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Railway-induced ground-borne noise in buildings: case-study of the CEVA line in Geneva (CH)

BOZZOLO Dario[1], BARBARO Vincenza[1], CORDIER David[1]

[1]IFEC ingegneria SA
dario.bozzolo@ifec.ch; vincenza.barbaro@ifec.ch; david.cordier@ifec.ch

Abstract
With more than 5'000 km of railway network, Switzerland has one of the largest densities of rail lines in the world. At the same time, it is estimated that about 30'000 people are affected by vibrations and ground-borne noise due to the train traffic throughout the country.
The project for the new CEVA-line between Geneva (CH) and Annemasse (F), inaugurated in December 2019, had to face huge concerns about potential disturbances and annoyance due to vibrations and ground-borne noise. In fact, the 14 km Swiss stretch is almost completely underground and passes under densely inhabited areas.
This paper will address the main steps followed during the project to assess the risk of annoyance due to ground-borne noise, from the theoretical prediction to the measurements in the field to get the necessary data for designing the required protection measures. The results of the control measurements carried out after the opening of the line (spoiler: the protections are effective!) are also presented in detail.

Keywords: railway, ground-borne noise, measurements, tunnel.

1 Context

1.1 Legal context

In the Swiss legislation, the Environmental Protection Act sets the background principles governing the field of protection against noise and vibrations since 1985. It specifies the limitation of emissions at the source and states furthermore: "*Ambient limit values for noise and vibrations must be set so that, in the light of current scientific knowledge and experience, ambient noise below these levels will not seriously disturb the well-being of the population.*" (art. 15) [1].
While an ordinance on airborne noise protection has been in force since 1986 [2], no ordinance on vibration and structure/ground-borne noise has been drafted to this day. In the railway sector, this lack of legislation is partially compensated by the directive "Guideline for the assessment of vibration and ground-borne noise of rail transport installations" [3]. This directive has been published in 1999 as a transitory solution and still defines the guideline values currently in force.
As shown on Figure 1, the directive provides two sets of guideline values: planning values, for new railway installations, and immission values, for existing ones. Both sets are distinguished according to the type of constructive zone (residential areas vs mixed areas) and the time period (day: 06-22, night: 22-06). The guideline values are expressed as $L_{Aeq,\ 16h}$ (the equivalent continuous A-weighted sound level over 16 hours) for day period or $L_{Aeq,1h}$ (the equivalent continuous A-weighted sound level over the hour with the highest night traffic) for night period.

Valeurs indicatives d'immissions L_{eq} du niveau sonore à l'intérieur du local en dB(A)		
	Jour L_{eq} -16 h	Nuit L_{eq} -1 h
Zones d'habitation, zones d'intérêt public (aires d'école, hôpitaux)	40	30
Zones mixtes, centre-ville, zones de village, zones agricoles, zones d'habitation déjà exposées	45	35

Valeurs indicatives de planification L_{eq} 1) du niveau sonore à l'intérieur du local en dB(A)		
	Jour L_{eq} -16 h	Nuit L_{eq} -1 h
Zones d'habitation, zones d'intérêt public (aires d'école, hôpitaux)	35	25
Zones mixtes, centre-ville, zones de village, zones agricoles, zones d'habitation déjà exposées	40	30

Figure 1 – Guideline values for railway-induced ground-borne noise [3]

1.2 Environmental impact assessments of railway projects

Environmental impact assessment is the methodology followed for the evaluation of infrastructure projects. Each relevant environmental aspect of a project is analyzed for both the construction and the operating phase to identify possible criticalities and eventual limitations, restrictions, or protective measures to adopt [4].
On railway projects, vibrations and ground-borne noise can be relevant for both phases, but only the operating phase is addressed in this document.
The general procedure for this environmental domain implies the following steps during the planning phase:

- Theoretical evaluation of the immission values;
- *In-situ* measurements when excessive immission values cannot be excluded to nearby receivers;
- Modelling of the project state with the calibration of the model thanks to the *in-situ* measurements,
- If needed, definition of protective measures to mitigate the impact.

In the following chapter a brief insight into the theoretical bases about railway ground-borne noise is provided, while the elements connected to the measurements are described in relation to the case-study, in chapter 4.

