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Investigations and results concerning railway-induced ground-borne vibrations in Germany

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Abstract

Besides noise reduction, ground-borne vibrations induced by railways are another important environmental issue associated with the construction of new or the reconstruction of existing railway lines that had to be tackled during the last decade. Annoyance can occur, particularly for lines in urban areas at small distances to neighbouring houses or lines in shallow depth tunnels under buildings. The ground-borne vibrations can be perceived by the inhabitants via the floor vibrations, as well as via the air-borne noise radiated inside the building by the vibrating building structures (secondary noise).

At present, legal specifications for judging railway-induced ground-borne vibrations do not exist in Germany. In order to review common practices, an experimental psycho-physical laboratory study was performed. To estimate the annoyance of railway-induced vibrations, the mean vibration energy of a train pass-by seems much more significant and related to the annoyance than the commonly used RMS value according to the German standard DIN 4150-2. The minimum difference in vibration that can be felt by people was found at a signal difference of 25%.

This paper will review results of a project performed in cooperation with the engineering office Obermeyer in Munich and the Technical University of Munich [A. Said, D. Fleischer, H. Kilcher, H. Fastl, H.-P. Grütz, *Zur Bewertung von Erschütterungsimmissionen aus dem Schienenverkehr, Zeitschrift fuer Lärmbekämpfung*, Vol. 48(6), Springer VDI Verlag, Düsseldorf, 2001.] and will link them to further demands on research and on development of suitable guiding principles and legislative regulations.

1. Introduction

1.1. Railway-induced building vibrations

Railway traffic running on the track causes high-frequency airborne noise from the track-wheel-excitation as well as ground vibrations. These ground vibrations may cause noticeable vibrations of nearby buildings. So, noise, called "secondary airborne noise", can be re-radiated by building vibrations, which may result in annoyance among the residents (Fig. 1) [1].

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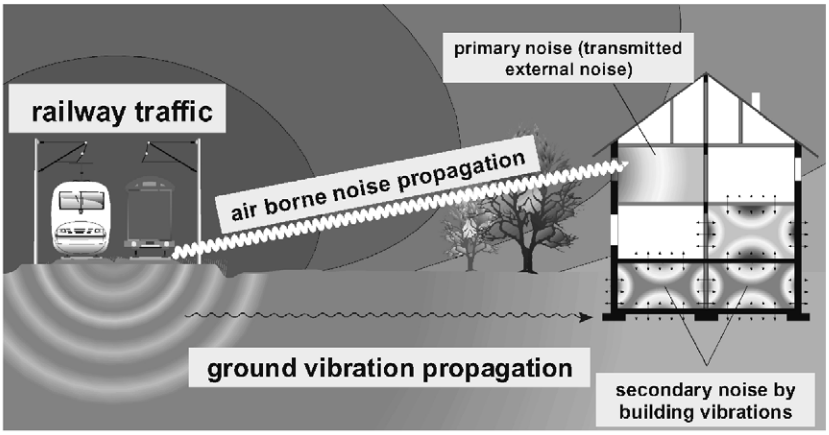


Fig. 1. Re-radiated noise by building vibrations, caused by railway-induced ground vibration.

1.2. Legal specifications

At present, there are no legal specifications or laws in Germany for vibration limits caused by railway traffic. For assessing railway-induced vibrations, the maximum of the vibration strength within a certain time period is used according to the German standard DIN 4150 part 2 [2]. Since the annoyance caused by vibrations is assessed by the maximum measured vibration, rms value during a train pass-by, vibration signals with the same maximum level but different total energy are rated equally. The German standard is also used for assessing upgraded existing railway lines. Therefore, it claims that the existing vibrations annoyance should not increase considerably. However, the term ‘‘considerable perception of a vibration’’, and particularly the perception of a vibration difference, is not specified.

1.3. Target of the presented studies

In order to get a more clear picture of the effects of railway-induced vibration annoyance perceived by inhabitants, a scientific laboratory study was performed. Its aim was to assess whether the maximum of the vibration strength describes the perception of vibration correctly, or if other sizes describe this perception with a better quality. Therefore, one study compares the perception of vibration using the KB_{Fmax} value as it is proposed in the German standard DIN 4150-2 with another method using the Kb_{eq} value, which is based on the energy average, in order to find out the most suitable descriptor for the rating of railway-induced vibrations. The KB signal is defined as a frequency-weighted signal of the vibration velocity [3].

