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Vibrations in the living environment

Relationships between vibration annoyance and vibration metrics

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Author:

W. Passchier-Vermeer*

K. Zeichart**

Gaubiusgebouw, Zernikedreef 9
Gortergebouw, Wassenaarseweg 56
P.O. Box 2215
2301 CE LEIDEN
The Netherlands

Phone +31 71 518 18 18
Fax +31 71 518 19 20

* TNO-PG, Leiden, The Netherlands

** Obermeyer Planen und Beraten, München, Germany

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CONTENTS

page

EXECUTIVE SUMMARY

Secondary analysis

This report presents results of a secondary analysis of data from a German survey about vibration perception and annoyance of residents living in the neighbourhood of a railway (Zeichart K, Sinz A, Schuemer R, Schuemer-Kohrs A. Erschütterunswirkungen aus dem Schienenverkehr. München: Obermeyer Planen und Beraten, 1993). The secondary analysis of these data is a part of a project on vibrations in the living environment, which has been commissioned by the Ministry of Housing, Spatial Planning and the Environment to TNO-PG. The first analysis of the data presented in the German report mainly aimed to provide background information for the German regulations on railway-induced vibrations. The secondary analysis, based on a proposal by TNO-PG, has been carried out by the first author of the German report.

Aims of the secondary analysis

The first aim of the secondary analysis is to determine the vibration metric which gives the 'best' relationship with vibration annoyance. In this respect a practical approach has been taken in considering only those metrics that are based on specifications given in International Standard ISO 2631-2 (1989), British Standard BS 6472 (1992) and DIN 4150, Teil 2: 1992. A further aim is to establish exposure effect relationships between the 'best' vibration metric and vibration annoyance. A further exploration of a possible interaction between vibration and noise exposure due to the same railway traffic was originally also an aim of the secondary analysis. However, this subject was already covered at the start of the secondary analysis and results were just about being published (Zeichart, 1998). In this report an English summary of the paper is given.

The survey

The secondary analysis is based on data of 417 participants living in the neighbourhood of a railway track for long distance traffic. Vibration and noise measurements have been carried out in the living room (WZ) and in the bedroom (SZ) of the participants. Participants answered questions of a (verbal) questionnaire on perception, specific disturbances (e.g. of rest, communication and TV watching) and annoyance due to vibrations and noise caused by railway traffic and on overall annoyance due to the presence of a railway in the neighbourhood. Sites have been selected according to high, medium and low vibration level, high, medium and low noise level and high, medium and low number of train passages per 24 hours. Each of the 27 possibilities thus specified contains more or less the same number of participants.

Variables in the analyses

Vibration metrics

In total 48 vibration metrics have been specified for daytime, nighttime and 24 hours vibration exposure. The definitions of these metrics are given in Annex A. These metrics have been derived from metrics closely related to or specified in the Standards mentioned. These metrics are KB_x, KBR_x (specified in DIN 4150, Teil 2: 1992), KBEQ_x (closely related to metric in ISO 2631-2 (1989)) and VDV_x (closely related to BS 6472 (1992)) (x indicates the measurement location - living or bedroom - and the period of the day - daytime (06.00 - 22.00 h) or nighttime (22.00 - 06.00 h)). Other metrics have been specified by combining and weighting day- and nighttime values. Of the 24 metrics thus obtained also a logarithmic transformation has been used in the analysis.

Number of vibrations per 24 hours

The number of train passages during 24 hours with perceptible vibrations is indicated by VIBNUM.

Noise exposure metric

Indoor railway induced noise exposure (L24) due to railway traffic for 24 hours is characterized by a combination of the equivalent sound level in the living room due to the passages of the trains during daytime and the equivalent sound level in the sleeping room due to the passages of the trains during nighttime.

Response variables

Vibration annoyance

In the determination of the 'best' vibration metric six vibration disturbance and annoyance measures have been used:

1. RTE: disturbance by vibrations during daytime;
2. RNE: disturbance by vibrations during nighttime;
3. question 13.3: annoyance due to vibrations during 24 hours using ;
4. question 17.1: annoyance due to daytime vibrations;
5. question 17.2: annoyance due to nighttime vibrations;
6. question 18: vibration annoyance due to vibrations during 24 hours using an annoyance 'thermometer'.

Two types of parameters are used to describe a vibration annoyance distribution in a group of participants:

- the mean of the transformed vibration annoyance scores of the participants in the group;

- the percentage of transformed annoyance scores exceeding specified cut off points. Three cut off points are used: 72 (resulting percentage denoted by %HAvib, percentage participants highly annoyed by vibrations), 50 (percentage denoted by %Avib, percentage participants at least annoyed by vibrations) and 28 (percentage denoted by %LAvib, percentage participants at least a little annoyed by vibrations).

Noise annoyance

Noise annoyance of a participant is specified by his/her transformed score on the noise annoyance question using the annoyance 'thermometer'. The mean transformed noise annoyance score as well as the percentages participants exceeding the three cut off points mentioned for vibration annoyance score are used to describe the noise annoyance distribution in a population. These percentages are denoted by %HAnoise, %Anoise and %LAnoise.

Overall railway annoyance

The overall annoyance of a participant due to the presence of a railway in the neighbourhood is specified by his/her transformed score on the question about annoyance due to the presence of the railway using the annoyance 'thermometer'. The mean transformed overall annoyance score as well as the percentages respondents exceeding the three cut off points mentioned for vibration annoyance score are used to describe the overall annoyance distribution in a population. These percentages are denoted by %HArail, %Arail and %LArail.

Best vibration annoyance metric and best vibration annoyance question

The Zeichart et al. report showed that different relationships of vibration annoyance and vibration level exist for low and high noise exposures. Therefore, participants have been divided into two noise exposure classes of equal size: L24 ≤ 39 dB(A) and L24 > 39 dB(A). Correlations have been determined for data of all participants and for data of participants divided in these two noise classes. Conclusions about the best vibration annoyance metric and best vibration annoyance question are based on the results of these three groupings. Correlation coefficients have been determined for combinations of vibration metric and vibration annoyance scores in as far as they relate to the same period of the day. For the relationships between 24 hours vibration exposure and vibration annoyance the highest correlation coefficient is obtained with the vibration annoyance thermometer score as vibration annoyance measure and VCKBL25[1] as vibration exposure metric. The relative weighting of night- and

[1] VCKBL25 is the logarithm of a combination of KB_x in the living room during daytime (x = WT) and KB_x in the sleeping room during nighttime (x = SZ), with a weighting factor w equal to 0.25 in the following formula: $VCKBL25 = \lg \left[(KB\_WT)^2 + w/2*(KB\_SN)^2\right]^{1/2}$.

daytime vibration levels with a weighting factor 0.25 in VCKBL25 has shown to be optimal. The variance (equal to the square of the correlation coefficient)in 24 hours vibration annoyance explained by 24 hours vibration level metrics (maximal 18% if VCKBL25 is taken as vibration metric) is larger than the variances in day- or nighttime vibration annoyance explained by night- or daytime vibration metrics (maximal 3% for nighttime and maximal 13% for daytime). Therefore the present analysis shows that VCKBL25 can be considered to be the 'best' vibration metric. There are, however, no statistically significant differences between the correlation coefficient of VCKBL25 and vibration annoyance scores and those correlation coefficients for the other 24 hours vibration exposure levels considered. Therefore also the other 24 hours vibration metrics considered in the analysis may stand for the 'best' 24 hours vibration metric.

In the further analyses VCKBL25 has been used as vibration metric. Transformed scores on the annoyance thermometer give a somewhat higher correlation with annoyance than the transformed scores for question 13.3. Since it imposes only a little extra effort to include both effect measures in an analyses both measures have been used in the further analyses in this report.

Relationships of vibration magnitude and vibration annoyance score

If the data of all participants (see left hand side figure 2 of the main text) are considered, vibration annoyance score is an increasing function of vibration magnitude VCKBL25. For participants divided in two VCKBL25 classes (VCKBL25 at most - 0.571 and VCKBL25 over - 0.571) the relationship between vibration magnitude and vibration annoyance for the two VCKBL25 classes are different. For the lower VCKBL25 class vibration annoyance increases with VCKBL25, but for the higher class vibration annoyance decreases statistically significant with increasing vibration level.

Number of perceptible vibrations and vibration annoyance

If vibration level VCKBL25 is taken into account there is no statistically significant effect of number of perceptible vibrations on vibration annoyance score. This was shown by using two types of statistical tests: a χ^2-test and a multiple regression analysis.

