS on people in nearby buildings**

- mitigation measure performances expressed in RIVAS as 1/3 octave ground vertical vibration insertion losses at 8m from tracks
- need for appropriate model to transfer performances from ground (8m) to building
- need for appropriate descriptors correlated to human response in building
- no EC funding in RIVAS for developing new models or new descriptors

Vibration and ground borne noise exposure in buildings and associated annoyance

RIVAS WP1.1: Assessment of human exposure

Method:

- use of existing and robust models predicting vibration and ground borne noise in buildings from ground vibration near tracks
- use of existing descriptors for both vibration and ground borne noise which have been associated with exposure-annoyance curves determined from large scale surveys.
- develop a simple calculation procedure to estimate the decrease of exposure in buildings and associated decrease of annoyance corresponding to each mitigation measure developed in RIVAS
- Present the results in a (public) deliverable (RIVAS D1.9)

Vibration and ground borne noise exposure in buildings and associated annoyance

Presentation in 2 parts (May 22 and 23)

Part 1 (May 22):

Transfer from ground to building (*):

- estimation of the transfer functions required
- configurations used for final evaluation: reference grounds, trains, track and buildings
- implementation of the calculation procedure; input data

Part 2 (May 23):

Descriptors and limits (*):

- descriptors, exposure-annoyance relationships and limits for the assessment of vibration and ground borne noise inside building
- two examples: track mitigation measures and mitigation measures in ground

Cost-benefit calculation

(*) detailed results on RIVAS Deliverable D1.6 (public)

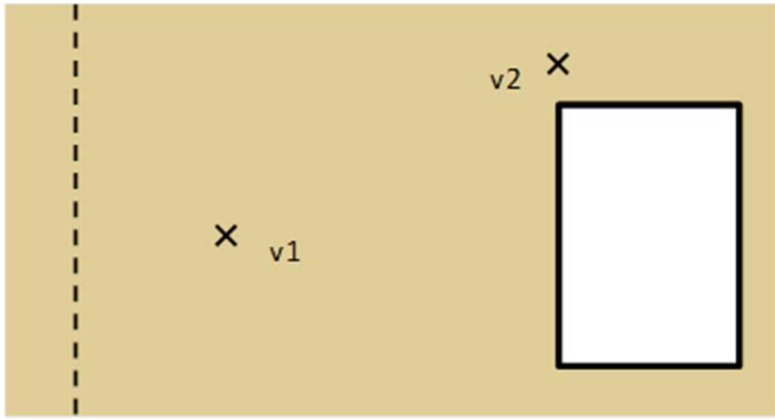
Vibration and ground borne noise exposure in buildings and associated annoyance part1

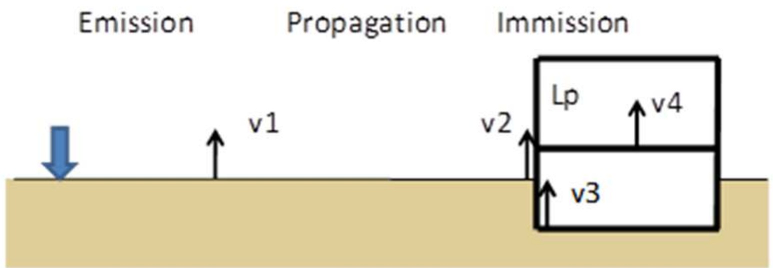
Ground to building transfer model

Decomposition of ground borne transmission path into **four (vertical) vibration transfer functions** (*)

- ground (8m) to (free field) ground at building distance (TF1)
- ground (building distance) to building foundations (TF2)
- building foundation to floor (TF3)
- floor vibration to room ground borne noise (TF4)

(*) according to VDI 3837 and US FRA document on noise and vibration impact assessment (1998)



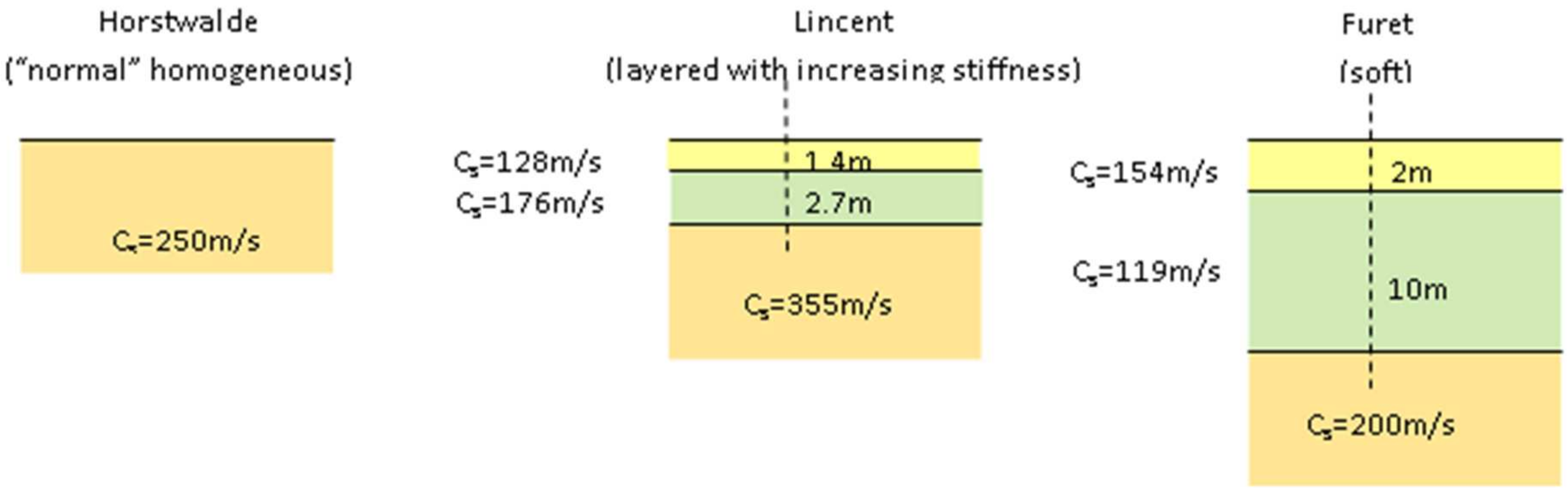


Ground to building transfer functions

Vibration and ground borne noise exposure in buildings and associated annoyance part 1