In addition, we investigated as to which vibration differences can be recognised, as the standard DIN 4150-2 claims to avoid a considerable increase of vibration perception when upgrading existing railway lines. Therefore, an analysis was performed as to which minimum of the difference of vibration energy can be felt by the tested persons.

2. Preparation for both the studies

2.1. Experimental setup

An acoustical vibration lab (test room) was realized, which looked like a common living room with a base of $20\,m^2$ and windows (Fig. 2a). In the floor of the test room, a bottom plate of size $1.8\,m \times 1.8\,m$ was integrated, which could be excited to vibrate (Fig. 2b). The whole floor was covered by a carpet so that the tested person could not see the vibration bottom plate; the test-chair was fixed.

The vibrating plate was excited by a shaker to achieve a typical train pass-by vibration signal with different amplitudes, with KB values from 0.1 to 1.0.

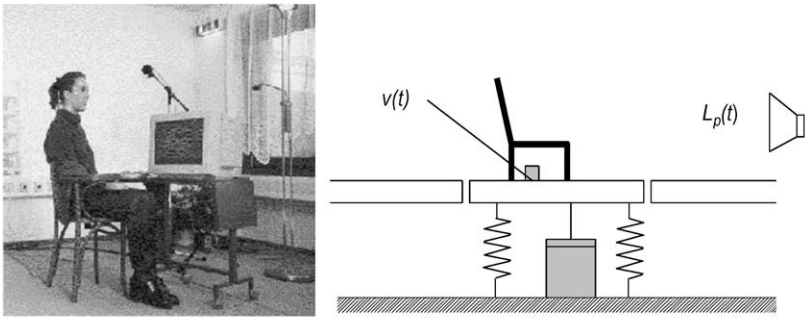


Fig. 2. Test room of the vibration lab: photo of the room (a, left) and schematic drawing (b, right).

In addition to the equipment concerning the vibrations, a loudspeaker was installed in the test room so that the tested person could hear the sound of a train pass-by while feeling the vibrations on the chair sitting on. So the tested person felt the measured vibration and noise signals of a train pass-by with typical shape and frequency composition. The complete experiment was controlled during the whole test session by a research engineer.

2.2. *Investigation methods*

In the performed studies, the tested persons had to assess different vibration values. Considering the fact that some people will determine very carefully whether they felt a change in a given signal, whereas others will make a choice as soon as they feel a bit of a change, the result of a certain experiment can be quite different even when each tested person was confronted with the same signal.

So various examination methods like the "signal detection theory" (= SDT) [4,5] or the "two alternative forced choice-method" (= 2-AFC) [6,7] have been tested in the preliminary investigations with a couple of tested persons in order to decide which method is most suitable for the studies.

Using the signal detection method, 50% of the vibration signals were two successive equal signals, and the other 50% of the given signals were two successive signals with different values. So the SDT gives a statement about the possible perception of a given vibration difference.

On the contrary, using the 2-AFC method, two different signals were presented to the tested person to decide which signal the person felt was stronger.

3. Studies performed

3.1. *Minimum difference in railway-induced vibration that can be felt by tested persons (distinct increase)*

The first preliminary examinations had been performed with five tested persons, with the result that a relative signal difference of 25% had to be used in the main examination. In the main investigation, 20 tested persons (10 females and 10 males, age between 19 and 63 years), took part. Running the test, two vibration signals were presented successively with a break of 3 s in between. Each signal of the signal pair had a duration of about 5 s. The signal pairs were of the same shape, but of partially different amplitudes. After the presentation of the two successive signals, the tested person had to decide whether they were equal or different. Thereby, 50% of the two particular signals were given as equal, and 50% were different. Table 1 shows the scheme of this SDT experiment.

In the study, the combination of four intensity levels of vibration (KB_{Fmax} values of 0.2, 0.4, 0.8 and 1.6) with three sound levels inside the test room (< 30, 45 and 55 dB(A)) led to 12 different categories. For each of the 12 categories, 100 signal pairs were presented to the tested person (Table 2). In Fig. 3, one signal pair is shown as an example. It can be seen clearly that the shape of the reference signal and the comparative signal is the same, but the reference signal has a lower amplitude than the comparative signal. The comparative signal had the signal strength increased by 25%, as determined in the preliminary examination. The airborne sound

Table 1
Scheme of the given signal and reaction of the tested person participating in the SDT study

Presented successive signals (E1 = reference signal, E2 = comparison signal)	Answer of the tested person	
	Both signals are different	Both signals are equal
25% E1/E1	Wrong	Right
25% E2/E2		
25% E2/E1	Right	Wrong
25% E1/E2		