2 Theoretical bases on the determination of railway ground-borne noise

To provide reliable vibration and noise predictions, VIBRA 1-2-3 [5] was developed in Switzerland in collaboration with the Swiss Federal Railway (SBB); it is a simplified method for the prediction of vibrations and structure-borne noise from railways.
VIBRA uses an empirical approach through which it is possible to determine the vibration in the building as a function of 8 variables or throughout the so called “transfer spectra”. For both methods VIBRA relies on a data base from vibration measurements.
As illustrated in Figure 2, VIBRA considers a series of vibration propagation steps, that depends on the characteristics of the railway line, of the ground, and of the building. Commonly, the vibration decreases from stage to stage, except between the foundations and the slab (floor) of the receiving room, where resonance phenomena can lead to an amplification of the immissions.

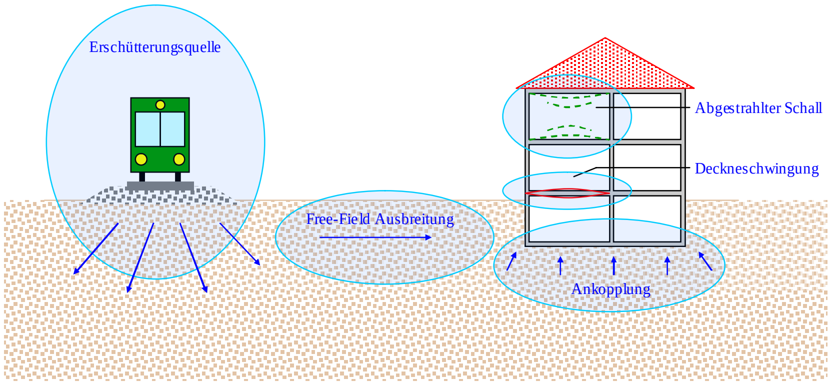


Figure 2 – Propagation of vibrations from the railway line to nearby buildings [5]

2.1 Mathematical bases from the VIBRA method

When it reaches a room, the vibration induces the displacement of the slab and of the walls that exert pressure on the air inside the room, acting as an impulse that generates a compression wave in a rod and resulting in the generation of noise. The following equations [5] can be used to calculate the displacement *u*:

$$u = \frac{\sigma_x}{E} x_n = \frac{\sigma_x}{E} v_c t_n \quad (1)$$

where σ_x is the stress exerted in the x-direction, *E* is the elasticity (Young's modulus) of the material and x_n the length of the compressed zone, which in turn can be calculated from the velocity of the wave in the material v_c and the duration t_n of the impulse.

Equation (1) can be rewritten to determine the particle velocity *v:*

$$v = \frac{u}{t_n} = \frac{\sigma_x v_c}{E} \quad (2)$$

and the Young's modulus can be written as

$$E = \rho v_c^2 \quad (3)$$

where ρ is the material density.
This leads to the following equation for the stress:

$$\sigma_x = v \rho v_c \quad (4)$$

Finally, using standard values for the air density (ρ = 1.2 kg/m^3) and the sound propagation velocity in the air at 20°C (v_c = 343 m/s), it is possible to estimate the generated pressure in the air as follow:

$$p \equiv \sigma_x = F_{KS} * v = 0.4v \quad (5)$$

where F_{KS} is an empirical coefficient and *p* is the air pressure.
This suggests that the pressure exerted on the air (in Pa) is about 40% of the oscillation velocity of the slab (measured in mm/s). From empirical measurements, it was observed that this relationship underestimates the ground-borne noise from 6 to 10 dB, mainly because the equation is in 1-D and because of the contribution

of the walls and of the ceiling in the room that is not considered. Therefore, for the coefficient F_{KS} in equation (5), VIBRA refers to values between 0.8 and 1.2.