Transfer (TF1) from ground (8m) to (free field) ground at building distance:

- **three reference soils** have been used in RIVAS (figure below)
- six transfer functions (8 to 12m, 8 to 16m, 8 to 20m, 8 to 24m, 8 to 28m, 8 to 32m) have been pre-calculated using ISVR 2D ½ ground model for each reference soil with soil input parameters obtained from on site measurements.



G1 ***G2*** ***G3***

Reference soils

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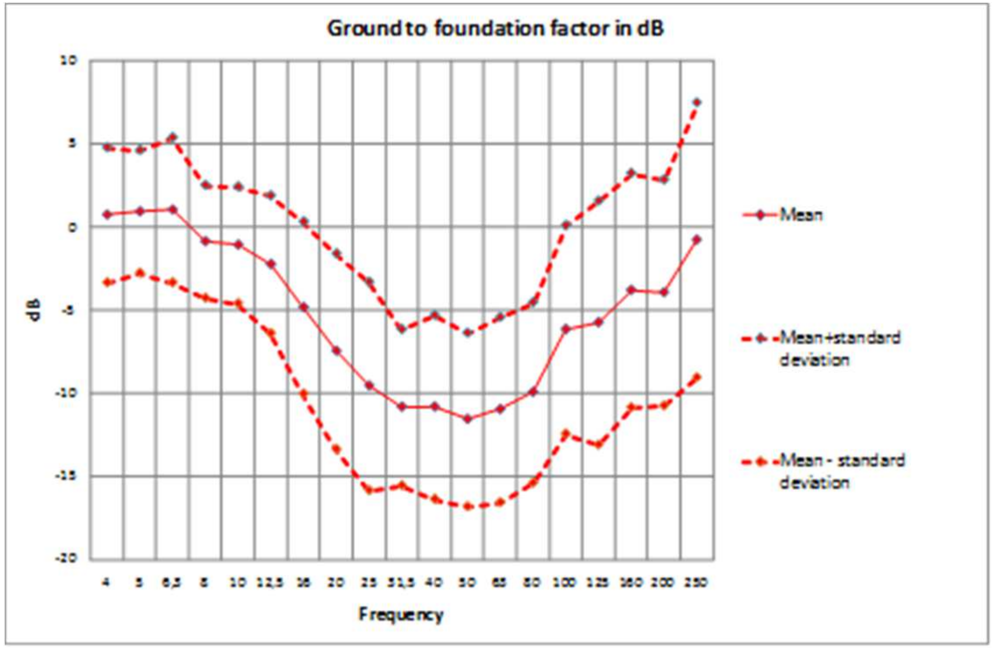
Transfer (TF2) from ground to building foundations (1):

- use of **SBB empirical (statistical) model VIBRA-2** (UIC RENVIB model)
- negative values (in dB) corresponding to attenuation
- standard deviation of the order of 5 dB
- validity checked with data from other countries (Germany, France, Spain and Sweden)
- lack of information on ground and building foundations compensated by estimating the effect on transfer functions of changes in ground and building foundations using CSTB 2D ½ ground structure model MEFISSTO (*)

(*) coherent with BAM model results



TF2 transfer function in dB for multifamily buildings (SBB model)

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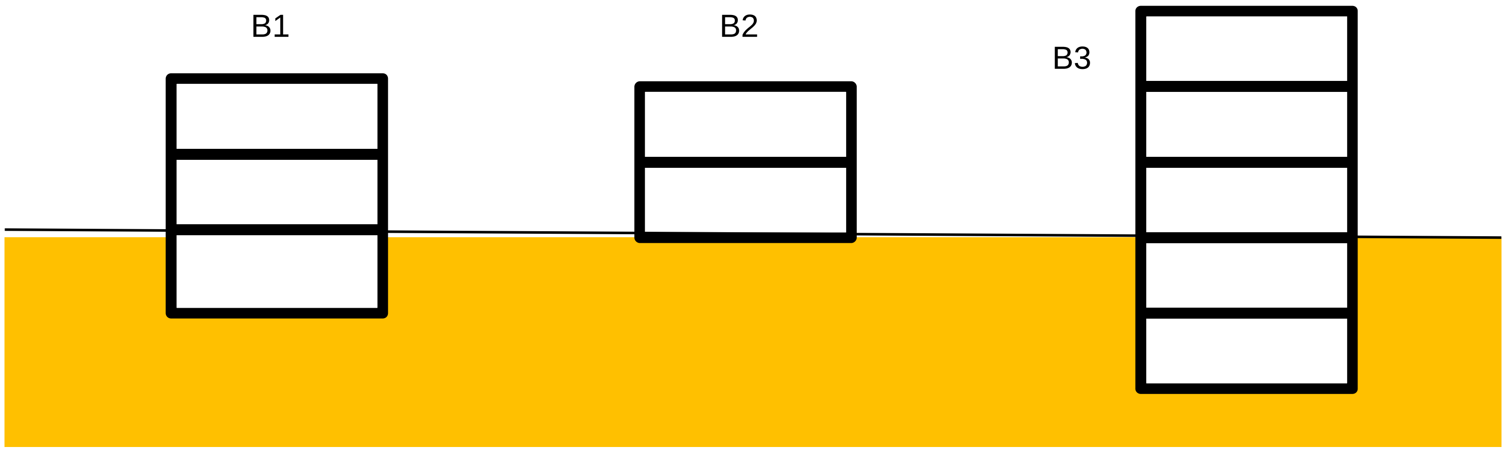
Transfer (TF2) from ground to building foundations (2):