For the group of all participants vibration annoyance scores have been considered as a function of VIBNUM and of VCKBL25. The variance explained in vibration annoyance scores by VCKBL25 is larger than the variance explained by VIBNUM. This also holds for noise and overall railway annoyance. Therefore, vibration level predicts annoyance scores better than number of perceptible vibrations.

Percentages annoyed participants

Percentages highly annoyed participants, percentage at least annoyed participants and percentage at least a little annoyed participants have been determined as a linear function of VCKBL25 for vibration annoyance, noise annoyance and overall railway annoyance.

The three percentages vibration annoyed participants at the mean value of VCKBL25 have been compared with the corresponding percentages noise annoyed participants. The comparisons show that the observed percentages vibration annoyed are in good agreement with the percentages estimated from an equation given in Passchier-Vermeer (1998) with percentage noise annoyed as indicator for percentage vibration annoyed.

Percentages annoyed participants for noise exposure classes

Participants have been divided in two noise exposure classes. The linear relationships of %HAvib with vibration level VCKBL25 in both noise exposure classes are about the same. A large difference exists between percentages at least vibration annoyed and at least a little vibration annoyed participants in both noise exposure classes. For the lower noise exposure class %Avib and %LAvib are increasing functions of vibration level VCKBL25. For the higher noise exposure class %Avib and %LAvib are very high, even if the vibration magnitude is low. Obviously, participants in the higher noise exposure class do not distinguish between the two components noise and vibrations in railway traffic and attribute annoyance to both components, even if one component (vibrations) has a relatively low level.

Vibration, noise and overall railway annoyance

There is a close correspondence in the trends obtained for the relationships between vibration annoyance and vibration level and those data and trends obtained for noise and overall annoyance. E.g. in all cases the three linear regression lines for each of the three annoyance scores as dependent variables and vibration level or number of perceptible vibrations as independent variable have about equal slopes, although the constants in the regression line shows some variation. Relevant in this respect is the low correlation between vibration and noise levels for the various (sub)groups considered. The low correlation therefore does not explain the close correspondences observed.

Over the whole range of VCKBL25 considered, overall annoyance score of the participants is higher than vibration annoyance and noise annoyance score. There is, however, only a slight difference between overall railway and noise annoyance score at the same value of VCKBL25. At the same value of VCKBL25 vibration annoyance scores appear to be higher than noise annoyance scores on the same annoyance thermometer. For all participants the mean vibration annoyance score is 0.68 times the mean annoyance score. This factor is in reasonable agreement with the factor (0.6) specified in Passchier-Vermeer (1998) for transportation noise and vibration annoyance.

Interaction between vibrations and noise

In Zeichart (1998) possible interactions between railway-induced vibrations and noise on vibration annoyance, noise annoyance and overall railway annoyance have been analysed. Also the trade-off between a metric of vibration exposure and of noise exposure are given in the publication. This report gives a summary of the results.
Conclusions are:

- Vibration and noise exposure both have an effect on daytime vibration annoyance. There is no interaction between vibration and noise exposure on vibration annoyance;
- Vibrations at night have no effect on nighttime vibration annoyance, but there is an effect on nighttime vibration annoyance by nighttime noise exposure;
- Noise and vibration exposure have an effect on noise annoyance during daytime. There is an interaction between noise and vibration exposure on daytime noise annoyance;
- Nighttime noise exposure affects nighttime noise annoyance. There is no effect on nighttime noise annoyance from nighttime vibration exposure;
- Overall railway annoyance is affected by noise and vibration exposure. An interaction between both exposures does occur. Noise exposure explains 8% of the variance in the overall annoyance data, vibration exposure 5% and the interaction between vibration and noise exposure 3%. The total variance explained by the two environmental factors vibration and noise exposure on overall railway annoyance is 16%.

For overall railway annoyance the trade-off between vibration magnitude (KBR) during daytime in the living room and outdoors equivalent sound level during daytime is that a change of 18.3 DB(A) in equivalent sound level corresponds with a change of a factor 10 in vibration magnitude.

Conclusion

An important aspect of the results of the secondary analysis is to which extent they are applicable in other situations with railway-induced vibrations, such as those in the Netherlands. The Zeichart et al. report and the secondary analysis provide useful information about the effects of railway vibrations on people. In effect, the German investigation is the only field investigation in which vibration level measurements are related to vibration annoyance and in which other aspects, such as simultaneous noise exposure, have been taken into account. Therefore, unfortunately, the results of the survey cannot be compared to results of other surveys and it is not possible to determine differences between surveys. Therefore other surveys are recommended. An important reason for this recommendation is also the observed weak relationship between vibration annoyance and vibration level. The correlation coefficients of the vibration exposure metrics considered and vibration annoyance scores for all respondents are at most 0.30[2]. This implies that only 9% of the variance in vibration annoyance is explained by vibration level and that other (as yet unknown) factors virtually should explain the other 91% of the variance. If in other situations one or more of these unknown factors would be different from those in the German situation this might result in other relationships between vibration annoyance and vibration level. A readily available example has been presented in Zeichart et al. (1993). In that report different relationships have been established for vibration annoyance in the F-train sites (railway tracks for long distance traffic. These sites have been considered in this secondary analyses) and in the F-train sites (railway tracks of overground suburban rapid transit systems). Annoyance scores for vibrations in the S-train sites appeared to be about half these scores in the F-train sites for situations with equal vibration and noise exposure levels. Such differences can also be observed for other environmental exposures, see for example Miedema and Vos (1996, 1998) with respect to noise exposure and noise annoyance. Therefore usully the results of different social surveys are necessary to specify general applicable exposure effect relationships. This approach is also recommended for the present subject.

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2 This correlation coefficient is of the same order of magnitude as correlation coefficients observed in most socio-acoustic surveys (Miedema and Vos, 1998; Passchier-Vermeer, 1998)

1. INTRODUCTION

1.1 Background

This report presents the results of a secondary analysis of data from a German survey on vibration perception and annoyance of residents living in the neighbourhood of a railway (Zeichart K, Sinz A, Schuemer R, Schuemer-Kohrs A. Erschütterunswirkungen aus dem Schienenverkehr. München: Obermeyer Planen und Beraten, 1993). The secondary analysis of these data is a part of a project on vibrations in the living environment, which has been commissioned by the Ministry of Housing, Spatial Planning and the Environment to TNO-PG. In an earlier stage a desk study on vibration exposure and annoyance has been carried out (Passchier-Vermeer, 1995). The German survey is the only known field investigation in which extensive vibration measurements have been carried out inside dwellings of residents and in which residents were questioned about vibration and noise perception and annoyance due to railway traffic. The main objective of the analysis presented in the German report was to provide background information for the German regulations on railway-induced vibrations. The report gives detailed information about a relationship between a vibration metric, based on the German KB-approach specified in the German Standard DIN 4150, Teil 2: 1992, and vibration annoyance. A possible interaction on the effects from exposure to vibrations and to noise also has been investigated in the German report.

The secondary analysis, based on a proposal by TNO-PG, has been carried out by the first author of the German report, K Zeichart. The objective of the secondary analysis is to determine the vibration metric which gives the 'strongest' relationship with vibration annoyance. In this respect a practical approach has been taken in considering only those metrics that are based on specifications given in international Standard ISO 2631-2 (1989), British Standard BS 6472 (1992) and DIN 4150, Teil 2: 1992. A further exploration of a possible interaction between vibration and noise exposure was also included in the TNO-PG proposal. However, at the start of the secondary analysis a publication on this subject was already prepared (Zeichart, 1998). In chapter 7 of this report an English summary of the results of that analysis is given.

The structure of the report is as follows. An overview of the German survey is given in section 1.2. In chapter 2 the vibration and noise exposure metrics, and in chapter 3 the response variables which are used in the analysis have been specified. Chapter 4 discusses the analyses of the data with the vibration annoyance scores as response variables, chapter 5 the effect of the number of vibrations per 24 hours on vibration annoyance scores, and in chapter 6 relationships between the 'best' vibration metric and percentages of persons with specified degrees of vibration annoyance are given. Chapter 7 gives a summary of the Zeichart paper on the interaction of vibrations and noise on annoyance due to railway traffic. The generalization of the results of the secondary analysis to other situations with railway-induced vibrations are considered in the concluding chapter 8. References are given after chapter 8. In annex A definitions of the variables used in the report are presented. More general definitions from which the definitions used in the report have been derived are given in chapter 8 of Passchier-Vermeer (1995). Annex B contains the tables and annex C the figures.

