In situ measurements of combined effect of railway noise and vibration on annoyance assessed with physiological responses

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Abstract

Noise and vibrations from train pass by may create disturbance and annoyance in residential area. The project VibAcouPhysio aims to explore the potential of physiological measurements to objectify perceived annoyance. In the first step, the VibAcouPhysio project investigated annoyance caused by railway noise and vibration under laboratory conditions. A significant correlation was found between physiological metrics; annoyance evaluated through questionnaires, and indoor noise and vibration descriptors derived from the noise and vibration signals. In this regard, noise includes both aspects: air-borne noise (transmitted through the façade) and structure-borne noise (radiated by the building structure subjected to vibration). The second phase of the project proposes a similar analysis based on in-situ measurements on a few voluntary participants living along railway lines. These measurements include continuous monitoring of physiological, noise and vibration signals, as well as perception surveys several times a day. The participants and their residences have been monitored for a week, day and night, allowing to also address the issue of sleep disturbance. The paper describes the measurements performed in-situ and proposes a preliminary analysis of the collected data.

Keywords: *railway noise, vibration, annoyance, physiological measurements*

1. Introduction

The VibAcouPhysio project aims to improve the consideration of acoustic and vibrational discomfort that may be experienced during exposure to railway traffic. This work follows up with questions raised during expert studies initiated by the LOM law [1].

When talking about annoyance due to noise and vibrations, it is important to have a notion of the subjective perception of this annoyance to understand how to address this problem. This is why the perceived annoyance due to noise and vibrations has been studied in general, since 1970 [2] and more specifically applied to railway traffic [3]. However, the complexity of this work leads to a great diversity of methods including laboratory studies in a controlled space [3] or in-situ studies [4]. These studies underline a correlation between the perceived annoyance and the noise and vibration exposure. However, it also shows the complexity to have objective results.

To address this issue, the project VibAcouPhysio proposes to use physiological parameters to complete evaluation of the perceived annoyance for railway noise and vibration. This project studies the correlation between exposure data (noise and vibration signals), perception data (questionnaire) and physiological data (physiologic reaction). First tasks were conducted with in laboratory measurements [5] and showed significant relationship between these datasets.

The second phase of the project aims to conduct similar study in an in-situ campaign to reflect the real conditions of residents. In this phase, the three datasets are studied with different indicators of noise and vibrations, physiological indicators and perceived annoyance.

This paper provides a brief description of the tests conducted as well as the data obtained. Next, the indicators related to exposure data and physiological data are presented. Finally, the last section presents the analysis of correlation between these two sets of data. This paper does not include analyses related to perceptual data.

2. Data collection

A multi-physics instrumentation system is designed to collect data on exposure, physiological reactions and perception of residents. The system is composed of:

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- Acoustic and vibration monitoring station positioned outside, as close as possible to the source (see section 2.2).
- Connected watches (heart rate) and several skin sweat sensors (see Section 2.3).
- BoxConfort [6] which submits questionnaires to the participant (see section 2.3).

The BoxConfort is a standalone device integrating a touchscreen. It allows the collection, recording, and remote transmission of data measured via a connected watch. The BoxConfort also offers the questionnaires at fixed times. The participant can easily respond via the touchscreen.
Data is collected in two stages. The first stage involves characterizing the site (transfer functions) and monitoring the residents to gather the necessary information for data processing. Then, the site is monitored with the multi-physics instrumentation system for a week. This organization allows obtaining data with a minimally intrusive measurement setup, and is illustrated in Figure 1.

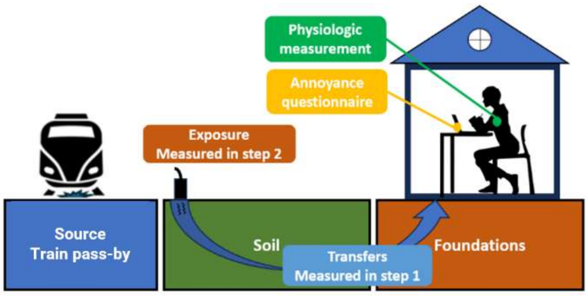

Figure 1. Campaign measurement schema.