Reference buildings chosen:

- small multifamily heavyweight building with heavyweight floors and basement (B1)
- single family house with wooden floor and shallow foundations (B2)
- bigger heavyweight apartment building with heavyweight floors and deeper (two level) foundations (B3)



Reference buildings

Transfer (TF2) from ground to building foundations (3):

Data used for reference soils and buildings:

- B1 (small multi-family building): SBB mean value used for “normal” ground and mean + 5dB used for soft ground (*)
- B2 (single-family building): 3dB added to values for small multi-family building (from SBB data)
- B3 (apartment building with deeper foundations): 5dB (*) subtracted to values for small multi-family building
- Cases with layered ground G2: corrections (*) applied to TF2 values for “normal” ground (different for each building type); rough tendencies: no change for B2, 2 dB subtracted for B1 and 4 dB subtracted for B3

(*) effect of changes in ground and building foundations calculated using CSTB model MEFISSTO

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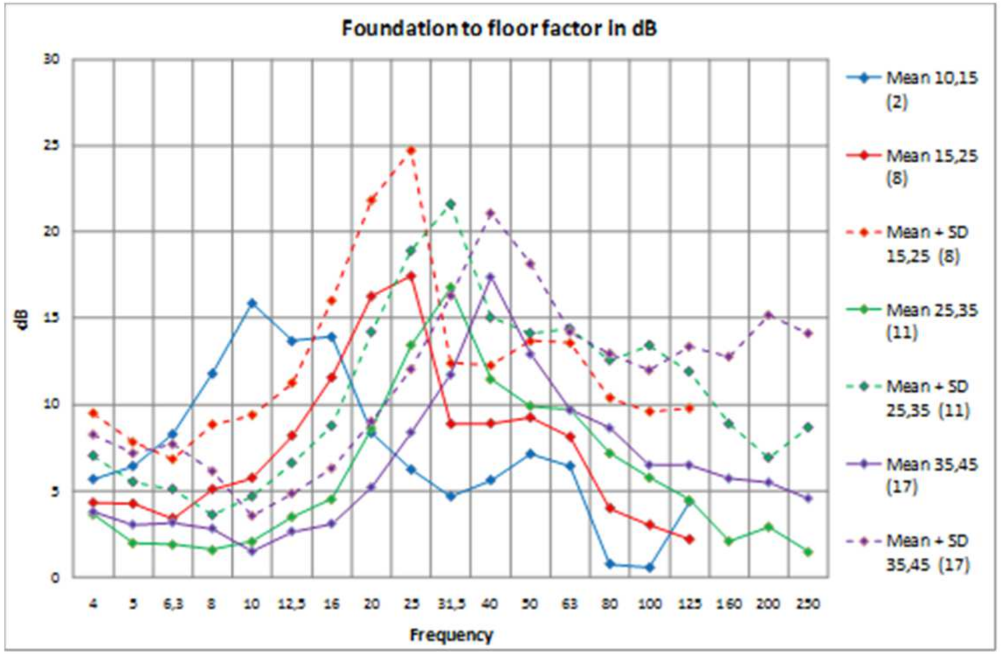
Transfer (TF3) from building foundations to floor (1):

- use of **SBB empirical model VIBRA-2**, (very similar to DB statistical data)
- positive values (in dB) corresponding to amplification
- standard deviation 4-8 dB
- two categories of data (**concrete** floors and **wood** floors) and several **sub-categories** depending on floor resonance frequencies
- validity checked with data from other countries (Germany, France, Spain and Sweden)



TF3 transfer functions in dB for concrete floors (SBB model)

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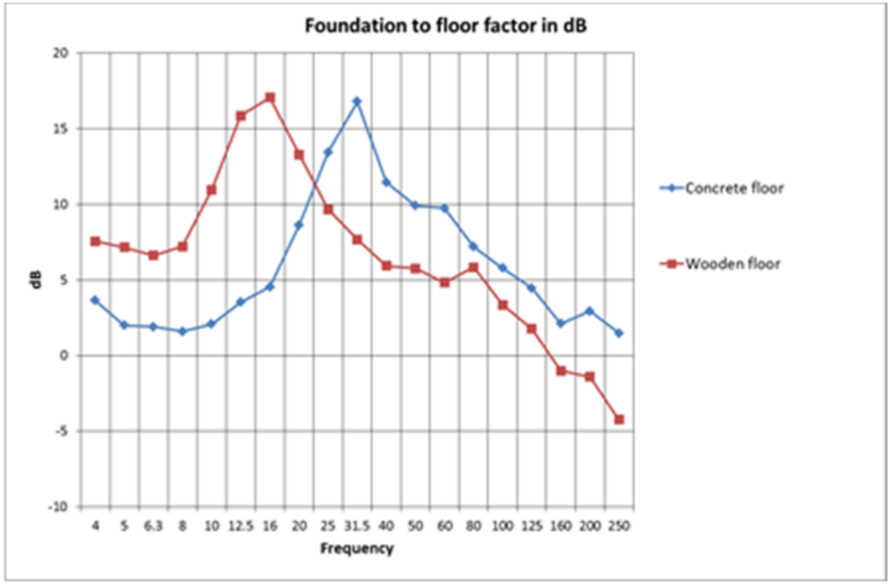
Transfer (TF3) from building foundations to floor (2):