1.2 The German vibration and noise survey

Sites have been selected in the vicinity of tracks for long distance traffic ('Fernbahn', denoted by F-trains) and in the vicinity of overground suburban rapid transit systems ('S-bahn': S-trains). For both types of trains sites have been selected according to combinations of vibration exposure levels, numbers of trains per 24 hours, and noise exposure level in such a way that different combinations contained about equal numbers of participants. This selection of sites resulted in low correlations between vibration and noise exposure levels. This has the advantage that interactions of railway-induced vibrations and railway-induced noise can be taken into account in the analyses.

In the F-trains sites 765 persons filled in a questionnaire and in the S-trains sites 261 persons. The distributions of age, gender, professional class, and education of the participants correspond to those of the German population (1990). Vibration and noise measurements have been carried out in 284 dwellings in the F-trains sites and in 102 dwellings in the S-trains sites. In each of the dwellings measurements have been carried out in the living room (WZ) and in the bedroom (SZ) of the participant. The total number of participants in those dwellings is 417 and 148 for F- and S-trains sites respectively. The largest part in the German report concerns the effects of vibrations in the F-trains sites. The secondary analysis is also mostly limited to effects on participants in these F-trains sites. This implies that the secondary analysis is based on data of 417 participants. In the German report results for S-trains are given in comparison to those for F-trains. Annoyance due to exposure to vibrations in the S-train areas appeared to be much less than in the F-train areas for situations with equal vibration and noise exposure characteristics. This difference will be discussed in chapter 8.

2. VIBRATION AND NOISE EXPOSURE VARIABLES

2.1 Specification of vibration variables

Direction of vibrations

Vibrations in a structure such as a dwelling are transmitted to people through contact with this structure. Vibrations in a structure may occur in any direction. Most of the railway traffic induced vibrations transmitted to people in dwellings in the German survey occur mainly in the vertical direction. It is stated in the German report that in 12% of the measurements (of F-train passages) the horizontal component was larger than the vertical one. In those situations the horizontal vibration velocity exceeded the vertical component on average by 3.5%. In the German report only the vertical vibrations are taken into account. In the secondary analysis the same procedure has been applied.

Frequency weighting

In the vibration measurements the frequency-weighting of the instantaneous vibration velocities in accordance with the German regulations has been used. In most situations railway traffic induced vibrations contained measurable vibration velocities only at frequencies above 10 Hz. The German weighting curve is, after conversion of the frequency-dependent weighting function for vibration velocity to vibration acceleration, above 10 Hz essentially the same as the weighting curves specified in ISO 2631-2 (1989) and BS 6472 (1992) for vibrations in the vertical direction. This implies that the weighting of the vibrations is in agreement with weightings specified in the three Standards, if the vibrations are limited to frequencies over 10 Hz. This will be discussed in the conclusion.

Vibration metrics

The definitions of the vibration metrics used in this report are given in Annex A. In the German regulations KB stands for the frequency weighted instantaneous vibration velocity in a given direction (in this report the vertical direction). If KB is measured using equipment with a time constant equal to 0.125 s (time characteristic fast (F)), the maximum value during a specified time or during a specified event is indicated by KB_{Fmax}. This characteristic determined for a specified time (in the German regulations 30 s) or event (in this case the passage of a train) is the basis for the two (German) vibration metrics used in this report: KB_x and KBR_x. In these metrics _x stands for a situation specified by a period of time and a measurement location. KB_x is the r.m.s value of KB_{Fmax}, specified for several situations and periods of time*. To determine KBR_x, a period of time is divided in a specific way in

* KB_x is independent of the number of events. If the number of events during a specified time is doubled by counting each event twice, KB_x will remain the same.

30-s periods. For each 30-s period KB_{Fmax} is determined, squared and the squared values obtained are added, divided by the number (T_z) of 30-s periods, and the root of the result is KBR_x**. Note that in KB_x and KBR_x only the maximum value of the instantaneous vibration velocity of an event (or over a period of time) is taken into account. Another metric KBEQ_x*** defined in annex A takes into account all vibration velocities occurring during an event or during a period of time. This metric conforms to the specifications given in ISO 2631-2 (1989) for the 'averaging' of vibration acceleration over a longer period of time. In British Standard 6472 (1992) VDV (Vibration Dose Value) is specified as vibration metric for vibration events. It is derived from the r.m.q value of the vibration accelerations during the event. In the British Standard the instantaneous acceleration values are taken to the power 4, instead of to the power 2 in the r.m.s. averaging method. In the analysis the r.m.q value is determined from the vibration velocities by using time weighting F****.

The following vibration metrics are used in the analysis to determine the 'best' vibration metric:

- KB_WT and KB_SN. In WT W stands for living room (Wohnzimmer) and T for daytime (Tags). Daytime is the period from 06.00 to 22.00 hours. In SN S stands for sleeping room (Schlafzimmer) and N for night (Nachts). Nighttime is the period from 22.00 to 06.00 hours;
- KBR_WT and KBR_SN. The number of 30-second periods (T_z) during daytime (16 hours) is equal to 1920 and during nighttime (8 hours) equal to 960;
- KBEQ_WT and KBEQ_SN;
- VDV_WT and VDV_SN.

The vibration metrics mentioned above are sometimes indicated by **V**_WT and **V**_SN, with **V** any of the four metrics KB, KBR, KBEQ and VDV.

The following vibration metrics combine the daytime vibrations in the living room are combined with the nighttime vibrations in the sleeping room:

$$VCVw = [(V\_WT)^2 + w/2*(V\_SN)^2]^{1/2}$$

** KB and KBR are not the same metric. The correspondence for n events between KB and KBR is as follows: $KB = [1/n\ \Sigma KB^2]^{1/2}$ and $KBR = [1/T_z\ \Sigma KB^2]^{1/2}$. Therefore: $KB/KBR = [T_z/n]^{1/2}$. With T_z = 1920 for daytime (T) of 16 hours and T_z = 960 for nighttime (N) of 8 hours it follws that:

$KBR\text{-}T = 0.023*n^{1/2}*KB\text{-}T$
$KBR\text{-}N = 0.032*n^{1/2}*KB\text{-}N$

*** EQ stands for *energy-equivalent*, since it is the vibration *energy* which is averaged in a specific way to obtain this metric.

**** This metric is not exactly equal to the VDV metric defined in the British Standard, since the vibration velocity is first quadratic averaged by a floating averaging function with time constant 0.125 s. This implies that very high instantaneous values of a signal with a very high crest factor are not fully accounted for by the fourth power. This effect seems negligible in the case of railway induced vibrations, which are considered not to have very high crest factors.

The factor w determines the relative weight of the day- and nighttime vibrations. The factor 2 has been included in the formula, since the total duration of daytime is 2 times the total duration of nighttime. In the secondary analysis w is varied by taking the value of w equal to 0.25, 0.5, 1.0, and 2.0. This results in 4 variables for each of the 4 vibration metrics **V**.

The secondary analysis has also been carried out by using a logarithmic transformation of the 24 metrics specified above. In the indication of the logarithmic variable of a metric the letter L has been included.

Thus, the following 48 vibration exposure metrics will be considered in the secondary analysis:
- 4 **V**_WT metrics;
- 4 **V**_SN metrics;
- 16 **VCV**w metrics;
- 4 **VL**_WT metrics;
- 4 **VL**_SN metrics;
- 16 **VCVL**w metrics.

Values of these vibration metrics have been attributed to each of the participants.

Number of vibration events

The number of train passages during 24 hours is indicated by n. In this report the number of perceptible vibrations per 24 hours (VIBNUM) is defined as the number of vibrations with $KB_{Fmax} > 0.1$.

2.2 Noise exposure metric

Noise measurements have been carried out inside the dwellings, in the living and bedrooms. Noise exposure during daytime due to the passages of trains is specified by the equivalent sound level ($L_{Aeq,day}$) in the living room during that time. Noise exposure during nighttime is specified by the equivalent sound level ($L_{Aeq,night}$) due to train noise in the sleeping room. The equivalent sound level(L24) inside the dwelling over 24 hours is defined by an exponential duration-weighted average of $L_{Aeq,day}$ and $L_{Aeq,night}$ (see annex A).