2.2 Use of the VIBRA method

Aside from the theoretical considerations, a practical tool has been developed for the use of the method [6]. It consists of a database that allows to estimate the vibration and the ground-borne noise immissions based on simple parameters (distance to the track, type of building etc.) and compares the results with the guideline values. The tool is organised in two parts: the VIBRA-1 part considers emissions as a global resulting value in the calculations, whereas the VIBRA-2 part uses spectra (third of octave values) for estimating a better representation of the propagation behaviour.
Both tools work with multiplicative coefficients that are applied to the different propagation steps from the position of the source (emission) to the receiver in order to estimate the attenuation (or amplification) that the signal undergoes. The values of these coefficients and the emissions of the trains are based on field measurements. Other correction coefficients, e.g. to consider the presence of switches, are also integrated in the VIBRA calculations.
In the context of the environmental impact assessments, the first modelling is done with VIBRA-1 [7]. Because of the usually large uncertainties on the parameters to be used in the model (trains diversity, ground and material properties, propagation paths etc.) and the limited precision of the empirical approach, all buildings whose immission values of ground-borne noise are higher than the guideline value minus 6 dB(A), have to be considered for further investigation. Depending on the railway traffic (velocity, train type and length), the distance from the tracks within which to consider the receivers can typically vary from 10 to 50 m.

3 The CEVA project

The CEVA-line (Cornavin – Eaux-Vives – Annemasse) connects the main station of Geneva to the French city of Annemasse over 16 km, 14 of which are in the Swiss territory, as shown in Figure 3. The railway line comprehends both tunnel sections and cut-and-cover sections (corresponding to the old Eaux-Vives-Annemasse railway). Indeed, a line existed between Annemasse and the Eaux-Vives since the 19th century. Already at that time, proposals to extend the line to the Cornavin station (Geneva main station) had been made but were never carried out. In the early 2000s, a new project was developed and approved by the Federal Office of Transport. The acceptance of the project was confirmed by a popular vote in 2009 and the first works started in 2011, after the Federal Court rejected the pending oppositions to the project.

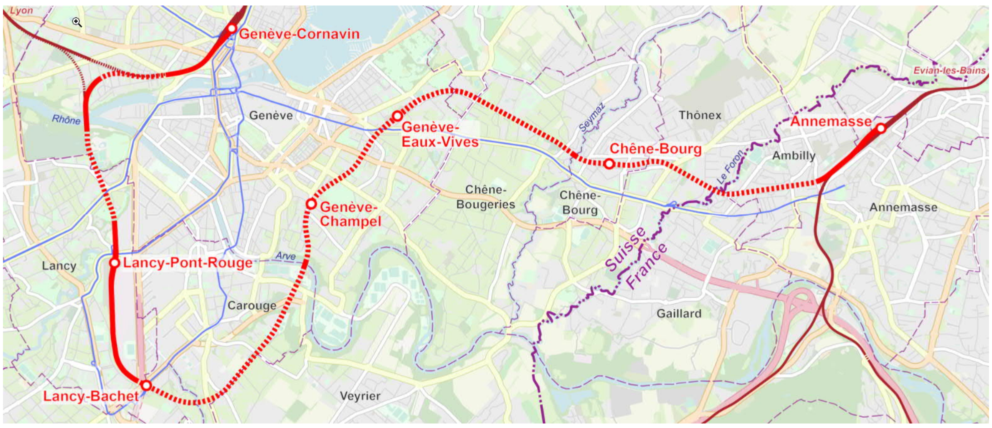


Figure 3 – Map of the CEVA railway line [www.wikipedia.org]

The opening of the line – which is exclusively devoted to passenger trains - took place in December 2019.

4 Railway-induced ground-borne noise by the CEVA project

4.1 Early-stage predictions

The first evaluations on vibrations and ground-borne noise on the CEVA project took place in 2004, up to the publication of the environmental impact assessment in 2006. At that stage of the project, the prognoses relied exclusively on a theoretical approach. The existing line between Eaux-Vives and Annemasse was indeed too different from the new line to provide useful information for refining the predictions by in situ measurements, as stated in Figure 4 with two views of the Chêne-Bourg station.