Data used for reference buildings:

- Concrete floors: SBB mean value for mean floor resonance frequency of 31.5 Hz
- wood floors: SBB mean value for mean floor resonance frequency of 16 Hz



TF3 transfer functions in dB for the reference buildings (SBB model)

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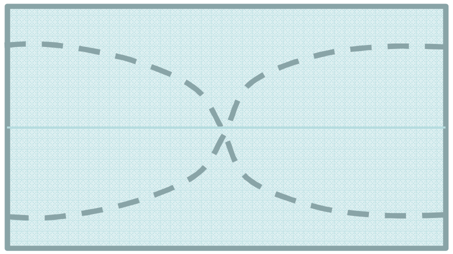
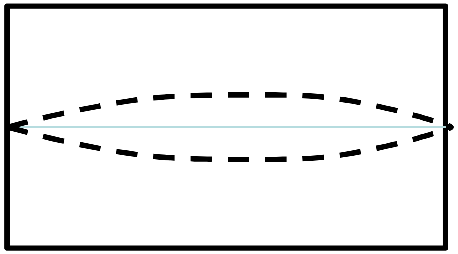
Transfer (TF4) from building floor vibration to room ground borne noise (1):

- Ground borne noise measurements problematic (mixture with transmitted airborne noise and erroneous results at low frequencies using one microphone)
- **Ground borne noise preferably calculated from floor vibration** using building acoustics radiation efficiencies; space average floor velocity required!
- space average ground borne noise a few dB higher than noise measured in room center
- space average floor velocity a few dB lower than floor velocity at mid span



Room mode shape



Floor mode shape

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Transfer (TF4) from building floor vibration to room ground borne noise (2):

For **concrete** floors

- transfer function TF4 (including both floor and ceiling sound radiation) relating, **per 1/3 octave band**, floor vibration levels measured at mid span to space average sound levels (both floor and ceiling radiates sound):

  Lp(av) ≈ Lv(meas) + 7 dB (Lv ref. 5 10^{-8} m/s)

- relationship coherent with empirical models (SBB and DB)
- relationship coherent with US FRA document:

  Lp(av) ≈ Lv(meas) (Lv ref. 1 inch/s)

For **wood** floors

- similar behavior of rather heavy (loaded) wood floors according to measured data (SBB and DB)
- lower sound radiation of lightweight wood frame floors according to building acoustic data

Vibration and ground borne noise exposure in buildings and associated annoyance part 1

Procedure to translate mitigation measure performances in terms of decrease of exposure inside buildings:

MATLAB procedure

- starting input: **ground vibration time signal at 8m from track**
- **1/3 octave filtering** performed **in time domain** from 4 to 250 Hz in order to calculate time dependent descriptors (running rms)
- 1/3 octave frequency weighting and transfer functions TF1-4 applied to get descriptors inside buildings; equivalent and max quantities calculated using the same transfer functions.
- 1/3 octave mitigation measure insertion losses (situation dependent) applied to get descriptors after mitigation
- **six reference situations considered:** two reference trains (passenger and freight), one reference track and 3 reference soils
- 1/3 octave ground vibration reference spectra at 8m calculated by ISVR source/ground model for reference situations
- real measured train time signals used, but first filtered in order to fit the reference spectra

End of part 1
Thank you for your attention

Part 2 tomorrow

Vibration and ground borne noise exposure in buildings and associated annoyance
Part 2

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Vibration and ground borne noise exposure in buildings and associated annoyance part 2

Exposure descriptors and limits

Method:

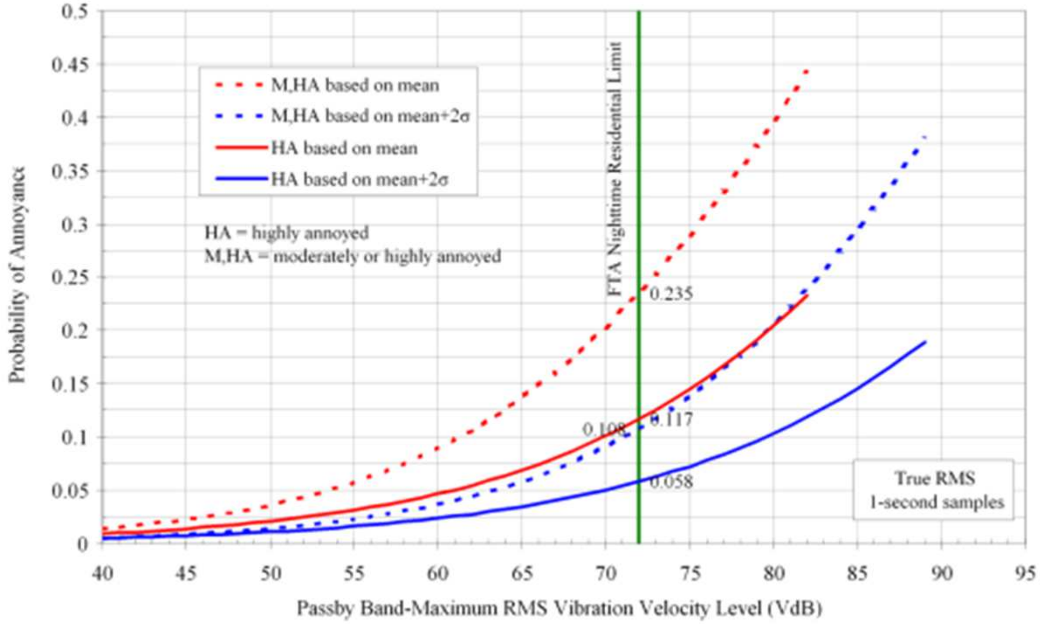
- existing descriptors identified in RIVAS review (deliverable D1.4)
- two types of descriptors equally meaningful: **maximum values** (of running rms quantities) more related to **disturbance** and traffic oriented **equivalent values** (rms or DVD) more related to **annoyance**
- so **four descriptor types have been used**: two for vibration and two for ground borne noise
- descriptors chosen: existing descriptors which have been associated with exposure-annoyance relationships determined from large scale surveys.
- limits deduced from exposure-annoyance relationships