Table 2
Combinations of the given signals of the examination and number of trials performed in each

KB_{Fmax} value	Airborne sound level of the train pass-by		
	< 30 dB(A)	45 dB(A)	55 dB(A)
0.2	100	100	100
0.4	100	100	100
0.8	100	100	100
1.6	100	100	100

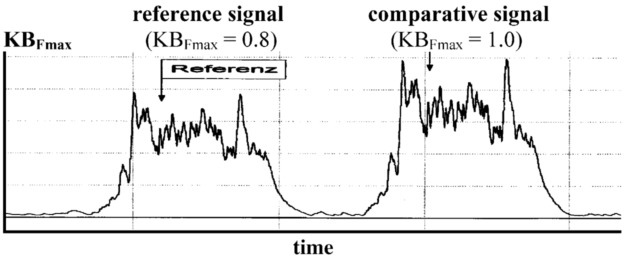


Fig. 3. Example of a signal pair with a different KB_{Fmax} value.

level was kept constant when the vibration stimulus was increased by 25% in order to ensure that the increased vibration stimulus was being judged by the tested person.

3.2. *Effect of the maximum peak value on the perception of railway-induced vibrations*

According to the German standard DIN 4150-2, only the maximum peak value of the vibration signal (KB_{Fmax} value) during a train pass-by is relevant for the perception of the vibration. This assessment should be investigated in a laboratory study. The task of this study was to check whether

- only the maximum value of the vibration signal affects the perception of the vibration;
- the integrated energy value of the vibration signal (equivalent value KB_{eq}) is a better descriptor for the subjective rating of railway-induced vibrations.

Using the same equipment as described in Chapter 3.1, two vibration signals with a duration of 10 s each were performed successively with a break of 3 s between them. Each signal pair consists of a reference signal with a distinct peak value (6 dB higher than the rest of the vibration signal) and a comparative signal (without distinct peaks). In Fig. 4, an exemplary signal pair with the same integrated energy value of the reference signal and the comparative signal is shown.

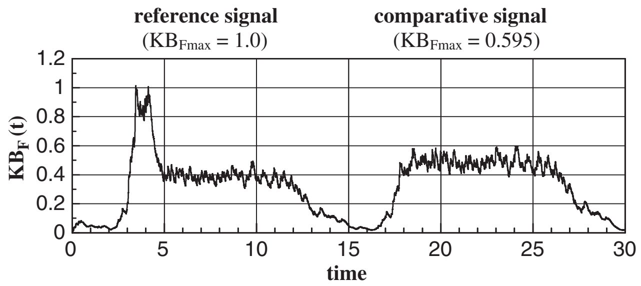


Fig. 4. An exemplary signal pair (at a constant airborne sound level $L_p = 40\,\text{dB(A)}$).

Table 3
Each single experiment consists of 14 trials (signal pairs)

Number of the signal pair	First signal in the specific pair		Second signal in the specific pair	
	Shape	KB_{Fmax}	Shape	KB_{Fmax}
1	Reference	1.0	Comparative	1.18
2	Reference	1.0	Comparative	1.0
3	Reference	1.0	Comparative	0.84
4	Reference	1.0	Comparative	0.71
5	Reference	1.0	Comparative	0.595
6	Reference	1.0	Comparative	0.5
7	Reference	1.0	Comparative	0.42
8	Comparative	1.18	Reference	1.0
9	Comparative	1.0	Reference	1.0
10	Comparative	0.84	Reference	1.0
11	Comparative	0.71	Reference	1.0
12	Comparative	0.595	Reference	1.0
13	Comparative	0.5	Reference	1.0
14	Comparative	0.42	Reference	1.0

In the study, only one reference signal was used and compared with one of seven different comparative signals, while also changing the order of the reference signal and the comparative signal. Thus 14 trials were performed during each single experiment (Table 3). The sound level inside the test room was 40 dB(A) during each test run.

First preliminary examinations were performed with six tested persons in order to test the experimental setup described. In the main investigation, 22 tested persons (13 females, 9 males, ages between 21 and 44 years) took part. During the test, each person was presented with the experiment described in Table 3 nine times. Thereby, the order of the 14 trials in each single experiment was varied in order to avoid systematic effects. After each presentation of a signal pair, the tested person had to decide which signal of the signal pair was felt as stronger (2-AFC method).

So 126 comparisons of two signals within a signal pair were performed per tested person, which amount to 2772 comparisons in total.