3. RESPONSE VARIABLES

3.1 Introduction

The (verbal) questionnaire considered the following subjects:

(1) response to vibrations: perception, specific disturbances (e.g. of communication), and annoyance due to vibrations caused by railway traffic;

(2) response to noise: disturbances and annoyance due to noise from railway traffic;

(3) total disturbance by railway traffic without specification of the cause (noise and/or vibration);

(4) other items, such as satisfaction with the environment, general susceptibility to environmental factors, and socio-demographic characteristics.

Participants were requested to rate their annoyance due to vibrations, noise, and their overall annoyance due to the presence of the railway on a 4 or 5 point scale with verbal category labels and on an 'annoyance thermometer'. The scale of this thermometer ranged from 0 (not at all annoyed) to 10 (extremely annoyed) and has no intermediate labels.

3.2 Measures of vibration annoyance

The questions have different numbers of response categories. Transformed scores have been assigned to these categories[*****] (see Miedema and Vos, 1996).

The transformed scores of the participants with respect to the following vibration annoyance variables will be used in the analysis:

1. RTE: disturbance by vibrations during daytime;
2. RNE: disturbance by vibrations during nighttime;
3. question 13.3: annoyance due to vibrations during 24 hours;
4. question 17.1: annoyance due to daytime vibrations;
5. question 17.2: annoyance due to nighttime vibrations;
6. question 18: vibration annoyance using the annoyance 'thermometer'.

Item 1 and 4 are related to the experience of daytime vibrations. They are indicated by A-T. Items 2 and 5 refer to nighttime experiences and they are indicated by A-N. The items 3 and 6 deal with experiences during the 24 hours period and they are indicated by A-24.

***** A category midpoint score is determined as follows: $score_{category\,i} = 100(i - 1/2)/m$ where m is the number of categories and i = 1,...., m the rank number of the category, starting with the lowest response category.

In the report two types of parameters are used to describe a vibration annoyance distribution in a group of participants:

- the mean of the transformed vibration annoyance scores of the participants in the group;
- the percentage of transformed annoyance scores exceeding a cut off point. This type of parameter will be used in chapter 6, where the relationship is given between the percentages responses to the 'best' vibration annoyance question above specified cut off points and the 'best' vibration annoyance metric. For a detailed description of the determination of the percentage of response scores above a cut off point, see Miedema and Vos (1996). In the report three cut off points are used: 72 (resulting percentage denoted by %HAvib, percentage participants highly annoyed by vibrations), 50 (percentage denoted by %Avib, percentage participants at least annoyed by vibrations) and 28 (percentage denoted by %LAvib, percentage participants at least a little annoyed by vibrations).

3.3 Measures of noise annoyance

The transformed scores of the participants on the following noise annoyance question will be used in the analysis:

- question 11: noise annoyance using the annoyance 'thermometer'.

The mean transformed noise annoyance score as well as the percentages participants exceeding the three cut off points mentioned for vibration annoyance score are used to describe a noise annoyance distribution in a population. These percentages are denoted by %HAnoise, %Anoise, and %LAnoise.

3.4 Measures of annoyance due to the presence of a railway

The transformed scores of the participants on the question about annoyance due to the presence of the railway (overall annoyance) will be used in the analysis:

- question 9.1: railway-induced annoyance using the annoyance 'thermometer'.

The mean transformed overall annoyance score as well as the percentages respondents exceeding the three cut off points mentioned for vibration annoyance score are used to describe an overall annoyance distribution in a population. These percentages are denoted by %HArail, %Arail, and %LArail.

4. THE 'BEST' VIBRATION METRIC AND THE 'BEST' VIBRATION ANNOYANCE MEASURE

4.1 Introduction

In section 4.2 the 'best' vibration annoyance measure and 'best' vibration metric will be specified. In section 4.3 the relationships between vibration annoyance and vibration level specified by the best vibration metric will be given. Relationships between the best vibration metric and noise (question 11) and overall railway annoyance (question 9.1) will also be presented.

Usually socio-acoustic surveys show a large variation in noise annoyance scores at the same noise level. An analogous phenomenon appears in the data on vibration annoyance and vibration level. The Zeichart et al. report shows a large variation in vibration annoyance scores at the same vibration level. Taking into account this large variation and the (limited) number of participants in the survey the analysis is limited to linear relationships between vibration metrics and vibration annoyance.

4.2 Determination of the 'best' measures

The Zeichart et al. report showed that different relationships between vibration annoyance and KB_x exist for low and high noise exposures. Therefore, in this analysis participants have been divided into two noise exposure classes of equal size: L24 ≤ 39 dB(A) and L24 > 39 dB(A). Analyses have been carried out on data of all participants, and on data of participants divided in these two noise classes.

Correlation coefficients have been determined for combinations of vibration metric (V) and annoyance score (A) in as far as they relate to the same period of the day. The following combinations have been considered, each combination covering 2 vibration metrics (the original metric and the logarithmic transformation)

A-T with V-WT: RTE, Q17_1 with KB_WZ, KBR_WT, KBEQ_WT, VDV_WT;
A-N with V-SN: RNE, Q17_2 with KB_SZ, KBR_SN, KBEQ_SN, VDV_SN;
A-24h with VCV(w): Q13_3, Q18 with VCKB25, ..., VCKB2, VCKBR25 ,..., VCKB2, VCKBEQ25, ..., VCKBEQ2, VCVDV25, ..., VCVDV2.

The correlation coefficients for each combination are presented in table 1 for noise exposure class L24 ≤ 39 dB(A), in table 2 for noise exposure class L24 > 39 dB(A), and in table 3 for all participants.

The first rows in table 1 show for the lower noise exposure situations that correlation coefficients for daytime vibrations are larger than for nighttime vibrations. The variance (which is the square of the correlation coefficient) in nighttime vibration annoyance explained by nighttime vibration level is at most 0.03 (3%). The variance in daytime vibration annoyance explained by daytime vibrations is from 0.06 (6%) to 0.12 (12%). With respect to exposure over 24 hours, the thermometer score (question 18) does give somewhat higher correlation coefficients with vibration metrics than question 13.3. The logarithmic transformations of the exposure metrics give slightly higher correlations with the scores on the annoyance thermometer than the original metrics. For all four vibration metrics the correlation coefficients decrease with increase of the weighting factor from 0.25 to 2. It has also been examined whether a weighting factor smaller than 0.25 would result in higher correlation coefficients than given in the tables 1, 2, and 3. This is not the case. Therefore the weighting factor of 0.25 is optimal. Then, from table 1 it can be concluded that in the case of lower noise exposures the highest correlation coefficient is obtained with VCKBL25 (logarithm of VCKB25) as vibration metric.

Table 2 shows that the correlation coefficients for vibration annoyance and vibration metric in the case of higher noise exposure are very small, and in some instances even negative. The main conclusion from this table is that the relationship between vibration annoyance and any vibration metric is very weak. For this noise class one can hardly choose a 'best' annoyance question and a 'best' vibration metric. Nevertheless the relationship of VCKBL25 with vibration annoyance has a higher correlation coefficient than the other relationships.

The correlation coefficients in table 3 for all participants are in between the coefficients given in table 1 and 2. The correlation coefficient of the annoyance score of question 18 and VCKBL25 is higher than the other ones, with one exception (VCKBL50) where the correlation coefficient is equal to the one with VCKBL25. In this casé the correlation coefficients of the annoyance score of question 13.3 and VCKBL25 is also higher than the other ones with this score as vibration annoyance measure.

The conclusion is therefore that the highest correlation coefficient is obtained with the vibration annoyance thermometer score as vibration annoyance measure and VCKBL25 as vibration exposure metric. In that case correlation coefficients are for the lower noise exposure class 0.42, for the higher noise exposure class 0.09 and for all participants 0.30.

By using Fisher's Z-transformation of the correlation coefficients it has been determined for the 24 hours exposure data whether statistically significant differences exist between the highest correlation coefficient and other coefficients in the tables 1, 2 and 3. Taking into account the number of participants in each of the groups, it has been calculated that correlation coefficients in table 1 smaller than 0.26 are statistically significant different from 0.42 (significance level 5%). This is not the case for any of the correlations between thermometer annoyance scores and vibration metrics. If question 13.3 is taken as vibration annoyance measure in only three cases, in which the relative weight of nighttime vibration levels is 1 and 2, there is a statistically significant difference.