Figure 4 - Chêne-Bourg station, old line [www.tdg.ch] vs new line [www.wikipedia.org]

Two important limitations in the use of the VIBRA model were identified at that time. As mentioned above, the characterization of a completely new line does not allow to collect information in the planning phase to calibrate the model with measurement data, with consequences on the reliability of the results. Moreover, the model is mainly built for "simple" 1-D cases, as illustrated in Figure 2. Cases as the CEVA project, with an underground vibration source, are characterized by a higher complexity due to transmission through different layers of the subsurface, underground structure-soil interface etc., which affects the uncertainty.
Because of these effects, the definition of protective measures was therefore postponed to a later phase of the project, when field studies could have been conducted, more specifically, by means of VibroScan trials (see chap. 5). The best time for such verifications usually falls between the end of the construction works and the beginning of the railway engineering works as it allows to reduce the unknown related to the underground structures, while limiting the costs of integration of possible protection measures in the project (the protections can be in place before the laying of the tracks).
This approach was supported by the competent Swiss authorities (Federal Office for the Environment, Federal Office of Transport) and was even approved by the Federal Court, which had been consulted because of the oppositions from local residents who feared that the risks connected to possible disturbances were not adequately managed.

4.2 Detailed predictions

The detailed predictions include the measurement campaign and the relative use of the data for the final definition of protective measures.

4.2.1 *In-situ* measurements

The *in-situ* measurements were carried out using the VibroScan method [8]. This technique offers the great advantage by allowing to intervene where the source of vibrations (here the passage of trains) is not yet measurable. The concept consists in producing vibration emissions by means of a vibrations generator mounted on a truck, as shown in Figure 5. The load on the underground structure's slab is calibrated to be similar to that one exerted by the passage of a train and is applied by a "sweep" in the frequency range of 5 to 250 Hz. Measurements at different stages of propagation between the source (tracks) and the receivers (sensitive room in the buildings) enable to characterize the response to the induced vibrations. In the data elaboration phase, this will allow to determine the vibrations and the ground-borne noise immissions of the train (see chap. 4.2.2).

Figure 5 - VibroScan truck on the CEVA-line

The measurement campaign involved more than 100 buildings along the Swiss part of the line and included single-family homes, apartments buildings, schools and office buildings. It took place in several interventions between early 2016 and mid-2018, according to the completion of the different sections of the underground structures. For each measured building, trials were done for 2 to 3 positions of the VibroScan truck in the tunnel/cut-and-cover. These positions were generally located within 50 m from the building along the track axis (horizontal distance). As illustrated in Figure 6, each trial is characterized by four vibrations and one ground-borne noise measurement points that refer to the VIBRA model:

- <u>Emissions measurement</u>
  3 monoaxial sensors (z-direction) were placed next to the VibroScan, as visible in Figure 5. The two most external, at 5.5 m from the VibroScan plate, were used as a reference for the emission (mean value), whereas the central one was used as a control point. The measurement device visible under the truck was used by the VibroScan team for internal controls,
- <u>Open field measurement</u>
  Triaxial sensor placed on a rigid surface outside of the measured building,
- <u>Building foundation measurement</u>
  Triaxial sensor placed near a bearing wall (structural element) of the building,
- <u>Sensitive room measurement (vibration)</u>
  In each building, at least two rooms were measured with a triaxial sensor placed in the middle of each slab,
- <u>Sensitive room measurement (ground-borne noise)</u>
  In one of the rooms where vibrations measurements took place, a phonometer (class I, according to the Swiss Metrology Office standards) was installed in the center of the room at 1.5 m from the ground.