4. Results

4.1. Results to determine the minimum difference in railway-induced vibration that can be felt (described in Section 3.1)

To interpret the results obtained with the study described in Section 3.1 the SDT parameters "discrimination index" and maximum value of "proportion correct" have been calculated for each tested person.

The calculation was done with formulas (1) and (2) as shown in [4]:

Discrimination index:

$$d' = 2Z\left[\frac{1+\sqrt{2P(c)_{\max}-1}}{2}\right]. \tag{1}$$

Maximum value of proportion correct:

$$P(c)_{\max} = \Phi\left[\frac{Z(\text{right})-Z(\text{wrong})}{2}\right], \tag{2}$$

where Z(right) is the proportion for the answer "right" in the Z-values, Z(wrong) the proportion for the answer "wrong" in Z-values, Z the Z-transformation and Φ the probability transformation (reverse Z-transformation).

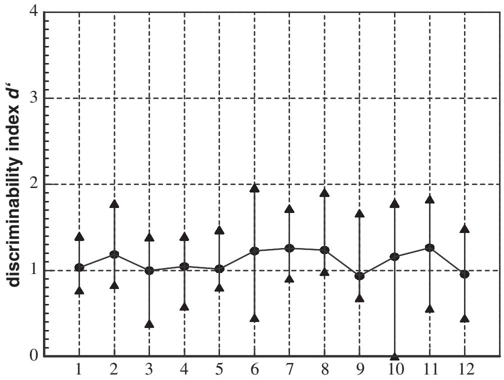
For each of the 12 categories, 2000 signal pairs were analysed. The evaluated median value of the discrimination index and its interquartile are shown in Fig. 5 for each category. It can be seen that there are large deviations within each category due to the individual perception of the tested persons. The median value of the discrimination index d' varies between 0.9 and 1.3. The arithmetic mean value of this index for all categories is $d'_{\text{mean}} = 1.1$.

In Ref. [8], it is pointed out that a discrimination index $d' = 1$ shows the evidence of a threshold value within SDT examinations (that value illustrates a tested person who is able to distinguish on an average). This means that the proportion for the right answer is 57% and for the wrong answer it is 43%. The evaluated value of $d' = 1.1$ is nearly 1.0, so that the relative signal difference of 25% can be considered as a "perceptible increase limit measured under laboratory conditions".

4.2. Results of the effect of the maximum peak value on the perception of railway-induced vibrations (described in Section 3.2)

To analyse the performed test runs, the relative percentage of the answers of the tested persons for the perception that the reference signal is the stronger one is plotted vs. the ratio $\text{KB}_{\text{eq,ref}}/\text{KB}_{\text{eq,comp}}$ of the signal energy values, and in another plot vs. the ratio $\text{KB}_{\text{Fmax,ref}}/\text{KB}_{\text{Fmax,comp}}$ of the signal peak values. These results are shown in Fig. 6. In both plots, we distinguish between the signal pairs as to where the signal with the maximum peak was the first or the second stimulus.

Using the 2-AFC method, two answers are possible. Thus the relative quotation of 50% is called the level of coincidence. In this case, the reference signal cannot be distinguished from the comparative signal.



category	KB_{Fmax}	Lp[dB(A)]
1	0.2	30
2	0.2	45
3	0.2	55
4	0.4	30
5	0.4	45
6	0.4	55
7	0.8	30
8	0.8	45
9	0.8	55
10	1.6	30
11	1.6	45
12	1.6	55

Fig. 5. Evaluated discrimination index d' for the 12 categories (certain combinations of KB_{Fmax} and L_p as listed on the right) with ● = median and ▲ = interquartile.