In table 2 for the 24 hours exposure data correlation coefficients smaller than - 0.04 would be statistically signicant different from the value of 0.09. Since such values are not present in table 2 none of the correlation coefficients differ statistically significant from the highest value. If correlation coefficients in table 3 would be 0.11 and smaller they would have been statistically significant different from 0.30. Again such values are not present in table 3.

Summary

The variance in 24 hours vibration annoyance explained by 24 hours vibration level metrics (maximal 18% if VCKBL25 is taken as vibration metric) is larger than the variances in day- or nighttime vibration annoyance explained by night- or daytime vibration metrics (maximal 3% for nighttime and maximal 13% for daytime). For the 24 hours vibration exposures the highest correlation coefficient is obtained with the vibration annoyance thermometer score as vibration annoyance measure and VCKBL25 as vibration exposure metric. The relative weighting of night- and daytime vibration levels with a weighting factor 0.25 in VCKBL25 has shown to be optimal. Therefore the present analysis shows that VCKBL25 can be considered to be the 'best' vibration metric. There are, however, no statistically significant differences in the correlation coefficients of the various 24 hours vibration exposure levels considered and 24 hours vibration annoyance scores. Therefore also the other 24 hours vibration metrics considered in the analysis may stand for the 'best' 24 hours vibration metric.

In the further analyses VCKBL25 will be used as vibration metric. Transformed scores on the annoyance thermometer give a somewhat higher correlation with annoyance than the transformed scores for question 13.3. Since it imposes only a little extra effort to include both measures in the analyses both measures will be used.

4.3 Relationships

A linear regression analysis has been carried out with the scores of questions 13.3 (vibrations), 18 (vibrations), 11 (noise) and 9.1 (overall railway) as dependent variables, and VCKBL25 as independent variable. Three cases have been considered: all participants and participants divided in (two) VCKBL25 classes. These two classes have equal number of participants. The results are given in table

4. 'B' is the slope of the best fitting straight line (each of the levels of significance of the slopes are less than 0.025), 'constant' the constant in the equation and R the correlation coefficient for the relationship between the dependent and independent variable. The higher the value of the correlation coefficient the more the variance in the annoyance score is explained by the independent variable. Table 4 shows that the correlation coefficient is in each case higher for the annoyance thermometer than for question 13.3. For all participants the correlation coefficient for vibration annoyance score using the annoyance thermometer and vibration metric is somewhat higher than for the noise and overall annoyance scores. It is somewhat surprising that for the lower VCKBL25 class the correlation coefficient of vibration annoyance and vibration level is somewhat *lower* than the correlation coefficient of overall annoyance and vibration level. However, since there is no statistically significant difference between the two coefficients, the correlation between vibration annoyance and vibration level is not different from that with overall annoyance. This implies that at the lower vibration levels overall annoyance has about the same confidence intervals as vibration annoyance. For the lower VCKBL25 class the relationships for annoyance scores and VCKBL25 are all four positive and all slopes are statistically significant different from 0. For the higher class the relationships are statistically significant negative. This implies that for the higher vibration levels all three types of annoyance decrease with increasing vibration level. This will be discussed in chapter 5, in which also a possible effect of number of vibrations on annoyance is taken into account.

<u>Summary</u>

The linear regression analysis carried out with the transformed scores due to vibrations, noise and overall annoyance on the annoyance thermometer as dependent variables, and VCKBL25 as independent variable, for all participants and for participants divided in two equal VCKBL25 classes, showed different relationships for higher and lower VCKBL25 class. For the lower VCKBL25 class the relationships of annoyance scores and VCKBL25 are statistically significant positive, but for the higher class the relationships are statistically significant negative.

For the lower VCKBL25 class the correlation coefficient of vibration annoyance and vibration level is somewhat, but not statistically significant, *lower* than the correlation coefficient of overall annoyance and vibration level and equal to the correlation coefficient if noise annoyance is the dependent variable. For the higher VCKBL25 class the correlation coefficient of vibration annoyance and vibration level is somewhat, but not statistically significant, *higher* than the correlation coefficients of overall and noise annoyance and vibration level.

5. EFFECT OF NUMBER OF VIBRATION EVENTS ON ANNOYANCE

In this chapter it will be examined whether number of vibrations has an effect on annoyance. Two types of statistical tests have been used. The first concerns a χ^2-test. The eight scores of RNE, RTE, and on the questions 13.3, 17.1, 17.2, 18, 9.1 and 11 have been taken as dependent variables. To perform the test each of these dependent variables have been divided in two classes. Also the number of perceptible vibrations per 24 hours (VIBNUM) have been divided in two classes with at most and more than 160 perceptible vibrations per 24 hours. The division in classes is such that both classes contain about equal number of participants. All eight χ^2 values turned out to be (statistically significant) different from 0 ($P < 0.05$). Therefore there is an effect from number of perceptible vibrations on the various annoyance scores. However, if the vibration levels are taken into account by dividing the participants in two equal VCKBL25 classes (VCKBL25 at most -0.571 and over -0.571) all 16 χ^2 values turned out not to be (statistically significant) different from 0 ($P < 0.05$). This implies that the number of perceptible vibrations does not have an effect on the eight vibration annoyance scores considered, if vibration level is taken into account.

Also a multiple regression analysis with VIBNUM and VCKBL25 as independent variables has been considered. First the correlation between the independent variables has been determined in order to be able to decide whether variables are allowed to be used as independent variables simultaneously in the analysis. Two variables which have a correlation with a correlation coefficient larger than about 0.7 to 0.8 or smaller than about -0.8 to -0.7 should not be used as independent variables in the analysis simultaneously. The correlation coefficient of VCKBL25 and VIBNUM is 0.84 if all participants are considered and 0.89 and 0.34 for the two VCKBL25 classes. Therefore only for the higher VCKLBL25 class VIBNUM and VCKBL25 are allowed to be entered both as independent variables in a multiple regression analysis. If in this multiple regression analysis the scores for questions 13.3, 18, 11 and 9 are used as dependent variables, then the four regression coefficients (slope of the best fitting straight line) of the scores and VIBNUM are not statistically significant different from 0 (significance levels are 0.97, 0.65, 0.25, and 0.65 respectively for questions 13.3, 18, 11 and 9). Adjusted R-values are 0.09, 0.13, 0.12 and 0.09. These values are equal to those given in table 4 if only VCKBL25 is taken as independent variable for questions 13.3, 18 and 9.1. For question 11 (noise annoyance) adjusted R is only marginally higher than R. Therefore, for the higher VIBNUM class VIBNUM does not add to the prediction of annoyance. The result of the considerations in this paragraph is therefore that VIBNUM and VCKBL25 are to be used separately as independent variables in the regression analyses.

For each of the scores of questions 13.3, 18, 11 and 9.1 the best fitting straight lines have been determined with VIBNUM and VCKBL25 each taken as independent variable separately. The results are given in table 5. Some of the data already appeared in table 4. 'B' is the slope of the best fitting straight line (between brackets the level of significance if this level is over 0.025), 'constant' the constant in the equation and R the correlation coefficient for the relationship between the dependent and independent variable. Results are presented for all participants, and for participants divided in two VIBNUM classes, and for participants divided in two VCKBL25 classes.

If the results for all participants are considered (upper part table 5) for all four annoyance scores the correlation coefficient is higher if VCKBL25 rather than VIBNUM is the independent variable. Apparently vibration level correlates higher with vibration, noise and overall annoyance than number of perceptible vibrations.

If the participants are divided in two VIBNUM classes (middle part of table 5), the relationships between annoyance scores and VIBNUM are very weak for the higher VIBNUM class: all slopes are not significantly different from 0, and all correlation coefficients are small. For this VIBNUM class the slopes of the regression lines of the relationships between VCKBL25 and annoyance scores are all statistically significant positive and the correlation coefficients of these relationships are much higher than those for the relationships between VIBNUM and annoyance scores. Therefore at higher number of vibrations, the number of vibrations is not of importance with respect to annoyance, but the levels of the vibrations are.

For the low VIBNUM class (number of trains with perceptible vibrations 160 or less per 24 hours) vibration, noise and overall annoyance increases statistically significant with number of vibrations. Note, that in this analysis vibration level is not taken into account. Also, the relationships with the number of perceptible vibrations have a somewhat higher correlation coefficient than relationships with VCKBL25. This implies that for situations with smaller number of train passages with perceptible vibrations during 24 hours, number of perceptible vibrations predict vibration, noise and overall railway annoyance somewhat better than vibration level does. The differences in the correlation coefficients are, however, not staistically significant different. Therefore, for situations with smaller number of trains with perceptible vibrations during 24 hours number of trains with perceptible vibrations predicts annoyance equally well as vibration level does.