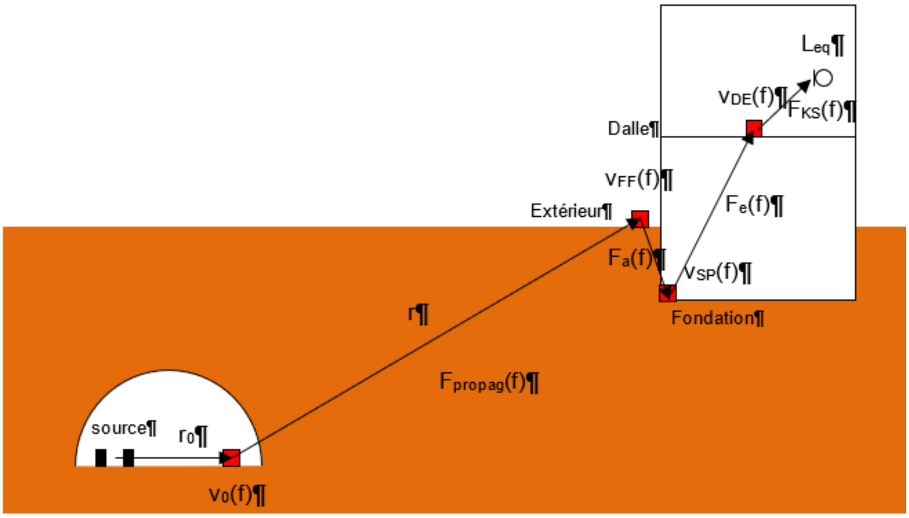


Figure 6 - Schematic representation of the measurement setup

During the measurement campaign, one VibroScan position could be measured in parallel in up to 3 buildings. This means that more than 15 measurement devices were acting simultaneously. To guarantee correct measurements, a perfect synchronization of the monitoring network is essential. In order to achieve this result, the recordings were set with timed recording at 2-minute intervals (every even minute) so that a 30 second window for measurements was opened every 2 minutes. For ground-borne noise, the measurements were continuous and the sweep data have been extracted during the processing phase on the basis of the temporal correspondence with the vibration measurements. The sweeps produced by the VibroScan last about 20 seconds and cover the entire frequency spectrum in three series of emissions: low frequencies: 5 - 75 Hz, medium frequencies: 74 - 143 Hz, high frequencies: 140 - 217 Hz. Each frequency range was repeated 3 times, so that a position was characterized by 9 sweeps.
Urban ground-borne noise surveys are particularly difficult to be carried out because of the extreme sensitivity to external disturbances (traffic, etc.); in this case, repeated sweeps can ensure representative results.

4.2.2 Establishment of the prognosis

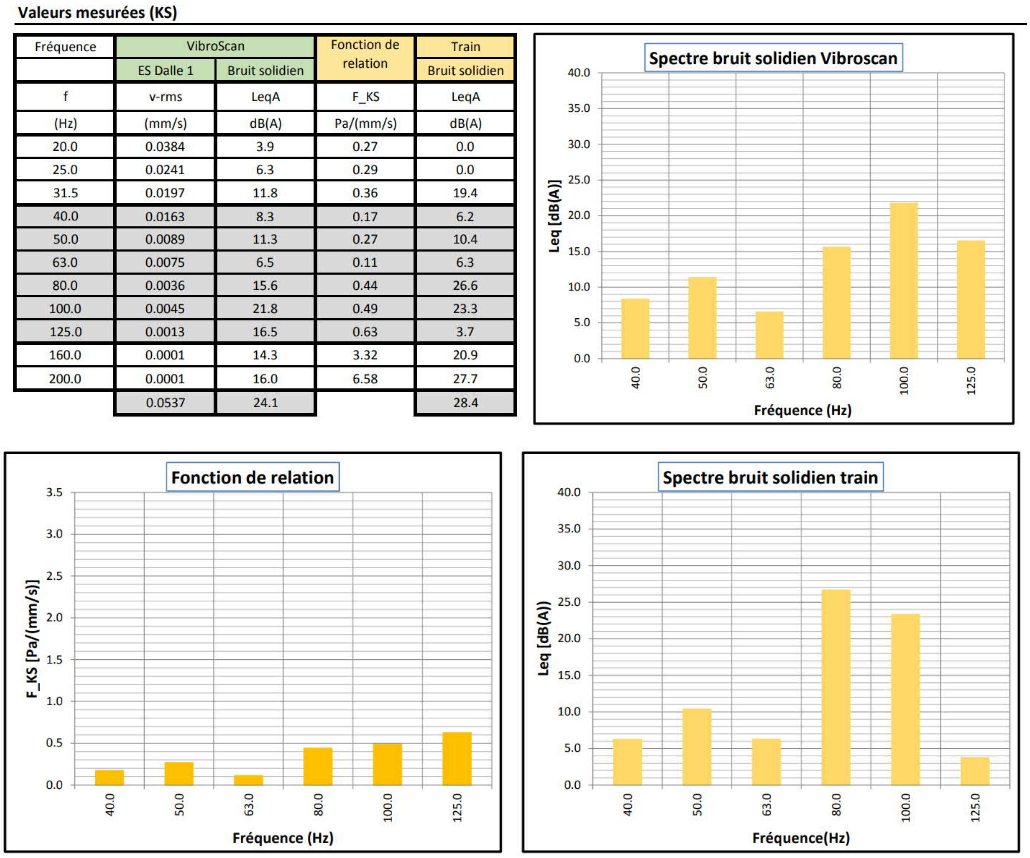
Once the data are gathered in the field, it is possible to evaluate the potential immissions at the receivers and to assess the necessity for protective measures.
To do this, a transfer function is calculated for each stage of the propagation as the ratio between the vibrations measured after and before each stage. These transfer functions are described by a set of coefficients corresponding to the ratios obtained for each third of octave of the spectrum. The effect of the attenuation due to the distance (*r* in Figure 6) is considered in the transfer function underground - free field. These coefficients correspond to the parameters used in the VIBRA-2 model in the calculations to determine the immissions.
With regard to the ground-borne noise, the relationship between the vibration velocity in the material and the pressure variation *p* of the air is described by the coefficient F_{KS} from equation (5) in chapter 2.1. The measurements allow to determine experimentally also this coefficient for each relevant third of octave value.
The A-weighted sound pressure level L_{Aeq} in dB(A) is calculated by