Vibration and ground borne noise exposure in buildings and associated annoyance part 2

Vibration descriptor for maximum values

Use of US exposure-annoyance curves (*) :

- Expressed in unweighted max (Slow) velocity levels
- very close to ISO 2631-2:2003 Wm-weighting
- national limit close to 5% of HA people
- max in a statistical sense (95% confidence, mean+1.8σ) over several train passages



(*) Zapfe *et all*, Transit Cooperative Research Program (TCRP) D-12, Final report (2009).

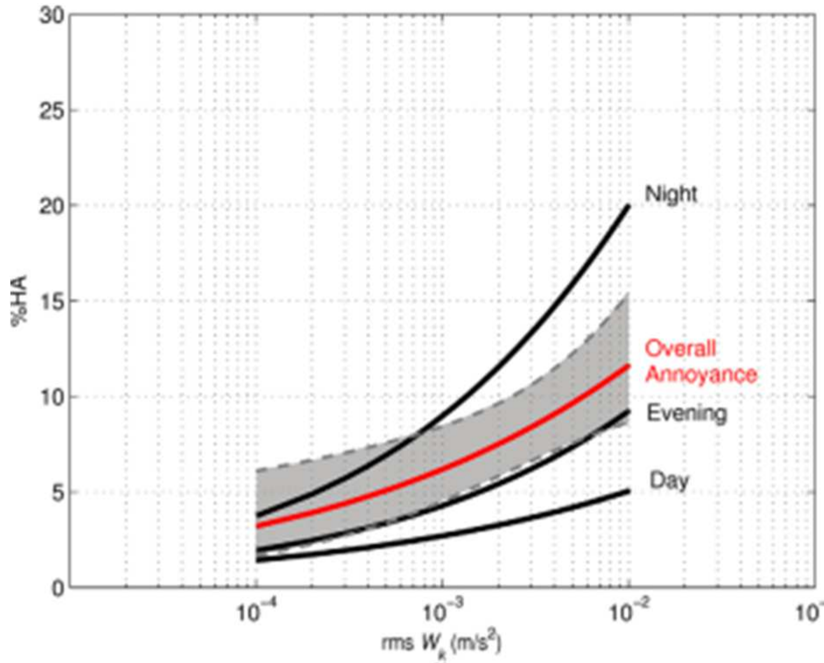
Vibration exposure-response relationships (US) for max values

Vibration and ground borne noise exposure in buildings and associated annoyance part 2

Vibration descriptor for equivalent values

Use of (recent) UK exposure-annoyance curves (*) :

- expressed in ISO 2631-1:1997 Wk-weighted equivalent acceleration
- Wk-weighting a few dB smaller than Wm-weighting
- single 24h descriptor (overall annoyance)
- proposal for combining exposures during day, evening and night with proper weighting: factor of 6.7 for evening and 50 for night



Vibration exposure-response relationships (UK) for equivalent values

(*) 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

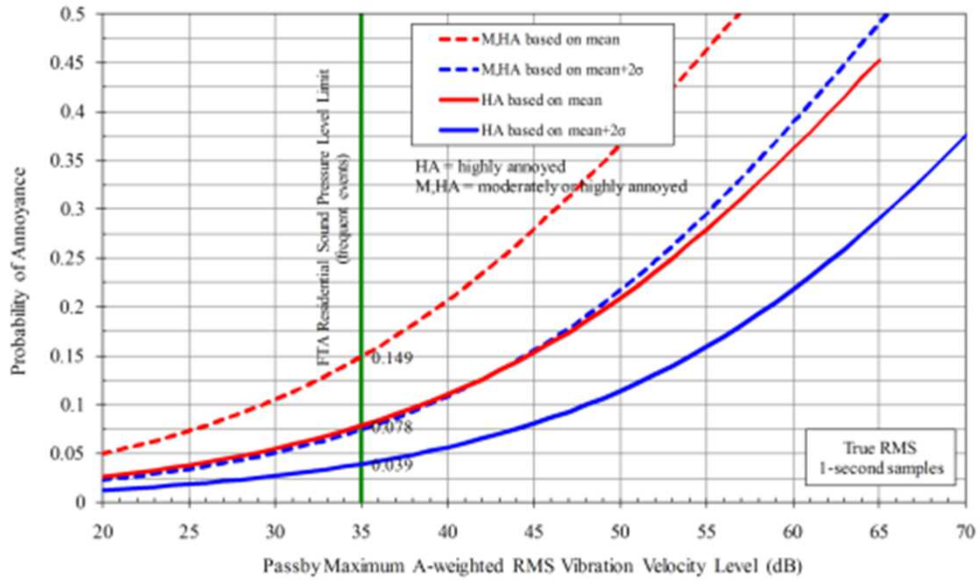
Vibration and ground borne noise exposure in buildings and associated annoyance part 2

Ground borne noise descriptor for max values

Use of US exposure-annoyance curves (*) :

- expressed in A-weighted max (Slow) sound level
- national limit close to 5% of HA people
- max in a statistical sense (95% confidence, mean+1.8σ) over several train passages

(*) Zapfe *et all*, Transit Cooperative Research Program (TCRP) D-12, Final report (2009).