If the participants are divided in two VCKBL25 classes (lowest part of table 5), the relationships between annoyance scores and VIBNUM for both classes are very weak: all slopes are not significantly different from 0, all correlation coefficients are very small. This implies, as was also shown in the χ^2-

tests, that number of perceptible vibrations do not have an effect on annoyance scores if vibration level is taken into account. This is illustrated in figure 1. The figure gives the best fitting straight lines of annoyance scores as a function of VCKBL25 for the two VIBNUM classes. Four measures of annoyance are used as dependent variables: vibration annoyance score of question 13.3, and scores on the annoyance thermometer for vibration annoyance, overall railway annoyance and noise annoyance. The straight lines are given for the range that VCKBL25 covers in each of the classes. The scores are slightly higher for more than 160 perceptible vibrations per 24 hours than for the lower class. The differences are, however, not statistically significant.

The figure also shows that overall railway annoyance scores are higher than noise annoyance and vibration annoyance scores. There is, however, only a slight difference between overall railway and noise annoyance score. For all participants the mean noise annoyance score is 56.0 and the mean railway annoyance score 56.1 (difference a factor 1.003). Noise annoyance scores appear to be much higher than vibration annoyance scores on the same annoyance thermometer. For all participants the mean vibration annoyance score is 37.7 and the mean noise annoyance score is 56.0. This concerns a factor 0.68. This factor is in reasonable agreement with the factor specified in Passchier-Vermeer(1998). In that report for aircraft, road and railway traffic the following relationship has been derived:

mean vibration annoyance score ≈ 0.6 mean noise annoyance score.

The results given in table 5 about vibration annoyance score are plotted in the figures 2 and 3. Figure 2 gives vibration annoyance score as a function of VCKBL25 for all participants and for participants divided in two VCKBL25 classes (left figure) and two VIBNUM classes (right figure). Figure 3 gives vibration annoyance score as a function of VIBNUM for all participants and for participants divided in two VCKBL25 classes (left figure) and two VIBNUM classes (right figure). The results in both parts of figure 3 and in the right hand side of figure 2 are quite understandable and explainable. Figure 2 (left part of the figure), however shows a discrepancy in the results that needs further clarification. As has been already stated in chapter 4 for the lower of the two VCKBL25 classes vibration annoyance increases with vibration level and for the higher class vibration annoyance decreases statistically significant with increasing vibration level. This results in a gap between the results for both classes. If the participants are divided in four classes (see for relationships within each of these classes the figure) the discrepancy even increases. The gap between vibration annoyance scores at VCKBL25 equal to - 0.571 of the two adjacent classes is then about 20. An obvious reason for the discrepancy at VCKBL25 equal to - 0.571 is the fact that only linear relationships have been considered. Presumably for higher order regression models the discrepancy would have been much smaller or might even be non-existent. Other factors that contribute to the discrepancy are the fact that transformed annoyance scores are on a

10-points scale and that there is a large scatter of the individual transformed annoyance scores at the same vibration level. Therefore the two 95% confidence intervals at VCKBL25 equal to - 0.571 are overlapping and the discrepancy is fully accounted for by the scatter in the data and the type of regression analysis.

Summary

Vibration annoyance increases if the number of perceptible vibrations increases. However, if participants are divided in two VCKBL25 classes, vibration annoyance scores within these classes are independent of number of perceptible vibrations. Therefore, the number of perceptible vibrations does not have an effect on vibration annoyance if vibration level VCKBL25 is taken into account.

For all participants vibration annoyance scores have been considered as a function of VIBNUM and of VCKBL25. The variance explained in vibration annoyance scores by VCKBL25 is larger than the variance explained by VIBNUM. This also holds for noise and overall railway annoyance. Therefore, vibration level predicts annoyance scores better than number of vibrations.

Participants have also been divided in two VIBNUM classes. For both VIBNUM classes vibration level VCKBL25 has a positive correlation with vibration, noise and overall railway annoyance. For the higher VIBNUM class vibration, noise and overall annoyance scores are independent of number of perceptible vibrations. For the lower VIBNUM class the annoyance scores increase with increasing number of perceptible vibrations. For this VIBNUM class annoyance scores correlate somewhat, but not statistically significant, better with VIBNUM than with VCKBL25.

Over the whole range of VCKBL25 considered, mean overall annoyance scores of the participants are higher than mean vibration annoyance and noise annoyance scores. There is, however, only a slight difference between overall railway and noise annoyance scores. At the same value of VCKBL25 noise annoyance scores are much higher than vibration annoyance scores on the same annoyance thermometer. For all participants the mean vibration annoyance score is 0.68 times the mean noise annoyance score. This factor is in reasonable agreement with the factor (0.6) specified in Passchier-Vermeer (1998) if noise annoyance is taken as an indicator for vibration annoyance.

6. PERCENTAGES ANNOYED PARTICIPANTS

6.1 Percentages annoyed participants for all participants

In this section the percentages annoyed participants are presented as a function of the vibration metric VCKBL25. First, the participants have been divided into 10 VCKBL25 classes, each class having about equal number of participants. VCKBL25 less than - 1.0 is the lowest class, and VCKBL25 over - 0.3 the highest class. To determine for each of these VCKBL25 classes the percentage highly vibration annoyed participants (%HAvib), percentage at least vibration annoyed participants (%Avib), and the percentage at least a little vibration annoyed participants (%LAvib), the transformed scores of question 18 (vibration annoyance thermometer) have been used as a basis. For each of the VCKBL25 classes also the transformed scores on question 9.1 with regard to overall railway annoyance (indicated by %HArail, %Arail and %LArail) and the transformed scores on question 11 with regard to noise annoyance (indicated by %HAnoise, %Anoise and %Lanoise) have been determined. The datapoints have been plotted in figure 4 for %HA, %HA rail, and %HAnoise. Figure 5 gives the percentages at least annoyed, and figure 6 the percentages at least a little annoyed. The datapoints have been fitted with first order (straight) regression lines. The coefficients of these lines are given in table 6. The 95% confidence intervals have also been plotted in the figures.

For all three percentages overall annoyance is higher than noise annoyance and vibration annoyance. Also for all three percentages noise annoyance exceeds vibration annoyance, and the difference between percentages noise and vibration annoyed increases with increasing VCKBL25.

In Passchier-Vermeer (1998) an equation has been given which allows the estimation of percentages vibration annoyed from known percentages noise annoyed by a type of transportation. This equation is:

$$\%XAvib = 0.5\ \%XAnoise \quad \text{if} \quad \%XAnoise < 50;$$

$$\%XAvib = \%XAnoise - 25 \quad \text{if} \quad \%XAnoise > 50,$$

with X is H, missing or L.

At the mean value of VCKBL25 the three percentages vibration annoyed participants have been compared with the corresponding percentages noise annoyed participants. The comparisons show that the observed percentages vibration annoyed are in good agreement with the percentages estimated from the equation given in Passchier-Vermeer (1998):

observed %HAvib = 13 estimated %HAvib = 17.5;

bserved %Avib = 31 estimated %Avib = 35;

observed %LAvib = 59 estimated %LAvib = 57.

6.2 Percentages annoyed participants for noise exposure classes

To determine whether noise exposure has an effect on percentages annoyed participants, participants have been divided in two noise exposure classes (L24 at most 39 dB(A) and above 39 dB(A)). In the figures 7, 8, and 9 the datapoints and the best fitting straight lines with 95% confidence intervals are plotted. The slope and constant of these regression lines are also included in table 6.

Figure 7 shows that the regression lines with %HAvib as dependent variable for both noise exposure classes are about the same. The same applies to %HArail. %HAnoise for the higher noise exposure class exceeds the straight line for the lower noise exposure class as should be expected. However at the highest range of VCKBL25 noise annoyance is for both classes about the same.

Figure 8 and the more so figure 9 show that there exists a large discrepancy between percentages vibration annoyed for both noise exposure classes. For the lower noise exposure class %Avib and %LAvib are increasing functions of VCKBL25, but for the higher noise exposure class percentages at least vibration annoyed and at least a little vibration annoyed are also high at the lower VCKBL25 values and hardly increase with increasing vibration level. Apparently, participants in the higher noise exposure class do not distinguish between the two components noise and vibrations in railway traffic and attribute annoyance to both components even if one component has a relatively low level.