$$L_{Aeq} = 20 * log\left(\frac{p}{p_{ref}}\right) - A \qquad (6)$$

where p_{ref} is the reference pressure (20 µPa) and *A* the decibel A weighting (for each third of octave).
Using equation (5) in (6), it is possible to relate the ground-borne noise level to the measured vibration in the room.

$$L_{Aeq} = 20 * log\left(\frac{F_{KS}v}{p_{ref}}\right) - A \tag{7}$$

where F_{KS} is the coefficient of the transfer function and v the velocity of vibration of the slab for each third of octave. Referring to ground-borne noise, VIBRA considers spectra in the range 40-125 Hz as default.
The collected data allow to entirely characterize the propagation path of the vibrations from the source to the receivers. To determine the immissions due to the passage of the trains underground, the measured source of emissions (VibroScan) is replaced in the calculation by the theoretical emissions of the trains that circulate on the CEVA line (passenger trains). Here, the following assumption is made: the transmission of vibrations in the ground and in buildings is identical for both the emission sources (VibroScan and trains). Under this assumption the determined coefficients of the transfer function can be used to calculate the expected immissions at every propagation step and finally to calculate the ground-borne noise immissions as illustrated in Figure 7.



Valeurs mesurées (KS)

Fréquence	VibroScan		Fonction de relation	Train
	ES Dalle 1	Bruit solidien		Bruit solidien
f	v-rms	LeqA	F_KS	LeqA
(Hz)	(mm/s)	dB(A)	Pa/(mm/s)	dB(A)
20.0	0.0384	3.9	0.27	0.0
25.0	0.0241	6.3	0.29	0.0
31.5	0.0197	11.8	0.36	19.4
40.0	0.0163	8.3	0.17	6.2
50.0	0.0089	11.3	0.27	10.4
63.0	0.0075	6.5	0.11	6.3
80.0	0.0036	15.6	0.44	26.6
100.0	0.0045	21.8	0.49	23.3
125.0	0.0013	16.5	0.63	3.7
160.0	0.0001	14.3	3.32	20.9
200.0	0.0001	16.0	6.58	27.7
	0.0537	24.1		28.4

Figure 7 - Example of the calculation of ground-borne noise immissions (KS) starting from measured values. The green columns refer to measured data and allow to calculate the F_{KS} coefficient. From F_{KS} coefficient and train emissions data (not shown here) it is possible to determine train ground-borne noise immissions.

As an emission source, data from measurements in the Concise tunnel were selected [9], which are close to the conditions present on the CEVA line. Since, however, a certain degree of uncertainty remained (e.g., on the response of different types of underground structures) safety margins were considered in the analysis.
Moreover, the Canton of Geneva has financed a "Comfort" scenario with limitations on the ground-borne noise level for the single train passage ($L_{Aeq, train}$ = 30 dB(A)) to ensure an even higher level of protection in respect to the legal standard. This scenario is more restrictive than the guideline values (that are based on the equivalent level for the evaluation periods day/night) and was therefore used to define the final grade of protection.