2.1 Overall campaign presentation

The measurements were conducted at 5 distinct sites, including 10 dwellings (2 small buildings, 8 houses) and 17 participants. Participants were selected based on the exposure of the dwellings and were rewarded with financial compensation. At each site, the measurements recorded exposure signals for all train passages over the course of one week. During this period, the physiological reactions of the participants were continuously recorded. Daily questionnaires were offered via the BoxConfort. A summary of the measured data is presented in Table 1.

2.2 Site Characterization (step 1)

The preliminary testing stage involved characterizing the vibrational and acoustic transfer functions between the monitoring station, close to the railway, and the interior of the dwelling. In all the sites, the exposure in two rooms is studied: the living room and the participant's bedroom. Different transfer functions were measured:

- Vertical velocity from monitoring station to rooms during train passages,
- Acoustic pressure from monitoring station to facade and rooms during train passages,
- Acoustic pressure from facade to rooms using a white noise sound source (loudspeaker).

Table 1. Summary of measurements: Site, dwelling (Place) and participant (Subject), number of train passages recorded, questionnaire participation rate (Rate), and housing exposure (Exp., = moderate, + high, ++ very high).

Site	Place	Subject	Pass-by	Rate(%)	Exp.
C1	P1	S1	373 (362/11)	60	+
	P2	S2		62	+
C2	P3	S3, S4	857 (792/65)	74 / 85	+
	P4	S5, S6		76 / 65	+
C3	P5	S7	624 (561/63)	66	++
	P6	S8		69	++
	P7	S9		72	+
C4	P8	S10	873 (808/65)	31	=
	P9	S11, S12		77 / 71	+
	P10	S13, S14		74 / 56	=
C5	P11	S15, S16, S17	363 (333/30)	75 / 53 / 56	++

These measurements aim to characterize the air-borne noise transmitted into the rooms during a train passage and therefore enabling the estimation of the ground borne noise. Once transmitted noise is decomposed, transfer functions can be estimated between external noise and transmitted air-borne noise, external vibrations and transmitted vibrations and finally transmitted vibrations and transmitted ground borne noise.

Figure 2. Photos of the test setup for the acoustic and vibrational characterization of the site, a) Instrumentation of a participant's room, b) Microphone on the facade and noise source used for air-borne transfers; c) measurement station at the property boundary, closest to the source (railway network).

2.3 Residents monitoring/screening

During the first stage, the participant is equipped with physiological sensors: skin swat sensors and connected watch presented in Figure. 3. A presentation of the BoxConfort is carried out.

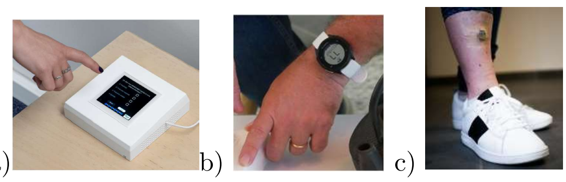

Figure 3. Photos of the test setup for measuring the participant's physiological and perceptive reactions, a) BoxConfort b) connected watch c) Skin temperature sensors.

During this step, an interview of the participant is carried out in which they are asked questions about factors that help characterize their housing, their overall exposure to noise and vibrations caused by passing trains, and their sensitivity to noise. The collection of sensitivity responses is performed through a questionnaire modelled on the questionnaire NoiseQ [7].

2.4 Continuous measurements (step 2)

During the second stage, data are collected over one week. Data can be classified into three groups.
Physiological data:

- Heart rate, captured by the watch with a time step of 1 second. Data are stored when the watch is connected to the BoxConfort, a setup that also allows identification of the participant's presence periods in their dwelling;
- Skin temperature, measured with a time step of 5 minutes and stored in the sensor.

Perceptive data, collected through several questionnaires:

- Five daily questionnaires including questions on sleep quality during the previous night, questions on the perception of the passing period and questions on the perception of the entire day;
- Ad hoc questionnaire, initiated by the participant, to report an annoying event.