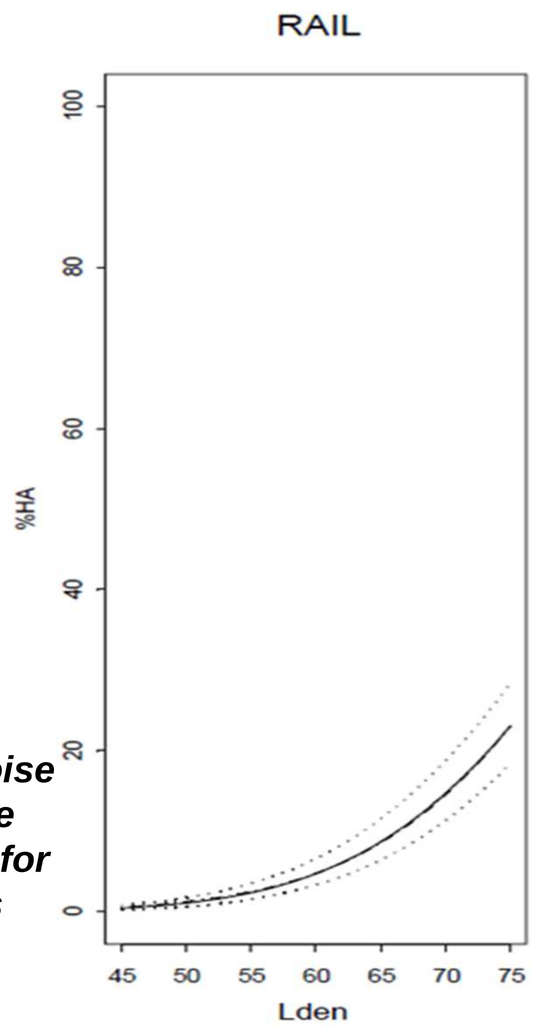
Ground borne noise exposure-response relationships (US) for max values

Vibration and ground borne noise exposure in buildings and associated annoyance part 2

Ground borne noise descriptor for equivalent values

Use of EEA exposure-annoyance curves (*) :

- expressed as <u>outdoor airborne sound</u>
- single 24h A-weighted equivalent sound level combining exposures during day, evening and night (well known den weighting)
- Indoor sound levels deduced from a mean 30dB façade insulation and assuming human responses to transmitted airborne noise and ground borne noise not too different
- national limits close to 5% of HA people



Outdoor airborne noise exposure-response relationships (EEA) for equivalent values

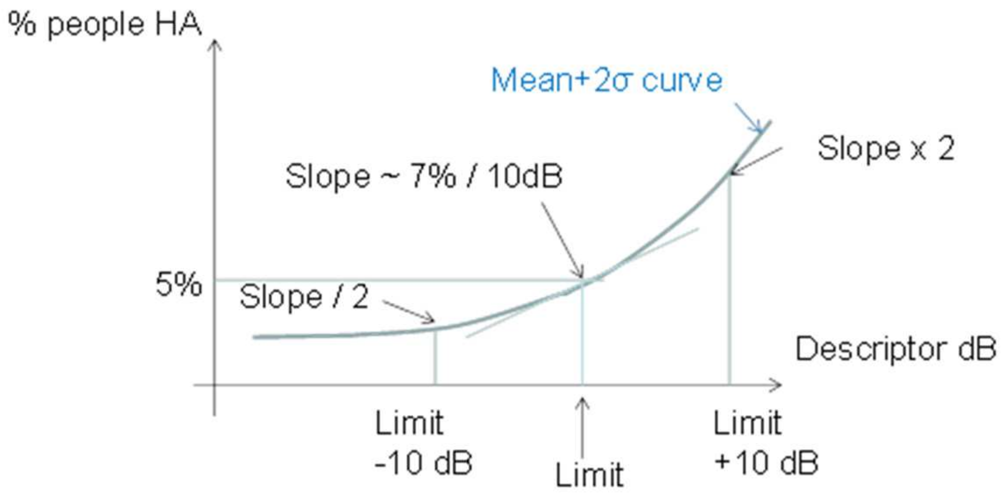
(*) European Environment Agency, Technical report N° 11/2010, "Good practice guide on noise exposure and potential health effects"

Vibration and ground borne noise exposure in buildings and associated annoyance part 2

Descriptors and limits: RIVAS choice (1)

Method (harmonizing)

- All exposure-annoyance curves have similar slopes → use of same idealized curve for all descriptors
- all train curves used (detailed results for passenger and freight trains not available for all descriptors)
- same Wm-weighting used for vibration descriptors
- need for limits



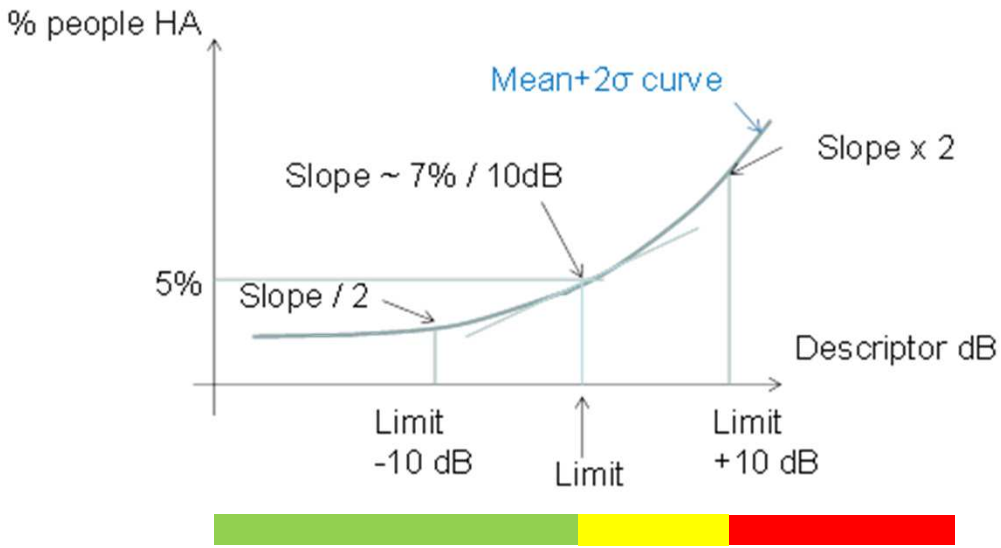
Idealized exposure-response relationships used in RIVAS