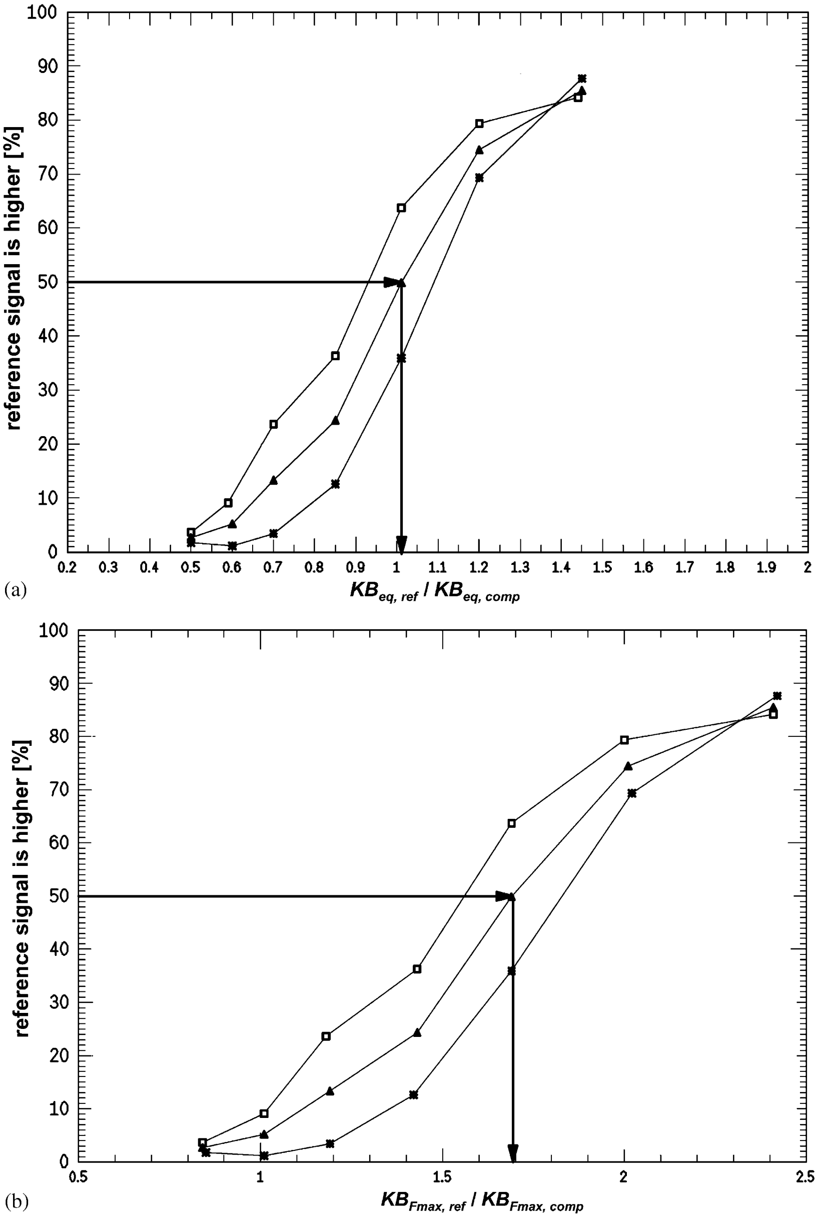


Fig. 6. The relative quotation of the answers of the tested persons that the reference signal is the higher one ($*$ = peaks first stimulus, □ = peaks second stimulus, ▲ = mean value). The energy mean $\mathrm{Kb}_{\mathrm{eq}}$ is shown in (a), while the $\mathrm{KB}_{\mathrm{Fmax}}$ according to DIN 4150-2 is shown in (b).

The first graph (Fig. 6 top) shows the answers of the tested persons when the reference signal was perceived as the higher signal. It can be seen that the ratio $\mathrm{KB}_{\mathrm{eq,ref}}/\mathrm{KB}_{\mathrm{eq,comp}}$ is 1.01 in case of the 50% level. This implies that the tested persons feel the vibration strength of two signals as equal when the content of energy of both signals is the same, even if both signals have different values of $\mathrm{KB}_{\mathrm{Fmax}}$.

On the other hand, vibration signals with the same value of $\mathrm{KB}_{\mathrm{Fmax}}$ can be felt as quite different, as shown in the second graph (Fig. 6 below). In this case, ratio $\mathrm{KB}_{\mathrm{Fmax,ref}}/\mathrm{KB}_{\mathrm{Fmax,comp}}$ is 1.69 at the 50% level. So—on an average—the tested person does not feel the reference signal to be equal to the compared signal until the $\mathrm{KB}_{\mathrm{Fmax}}$ value of the reference signal is 1.69 times the comparative signal. This implies that the $\mathrm{KB}_{\mathrm{Fmax}}$ value is not a good marker for the perception of railway-induced vibration events.

5. Conclusion

The perception threshold for different railway-induced vibration events was confirmed at a 25% increase/decrease of KB_F. The energy average KB_{eq} is a suitable descriptor for the subjective rating of railway-induced vibrations. The maximum value KB_{Fmax} leads to an overestimation of peaks. As a consequence, it is recommended that the German standard DIN 4150 part 2 should be revised with regard to the assessment of railway-induced vibration.

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