Exposure data:

- Ground vibration near source in three directions (tri-axial), i.e. perpendicular to the track (Per), parallel to the track (Par) and vertical (Ver);
- Acoustic pressure near source;
- Video of the railway track during passage.

It must be noted that data of the acoustic and vibrational exposure are recorded based on a trigger set on vertical acceleration. These data can be synthesized for each passage, as illustrated in Figure 4.

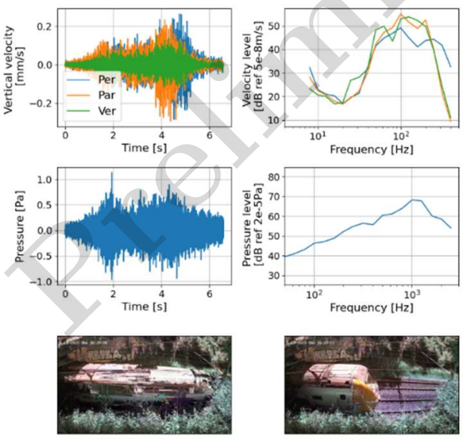

Figure 4. Outdoor exposure for one train pass-by in site 2.

3. Data processing

In this study, the statistical analysis is based on each event of a pass-by postprocessed for each dwelling, room and subject. A database has been constructed containing all the pass-by events. Each event is associated with acoustic and vibration, physiological and perception indicators in addition to a subject, the localization and the time of this event.

3.1 Acoustic and vibration indicators

The selected acoustic indicators are based on standards and practices currently in force in the European Union. These indicators are summarized in Table. 2.
These indicators apply to all acoustic signals, global noise, air-borne noise, and structure-borne noise (also denoted ground-borne noise). Indicators are computed on all train pass-by (Tp) as equivalent or maximum level (integration time Fast or Slow). Thus, 39 indicators are computed for each pass-by and each dwelling, including variation between the two characterized rooms, the three noise types (global, air-borne and ground-borne noises), and the different weightings.

Table 2. Acoustic indicators, presented with notations (Not.), weighting used (Pond.), integration time (Ti), indicator type (Type), and origin.

Not	Pond	Ti [s]	Type	Origin
$L_{p,F,max}$	A,C,Z	0.125 (Fast)	Max	[8,9]
$L_{p,S,max}$	A,C,Z	1 (Slow)	Max	[9,10]
SEL	A	-	Equ.	[11,12,13]
$L_{p,eqTp}$	A,C,Z	-	Equ.	[9]
$L_{p,S,eqTp}$	A,C,Z	1 (Slow)	Equ.	[12,13]

The vibration indicators listed in the Table 3 are commonly used in the EU and defined in scientific or normative literature. Some indicators are natural extensions of standardized indicators.

Table 3. Vibration indicators, presented with notations (Not.), weighting (Pond.), integration time (Ti), indicator type (Type: velocity or acceleration / maximum or equivalent), and origin.

Not	Pond	Ti [s]	Type	Origin
$L_{v,eqTp}$	W_m	-	Vel.Equ.	[14]
$L_{v,S,eqTp}$	W_m	1 (Slow)	Vel.Equ.	[15]
$L_{v,F,max}$	W_m	0.125 (Fast)	Vel.Max.	-
$L_{v,S,max}$	W_m	1 (Slow)	Vel.Max.	[15]
PPV	-	-	Vel.Max.	[10,15-18]
$KB_{F,max}$	KB	0.125 (Fast)	Vel.Max.	[9,10,16, 17,19]
$KB_{S,max}$	KB	1 (Slow)	Vel.Max.	-
$MTVV_w$	W_m	RMS	Acc.Max.	[9,14]
VDV_w	W_m	-	Acc.Equ.	[9,10,14]

Indicators used in this investigation are those using W_m and KB weightings. For vibration signals, only the vertical components are retained in the subsequent analysis.
In total, the number of indicators retained for vibration exposure is 9 for each studied room in the dwelling.