<u>Summary</u>

Percentages highly annoyed participants, percentage at least annoyed participants, and percentage at least a little annoyed participants have been determined as a linear function of VCKBL25 for overall railway annoyance, vibration annoyance, and noise annoyance.

The three percentages vibration annoyed participants at the mean value of VCKBL25 have been compared with the corresponding percentages noise annoyed participants. The comparisons show that the observed percentages vibration annoyed are in good agreement with the percentages estimated form an equation given in Passchier-Vermeer (1998) with percentages noise annoyed as indicator for percentages vibration annoyed.

Participants have been divided in two noise exposure classes. The regression line with %HAvib as dependent variable and VCKBL25 as vibration metric of both noise exposure classes are about the same. This also holds for %HArail. %HAnoise at a given value of VCKBL25 for the higher noise exposure class is higher than for the lower noise exposure class. A large difference exists between percentages at least vibration annoyed and at least a little vibration annoyed participants in both noise exposure classes. For the lower noise exposure class %Avib and %LAvib are increasing functions of VCKBL25, and for the higher noise exposure class percentages at least annoyed and at least a little annoyed are high at the whole VCKBL25 range considered and hardly increase with increasing vibration level. This also holds for percentages noise and overall railway annoyed participants.

7. INTERACTION AND TRADE-OFF BETWEEN VIBRATION AND NOISE EXPOSURE

In Zeichart (1998) possible interactions between railway-induced vibrations and noise on vibration annoyance, noise annoyance and overall railway annoyance have been analysed. Also the trade-off between a vibration and a noise exposure metric are given in the publication. This chapter gives a summary of the results.

7.1 Interaction between vibration and noise exposure

The analyses concern the following three questions:

- Is vibration annoyance affected by noise exposure caused by the same railway traffic?
- Is noise annoyance affected by vibration exposure caused by the same railway traffic?
- To what extend is overall annoyance affected by vibration and noise exposure caused by railway traffic?

For vibration annoyance a combined measure based on ten items in the questionnaire (Zeichart et al., 1993) has been determined. A combined measure of noise annoyance has been based on eight items and for overall railway annoyance question 9.1 has been used in the analyses. The analyses have been performed separately for daytime and nighttime exposures. *Outdoors* equivalent sound levels due to railway noise have been calculated from detailed information about type of trains, distance from the railway track, meteorological and environmental conditions. (In the original German survey noise measurements have been carried out *indoors*, and an estimate of the indoors railway noise exposure has been used in the main analyses.) The participants have been divided into 9 classes according to outdoors noise exposure and indoors vibration exposure. Details of the 9 day- and nighttime classes are given in table 7. Note that a participant may be in another class for day- and nighttime.

Vibration exposure has been expressed in day- and nighttime KBR_x values, since it was shown that if the respondents are divided in two outdoors noise exposure classes the correlation coefficients for the relationships between vibration annoyance and vibration metric were somewhat higher for KBR_x than for KB_x (the metric used in the original report to specify exposure effect relationships).

In table 8 the results are given of an analysis of variance. To determine an interaction effect of daytime noise exposure on daytime vibration annoyance the combined measure of daytime annoyance questions has been taken as dependent variable and daytime equivalent sound level and KBR_WT as independent variables. For an interaction effect of nighttime noise exposure nighttime combined annoyance measure, nighttime equivalent sound level and KBR_SN have been taken as variables. The results are given in the upper part of table 8. F is the F ratio and p the significance level of F. If p is less than 0.025 usually an effect is considered to be statistically significant.

The first row of table 8 shows that vibration exposure and noise exposure both have a statistically significant effect on daytime vibration annoyance. There is no interaction between vibration and noise exposure. The second row shows that the level of the vibrations at night have no effect on nighttime vibration annoyance, but there is an effect on vibration annoyance by nighttime noise. There is also no interaction between vibrations and noise exposure.

In the second half of table 8 results are given for effects on noise annoyance. To determine an interaction effect of vibration exposure on daytime noise annoyance the combined noise annoyance measure is taken as dependent variable and daytime equivalent sound level and KBR_WT as independent variables. To determine an interaction effect of vibration exposure on nighttime noise annoyance the combined nighttime annoyance measure is taken as dependent variable and nighttime equivalent sound level and KBR_SN as independent variables. Obviously, daytime noise annoyance is determined by noise exposure, vibration exposure and an interaction effect. For nighttime noise annoyance none of the main independent variables have a statistically significant effect. If the level of significance is taken as 0.05, nighttime noise exposure does have an effect on nighttime noise annoyance.

Table 9 gives the results of the analysis if overall annoyance (scores of question 9.1) is taken as dependent variable and daytime equivalent sound level and KBR_WT as independent variables. The overall annoyance is determined by noise and vibration exposures. An interaction between both exposures does occur. Vibration annoyance affects overall railway annoyance more in the case of lower noise exposure and less in the case of higher noise exposure. Noise exposure explains 8% of the variance in overall annoyance, vibration exposure 5% and the interaction between noise and vibration exposure 3%. The variance in overall annoyance explained by the two factors is therefore 16%.

7.2 Trade-off between vibration and noise exposure metrics

A linear multiple regression analysis has been performed to determine the trade-off between KBR_WT and daytime equivalent sound level. In the multiple regression analysis the interaction effect between vibration and noise exposure has not been taken into account. Overall annoyance (question 9.1) has been taken as dependent variable and KBRL_WT (the logarithm of KBR_WT) and the equivalent sound level in the living room during daytime as independent variables. The following equation is applicable:

$$\text{Overall annoyance score} = 2.65 + 1.65\ \text{KBRL\_WT} + 0.09\ L_{Aeq,06\text{-}22h}$$

This implies that a change of KBRL_WT of 1 (or KBR_WT of 10) is equivalent to a change of 18.3 dB(A) in $L_{Aeq,06\text{-}22h}$.

<u>Summary</u>

In Zeichart (1998) possible interactions between vibration annoyance, noise annoyance and overall railway annoyance occurring from the same railway have been analysed. Also the trade-off between a metric of vibration exposure and of noise exposure are given in the publication. This report gives a summary of the results.

Conclusions are:

- Vibration and noise exposure both have an effect on daytime vibration annoyance. There is no interaction between vibration and noise exposure on vibration annoyance;
- Vibrations at night have no effect on nighttime vibration annoyance, but there is an effect on vibration annoyance by nighttime noise exposure;
- Noise and vibration exposure have an effect on noise annoyance during daytime. There is an interaction between noise and vibration exposure on daytime noise annoyance;
- Nighttime noise exposure affects nighttime noise annoyance. There is no effect on nighttime noise annoyance from nighttime vibration exposure;
- Overall railway annoyance is affected by noise and vibration exposure. An interaction between both exposures does occur. Noise exposure explains 8% of the variance in the data, vibration exposure 5% and the interaction between vibration and noise exposure 3%. The total variance explained by the two environmental factors vibration and noise exposure on overall railway annoyance is 16%.

For overall railway annoyance the trade-off between vibration level (KBR) during daytime in the living room and outdoors equivalent sound level during daytime is that a change of 18.3 dB(A) in equivalent sound level corresponds with a change of a factor 10 in vibration level.

8. CONCLUSION

This conclusion discusses four aspects of the secondary analysis to which the foregoing chapters referred.

Direction of vibrations

In the analyses only vertical vibrations have been taken into account. Although most of the railway traffic induced vibrations in dwellings in the German survey occur mainly in the vertical direction, it is stated in the German report that in 12% of the measurements (of F-train passages) the horizontal component was larger than the vertical one. In those situations the horizontal vibration velocity exceeded the vertical component on average by 3.5%. The effect of taking into account the maximal vibration level in any direction instead of the vibration level in the vertical direction seems marginal. The effect for instance on average KB_x would be only 0.4%. It is also hard to imagine that small changes in 12% of the vibration levels in the survey would have a substantial effect on the correlation of vibration level and vibration annoyance.