Vibration and ground borne noise exposure in buildings and associated annoyance part 2

Descriptors and limits: RIVAS choice (2)

Limits

- Chosen from existing exposure-response curves (~5% HA people)
- rather severe limits according to national standards)
- less severe limits 10 dB higher (factor of 3) also used, corresponding to ~10% of HA people → yellow zone
- severe limits → green zone



Idealized exposure-response relationships and zones

Descriptors and limits; RIVAS choice (3)

Descriptors and Limits

- both acceleration and velocity used; Wm-weighted acceleration and velocity (*) related: $a_w = 35.7\ v_w$
- - vibration velocity also expressed in log scale (consistent with sound levels)

Descriptors	Limits (green zone)		Limits (yellow zone)	
	velocity	acceleration	velocity	acceleration
Max (slow, W_m) vibration $Lv_{w,Smax}$ ref. 5 10^{-8} m/s →	0.10 mm/s 66 dB	3.6 mm/s^2	0.30 mm/s 76 dB	10.8 mm/s^2
Eq. (24h, W_m) vibration $Lv_{w,den}$ ref. 5 10^{-8} m/s →	0.028 mm/s 55 dB	1.0 mm/s^2	0.084 mm/s 65 dB	3.0 mm/s^2
Max (slow, A) GBN	38 dB(A)		48 dB(A)	
Eq. (24h, den, A) GBN	32 dB(A)		42 dB(A)	

RIVAS descriptors and limits
(still under discussion)

(*) Wm-weighting for velocity consistent with Wm-weighting for acceleration; see NS 8176)

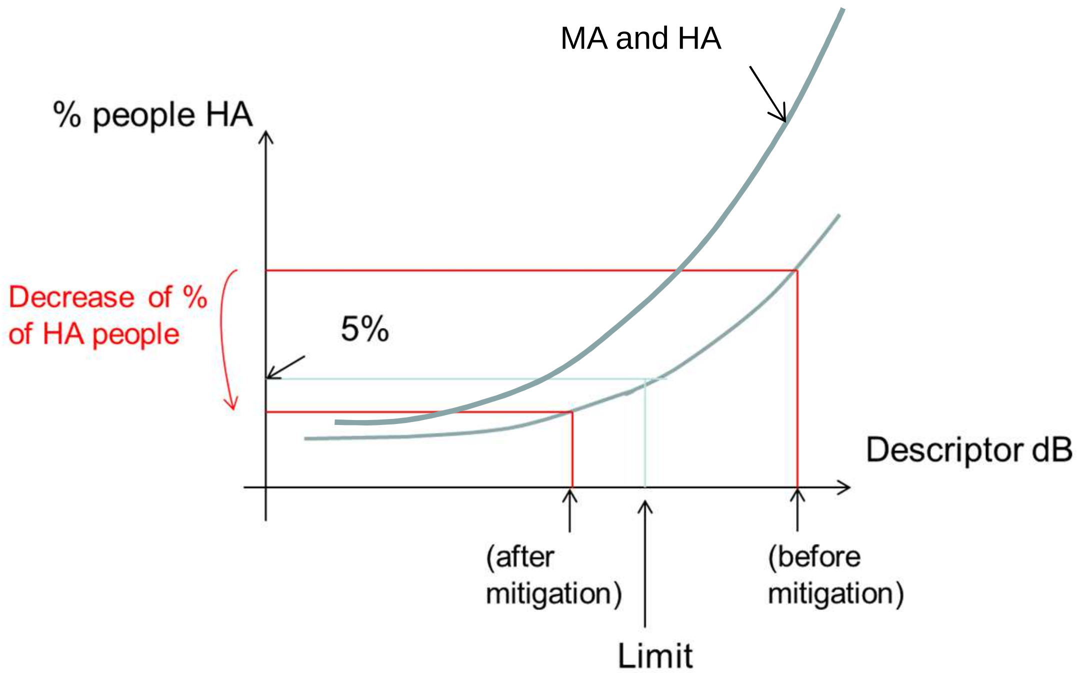
Vibration and ground borne noise exposure in buildings and associated annoyance part 2

Cost-benefit calculation

Method

For each descriptor:

- descriptor values calculated per building before and after mitigation
- decrease of % of HA people deduced from corresponding exposure-response curve
- **decrease of number of HA people** calculated per building (from number of inhabitants)
- decrease of number of MA+HA people higher and maybe more convincing