3.2 Indicator significant

To simplify the exposure description, the number of indicators is limited in the following. Indeed, many of

these indicators can be redundant by being highly correlated with one another or exhibiting insufficient dispersion as shown by Nowakowski [20] to distinguish between the signals. For example, Figure 5 shows that the type of indicator (max or eq.) is often not enough to differentiate the exposure signals with a correlation superior to 0.9. The same observation can be made concerning the weightings C or Z. Although these different indicators do not represent the same phenomenon, they cannot be distinguished in a statistical study.
On the contrary, this study underlines the difference between the acceleration and velocity which seems to characterize different properties of the signal. This conclusion correlates with the ones made in other similar studies like in the French GENIFER project [21] dealing only with railway noise exposure.

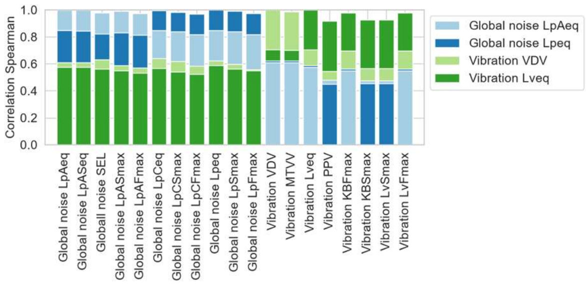

Figure 5. Correlation between exposure indicators.

A similar study has been conducted including the ground-borne noise. In regards of these results, 8 indicators of noise and vibration exposure are kept in the following study and are summarized in Table 4.

3.3 Physiological indicators

Physiological measurements are recorded during all periods where the subject is present in the dwelling (when watch is connected to the BoxConfort). Then, the related indicators are computed; following characteristics defined in the Table 5 below.

Table 4. Acoustic and vibration indicators selected for the study

Notation	Type of Exposure
$L_{pA,eqTp}$	Global noise
$L_{p,eqTp}$	Global noise
$L_{p,eqTp}$	Ground-borne noise
$L_{pA,eqTp}$	Air-borne noise
$L_{p,eqTp}$	Air-borne noise
VDV	Acceleration
$L_{v,eqTp}$	Velocity
$L_{v,S,max}$	Velocity

These indicators can be computed for any period, and in particular: during the train pass-by (period P), 10 seconds before (period A) or 10 seconds after (period B). The heart rate variation metric (Δ_{BPM}) is derived as the difference between post-passage (period B) and pre-passage (period A). The indicator based on skin temperature is not included in the analysis below, due to the lower sampling resolution (5 minutes).

Table 5. Physiological indicators.

Not.	Type	Res.	Period
BPM_{mean}	Mean heart rate	1 s	P, A, B
BPM_{max}	Maximum heart rate	1 s	P, A, B
Δ_{BPM}	Heart rate variation	1 s	B-A
T_{skin}	Skin temperature	5 min.	-

3.4 Construction of event series

To study the existing link between the different indicators, the data is connected in time and space through the creation of event series. These events are defined by the set of exposure, physiological, and perceptual indicators obtained for a single train passage and a unique participant.
Selecting complete events allows for the elimination of incomplete datasets (missing indicators) and measurement anomalies (inactive sensors, watch removed, etc.). For all subjects, the number of total complete events is 1448.
These data can be summarized by a chronogram as proposed in Figure 6. This chronogram represents for one site and one subject, an exposure indicator ($L_{pA,eqTp}$) and a physiological indicator (BPM_{mean}) associated to each event. It also underlines the specific periods: night and subject absence from dwelling.
This representation allows for the evaluation of relevant periods for data analysis (positions and number of complete events). The periods of the day when exposure is highest are also visible.