Finally, the calculated immissions for vibrations and ground-borne noise were used to determine the need of protective measures. Two types of measures have been implemented:

- Low vibration track (high attenuation), LVT/ LVT-HA,
- Mass-spring system.

For each building, the worst case from the measurements (among the various VibroScan positions measured) was chosen as a reference to ensure the maximum safety in the choice of the protective measure. The whole line was in the end protected with one of the two measures.

4.3 Control measurements

In order to document the actual vibration and ground-borne noise immissions, a measurement campaign has been planned after the line opened in December 2019. All buildings investigated with the VibroScan trials with some additional ones (for a total of almost 120 buildings) were planned for the campaign. Due to the sanitary situation, only 50 measurements could take place yet[1].
These measurements were based on the VibroScan measurement setup, with instruments installed in the tunnel, in the free field and in the buildings. A two-hour measurement in each building was conducted, since this duration makes it possible to measure a representative number of train passages (15-20 trains). To further increase the representativeness, some buildings were subject to extended measurements (12 h) that allowed to verify that there were no significant differences between the various train models (all trains are passenger convoys) or between the different periods of the day. These verifications have confirmed that the emissions are very similar throughout the day and that a 2-hour control measurement is sufficient to get a representative understanding of the situation.
The investigations have shown that in the sections where a mass-spring system was implemented, there is no immission by the receiver (vibrations < 0.1 mm/s and ground-borne noise < background noise level). During the measurements, the background noise level in the rooms where the instruments were placed was typically between 17 and 24 dB(A). On the sections with LVT or LVT-HA protections, ground-borne noise immissions was measured in some cases, with levels up to 28 dB(A) during the transit of the train. Figure 8 shows an example of a measurement with the background noise at approx. 17 dB(A) and the passing train.

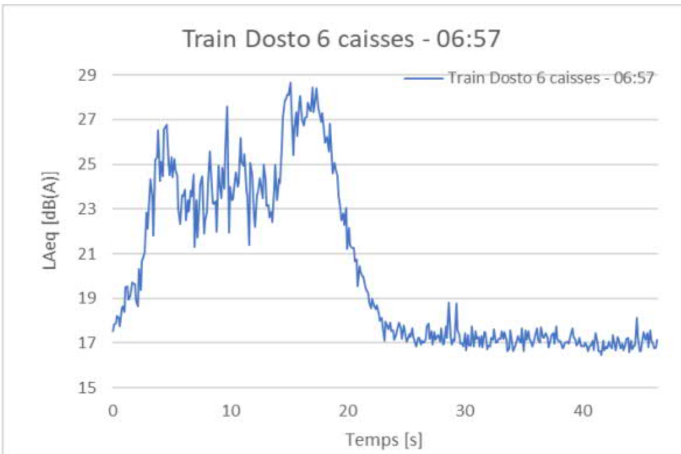


Figure 8 - Example of measured ground-borne noise on a section with LVT-HA

Such immissions are noticeable by people in the buildings but fully met the target value of 30 dB(A) for the equivalent level of the train pass-by set by the “Comfort” scenario of the Canton Geneva.

[1] At the time of writing, the second part of the measurements is scheduled for September 2021

5 Conclusions

The Swiss standard methodology for the assessment of vibration and structure-borne noise in railway projects requires a modeling with the VIBRA tool, together with calibration measurements in the field. In complex cases, such as the new CEVA line in Geneva, the standard procedure does not guarantee sufficient reliability in the immission prognosis, therefore the need of using VibroScan tests to reduce uncertainties represents an interesting alternative. The main negative point is that the data needed to define the protection measures are only available in an advanced phase of the project (in the construction phase). A high degree of flexibility is therefore necessary, both for the collection of data and for the implementation of the protections.
With more than 100 measured buildings, the evaluations carried out on the CEVA project probably represent the largest vibration and ground-borne noise measurement campaign in Switzerland. The control measurements, equally extensive, have confirmed that the implemented protective measures allow the target values to be respected for all the buildings along the line.

Acknowledgements

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