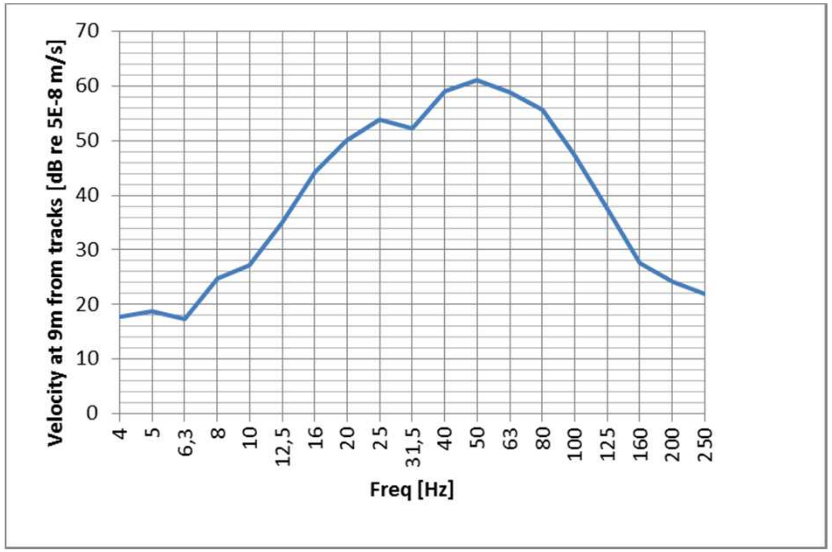
Idealized exposure-response relationship used in RIVAS

Vibration and ground borne noise exposure in buildings and associated annoyance part 2

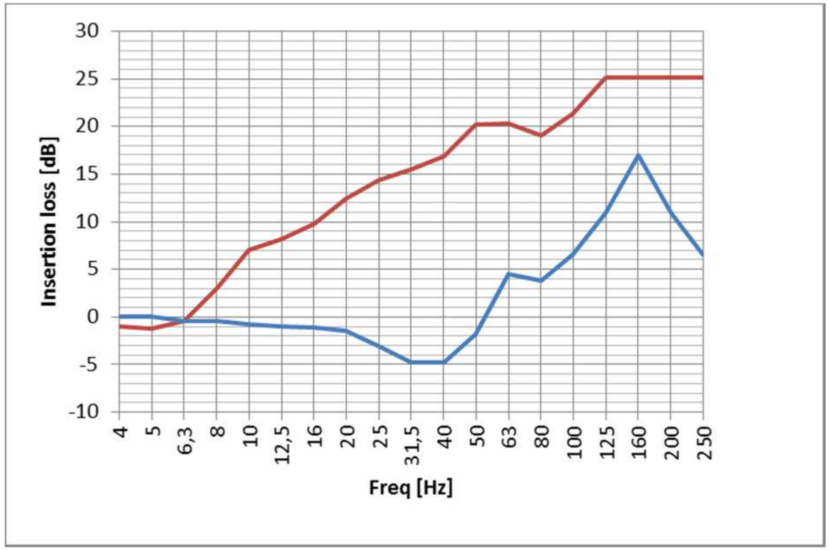
Examples (1)

Configuration studied:

- small heavy building with heavy floors and basement (B1) on homogeneous ground (G1) at 12m from tracks
- passenger train (56km/h) on similar ground (cs~200m/s) and "standard" ballasted tracks
- Ex: (i) under sleeper pad (50MN/m); (ii) 12m deep (ideal) open trench at 5.6m from tracks



Ground velocity spectrum (9m)



Insertion losses: USP (blue), open trench (red)

Vibration and ground borne noise exposure in buildings and associated annoyance part 2

Examples (2)

Results for descriptors

- using RIVAS descriptors, **limits and zones** (green, yellow and red)
- with assumption of 50 train passages (10s) per 24h (day: 25, evening: 15, night: 10)

Descriptors	No mitigation measure		With under sleeper pad		With open trench	
	Velocity	Acceleration	Velocity	Acceleration	Velocity	Acceleration
Max (slow, Wm) vibration	0.12 mm/s	4.36 mm/s²	0.17 mm/s	6.19 mm/s²	0.02 mm/s	0.66 mm/s²
$L_{Vw,S,max}$ ref. 5.10^{-8} m/s	67.5 dB		70.5 dB		51.0 dB	
Eq. (24h, Wm) vibration	0.011 mm/s	0.388 mm/s²	0.016 mm/s	0.569 mm/s²	0.002 mm/s	0.066 mm/s²
L_{Vw} ref. 5.10^{-8} m/s	47.0 dB		50.3 dB		31.6 dB	
Eq. (24h, den, Wm) vibration	0.22 mm/s	7.77 mm/s²	0.32 mm/s	11.38 mm/s²	0.04 mm/s	1.33 mm/s²
$L_{Vw,den}$ ref. 5.10^{-8} m/s	72.7 dB		76.0 dB		57.4 dB	
Max (slow, A) GBN	45.4 dB(A)		44.3 dB(A)		25.6 dB(A)	
Eq. (24h, den, Wm) GBN	27.6 dB(A)		27.0 dB(A)		8.1 dB(A)	

Vibration and ground borne noise exposure in buildings and associated annoyance part 2

Examples (3)

Results in terms of benefit (decrease of number of people MA+HA) (*)

- results for 120 people exposed: 8 (same) buildings at same distance from tracks, with 15 inhabitants each

	Under Sleeper Pad		**Open Trench**	
	Decrease, descriptor (in dB)	Decrease, number of people	Decrease, descriptor (in dB)	Decrease, number of people
Max values vibration	+3	+6 (+5%)	-16	-11 (-9%)
Equivalent values vibration (den)	+3	+3 (+3%)	-15	-14 (-12%)
Max values ground borne noise	-1	-1 (-1%)	-20	-14 (-12%)
Equivalent values ground borne noise	--	--	-19	-12 (-10%)

(*) rough first estimation from exposure-response curves

Vibration and ground borne noise exposure in buildings and associated annoyance part 2

Conclusion

- **Calculation tool ready for evaluating mitigation measures in terms of decrease of exposure inside buildings and associated decrease of annoyance / disturbance**
- **still decisions to make (within RIVAS) about limits, reference building distances to tracks and reference traffic**
- **Results published at the end of the year (Deliverable D1.9)**

End of part 2
Thank you for your attention