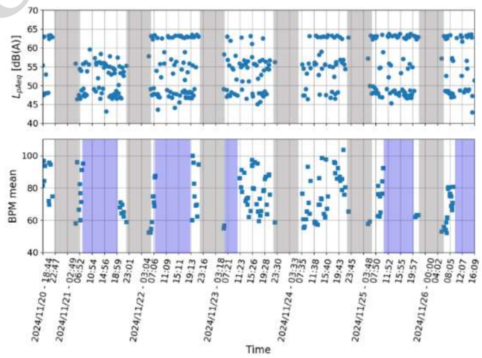

Figure 6. Histogram for site 1 and subject S2, shaded areas indicate in grey nighttime (10.pm to 6.am) and in blue subject absence, for exposure indicator $L_{pA,eqTp}$ and physiological indicator BPM_{mean}.

4. Data analysis

The construction of the database allows to consolidate data before in-depth correlation analysis between the different indicators. In this paper, only exposure data and physiological data are processed.

4.1 Analysis method

To explore the relationships between noise and vibration exposure indicators and physiological response, Spearman correlation analyses were conducted at the individual level. For each train passage, second-by-second heart rate data were averaged over the entire event to obtain a single representative value. Principal component analysis,

correlation matrices, and boxplot-based comparisons were performed to further examine these relationships.
Several limitations should be noted:

- Small number of participants;
- Homogeneous and consistently high exposures;
- Measurement uncertainties.

This analysis does not aim to establish a dose–response relationship nor to define exposure thresholds or explore subjective perception of noise and vibration.

4.2 Correlations heart rate and exposure indicators

Spearman correlation coefficients (ρ) were computed across all subjects between environmental exposure indicators and heart rate metrics. Statistical significance was assessed using corresponding p-values, indicated in Figure 7 using asterisks (* $p \geq 0.05$, $p < 0.05$ elsewhere).

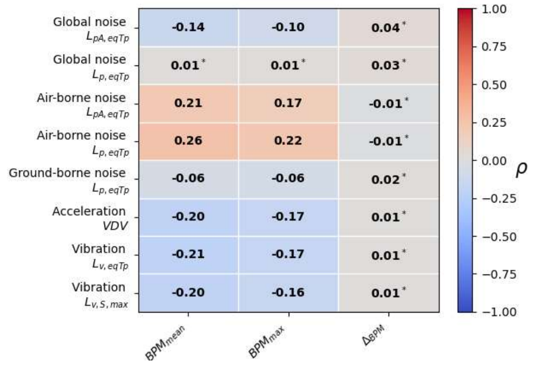

Figure 7. Heatmap of Spearman correlations

Heart rate during train passages was weakly but significantly associated with vibration levels $L_{v,eqTp}$ (BPM_{mean}: ρ=-0.21; BPM_{max}: ρ=-0.17, p<0.001), indicating smaller cardiac activity under higher vibration velocity exposure. Negative correlation coefficients are also observed with ground-borne noise indicators as expected since the ground-borne noise is deduced from the vibration velocity. Air-borne noise exposure expressed as $L_{pA,eqTp}$ shows a positive correlation coefficients with heart rate indicators. Overall, although correlation coefficients were weak, the results show that vibration velocity and air-borne noise impact both physiological reactions.
Global noise levels, reflecting the combination of air-borne and ground-borne noises, show a weak negative correlation (ρ=-0.14). Since physiological indicators are correlated with both air-borne and ground-borne noises, it is not possible to determine their contribution to this correlation coefficient.
No meaningful relationship was found between any environmental indicator and Δ_{BPM}.

4.3 Quartiles of exposure and heart rate

To assess the influence of acoustic exposure on heart rate, a categorization approach was applied to all noise indicators. Continuous variables were divided into four equal-sized classes (quartiles), allowing comparison across increasing exposure levels.

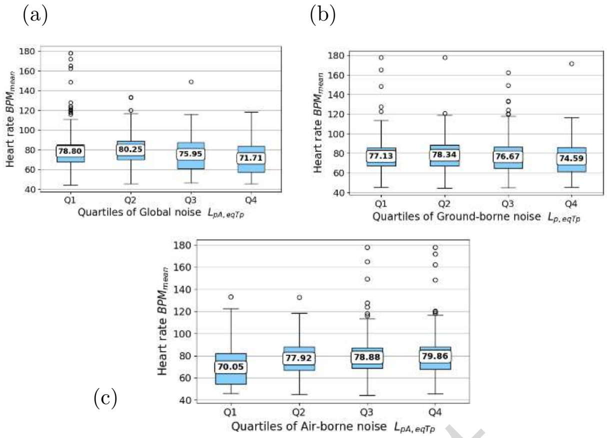

Figure 8. Heart rate distribution across noise indicators quartiles: (a) Global noise $L_{pA,eq}$, (b) Ground-borne noise $L_{p,eq}$ and (c) Air-borne noise $L_{pA,eq}$.

Results show an overall association between noise and mean heart rate, though not strictly monotonic. For air-borne noise, heart rate is significantly higher in all higher classes (Q2-Q4) compared to Q1. Inverse patterns are observed for global and ground-borne noises (Q4 smaller than other quartiles). This result is consistent with the sign of the correlation calculated for each indicator in the previous section.

4.4 Analysis of physiological responses during night

Preliminary analysis of physiological responses during night was restricted to the height participants with sufficiently complete heart rate recordings. Only nighttime train pass-by (22:00–06:00) were considered because physiological responses in this period is expected to be less influenced by daily activities and external stimuli. Heart rate was smoothed using a 10-s moving average and normalized at the individual level of the night (z-score computed on heart rate recorded in the entire night). For each train passage, heart rate z-score from 30 s before to 30 s after the beginning of the event were extracted, interpolated to a common 1-s time grid, and baseline-corrected using the pre-event period. Event-related responses were then averaged across pass-by to obtain the mean cardiac response associated with train exposure (including all participants with sufficiently complete heart rate recording). The mean passage duration displayed in Figure 9 is the mean duration of all used events.

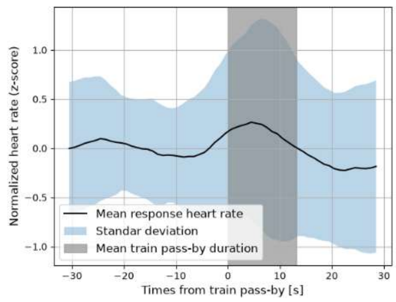

Figure 9. Average normalized heart rate response (z-score) around nighttime train passages (22:00–06:00).

The average nighttime heart rate response showed a maximum during the event and gradual decrease after. Given the small amplitude of the response and the relatively large variability between events, these results suggest a limited but detectable temporal association between train passages and cardiac activity during the night.

4.5 Comparison with laboratory results

During the laboratory experiments, physiological measurements including heart rate (HR), electrodermal response (EDR), cutaneous microcirculation (MC), and respiratory rate were recorded to assess the effects of exposure to railway noise and vibrations. Regarding heart rate, the amplitude of the heart rate during exposure to the railway stimulus revealed significant relationships between physiological responses and descriptors of perception and annoyance. Specifically, heart rate amplitude showed significant negative correlations with the perception and annoyance associated with noise, vibration, and their combination. However, this study also found that the perception of noise and vibrations is dampened when the subject is performing a cognitive task. This latter result provides an additional explanation for the low correlation scores observed during in situ measurements, where the subject is less or little attentive to the noise in their daily environment.

5. Conclusion

The VibAcouPhysio project aims to present the question of the perceived annoyance due to train noise and vibration exposure under a new perspective by using physiological parameters. If this approach showed concluding results in the first laboratory phase, this paper presents an extension to in-situ situations. This research is challenging due to many uncertainties that may influence the acoustic, vibration and physiological data. However, a correlation between physiological and exposure is underlined in this paper, opening the discussion of considering physiological indicators in perception studies. Future works concern relationship with perception dataset. Based on the same events, correlation with the exposure or the physiological reaction will be studied. Furthermore, comparisons with a previous study (based on laboratory results) reveal weaker correlations for in situ measurements. This is assumed to be due to daily activities, which may disturb physiological responses.

To investigate the influence of train type and to determine indicators that best correspond to physiological responses, more detailed laboratory measurements are planned.

6. Acknowledgments

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