Frequency weighting

The vibration measurements in the survey have been performed by using the frequency-weighting of the instantaneous vibration velocities in accordance with the German regulations. In most of the German situations railway traffic induced vibrations contained measurable vibration velocities only at frequencies over 10 Hz. The German weighting curve is, after conversion of the frequency-dependent weighting function for vibration velocity to vibration acceleration, above 4 Hz essentially the same as the weighting curves specified in ISO 2631-2 (1989) and BS 6472 (1992) for vibrations in the vertical direction. This implies that the weighting of the vibrations is in agreement with weightings specified in the three Standards, if the vibrations are limited to frequencies over 4 Hz. If the vibrations would have contained frequencies below 4 Hz for sitting and standing persons (most appropriate during daytime) horizontal vibrations have according to ISO 2631-2 (1989) a weighting different from the German one and vibration annoyance might have been somewhat underestimated by using the German weighting curve. For lying persons (most appropriate during nighttime) the German, ISO and British frequency weighting curves below 4 Hz are essentially the same.

Vibration, noise and overall railway annoyance as a function of vibration level

There is a close correspondence in the data and trends obtained for the relationships between vibration annoyance and vibration level and those data and trends obtained for noise and overall annoyance. E.g. table 4 shows linear regression lines for each of the three annoyance variables which have the same trends: three positive slopes for the group of all participants and three positive and three negative slopes for the groups of participants in the higher and lower vibration level class. Relevant in this respect is the low correlation between noise and vibration levels for the three groups considered. For all participants the correlation coefficient of the relationship of equivalent sound level over 24 hours (L24) and VCKBL25 is 0.34, for the participants with the lower vibration levels the correlation coefficient is also 0.34 and for the participants with higher vibration levels the correlation coefficient is 0.29. These low correlation coefficients do therefore not explain such close correspondences. The same phenomenon is depicted in table 5. E.g., table 5 shows that not only the regression lines show the same trends, but also that the correlation coefficients for each of the three types of annoyances are about the same. In fact, the variance explained by vibration level VCKBL25 in overall and noise annoyance scores is only slightly, and statistically not significant, less than the variance explained in vibration annoyance scores. If the lower vibration levels are considered vibration level VCKBL25 explains more, but not statistically significant more, of the variance in overall annoyance than in vibration annoyance.

A similar observation has been made in Passchier-Vermeer (1998). In that report for three types of transportation (aircraft, road and railway traffic) vibration annoyance and noise annoyance have been considered as a function of noise exposure level. Also for these relationships, in which effects have been considered as a function of noise exposure level rather than as a function of vibration level, trends and data showed a close correspondence.

Taking both observations together the hypothesis emerges that there is within persons a relatively high intra-correlation between various annoyance scores.

General applicability of the results

The Zeichart et al. report and the secondary analysis provide useful information about the effects of railway vibrations on people. In effect, the German investigation is the only field investigation in which vibration level measurements are related to vibration annoyance and in which other aspects, such as simultaneous noise exposure, have been taken into account. Therefore, unfortunately, the results of the survey cannot be compared to results of other surveys and it is not possible to determine differences between surveys. Therefore other surveys are recommended. An important reason for this recommendation is also the observed weak relationship between vibration annoyance and vibration level. The correlation coefficients of the vibration exposure metrics considered and vibration annoyance scores for all respondents are at most 0.30[******]. This implies that only 9% of the variance in vibration annoyance is explained by vibration level and that other (as yet unknown) factors virtually

[******] This correlation coefficient is of the same order of magnitude as correlation coefficients observed in most socio-acoustic surveys (Miedema and Vos, 1998; Passchier-Vermeer, 1998)

should explain the other 91% of the variance. If in other situations one or more of these unknown factors would be different from those in the German situation this might result in other relationships between vibration annoyance and vibration level. A readily available example has been presented in Zeichart et al. (1993). In that report different relationships have been established for vibration annoyance in the S-train areas and in the F-train areas. Annoyance scores for vibrations in the S-train areas appeared to be about half these scores in the F-train areas for situations with equal vibration and noise exposure levels. Such differences can also be observed for other environmental exposures, see for example Miedema and Vos (1996, 1998) with respect to noise exposure and noise annoyance. Therefore usually the results of different social surveys are necessary to specify general applicable exposure effect relationships.

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Annex A TERMS, DEFINITIONS AND EQUATIONS

Displacement: A vector quantity that specifies the change of position of an object or part of it with respect to a reference frame (in metre, m).

Usually displacement is determined in three specified axes.

Velocity: A vector quantity that specifies the rate of change of displacement (in ms^{-1}).

Usually velocity is determined in three specified axes.

Acceleration: A vector quantity that specifies the rate of change of velocity (in ms^{-2}).

Usually acceleration is determined in three specified axes.

Root-mean-square value (r.m.s.): The r.m.s. value of a function, x(t), over a time interval between t_1 and t_2 is specified by the following formula:

$$x_{r.m.s.} = \frac{1}{t_2 - t_1}[\int_{t_i}^{t_2} x^2(t)dt]^{½}$$

Root-mean-quad value (r.m.q.): The r.m.q. value of a function, x(t), over a time interval between t_1 and t_2 is specified by the following formula:

$$x_{r.m.q.} = \frac{1}{t_2 - t_1}[\int_{t_i}^{t_2} x^4(t)dt]^{¼}$$

Frequency weighting: A transfer function used to modify a signal according to a required dependency on frequency.

Vibration KB-value: The value of a vibration at time t defined by:

$$KB_\tau(t) = [\frac{1}{\tau}\int_{x=o}^{t} e^{-(t-x)/\tau}\, KB^2(x)dx]^{½}$$

in which:

KB(x) the frequency-weighted vibration velocity at time x;

τ time-constant.

Vibration maximum KB-value ($KB_{Fmax,e}$): the maximum KB-value of event e occurring at a location, with the KB-value determined with time constant τ equal to 0.125 s.

KB at a specified location for a specified period (KB_x):

$$KB\_x = [\frac{1}{n} \sum_{e=1}^{n} KB_{Fmax,e}^{2}]^{½}$$

in which:

x measurement location WZ: living room, and SZ: bedroom,
observation period: daytime 06.00 - 22.00 hours, nighttime 22.00 - 06.00 hours;

n number of events during an observation period (in this report train passages).

Vibration KB_{FTi}-value: the KB_{Fmax}-value for the period T_i of 30 s. To that end the observation period is divided into periods T_i of 30 s, i indicating the i-th 30 s period.

Vibration effective KB_{Fmax} value for N periods of 30 s (KBR(N)): the value specified by:

$$KBR(N) = [\frac{1}{N} \sum_{i=1}^{N} KB_{FTi}^{2}]^{1/2}$$

in which:

N number of periods during the total observation period.

KBR at a specified location and a specified observation time (KBR_x):
KBR(N) with N equal to 1920 and 960:
for x = WZ (living room), the number of 30-second periods (N) during the daytime (16 hours) is equal to 1920 and for x = SZ the number of 30-second periods (N) during the nighttime (8 hours) is equal to 960.

Equivalent KB value of vibration event i:

$$KB_{eq,i} = [\frac{1}{T(z)} \int_0^{T_e} KB^2_{F,i}(t)\ dt]^{½}$$

in which:

$KB_{F,i}(t)$ the value of KB_F at time t of event i (in this report a train passage);

T_e the duration of the event in seconds;

T(z) a reference time, taken equal to 30 s.

Equivalent KB value at a specified location and observation time:

$$KBEQ\_xz = [\frac{1}{T(z)}\ (KB^2_{eq-,-i}]^{½}$$

Vibration dose value (VDV):

$$VDV = [\int_{t=0}^{t=T} a_w^4(t)dt]^{¼} \quad [ms^{-1.75}]$$

in which:

a_w (t) the frequency-weighted acceleration in ms^{-2};

t time in seconds;

T the period over which VDV is determined.

VDV at a specified location and observation time:

$$VDV\_xz = [\frac{1}{T(z)}(VDV^4]^{¼}$$

Equivalent sound level over a period of time:

$$L_{Aeq,T} = 10\log\frac{1}{T}\int_0^T \frac{p_A^2(t)}{p_0^2}dt \quad dB(A)$$

in which:

- p_A (t): the A-weighted sound pressure at time t;
- p_0: reference sound pressure of 2.10^{-5} Nm^{-2};
- T: duration.

Equivalent sound level over 24 hours (L24):

$$L24 = 10\log[\frac{15}{24}\ 10^{L_{Aeq,d}/10} + \frac{9}{24} 10^{(10+L_{Aeq,n})/10}] \quad dB(A)$$

in which:

- $L_{Aeq,d}$ the equivalent sound level determined in the living room for the period from 06.00-22.00 h
- $L_{Aeq,n}$ the equivalent sound level determined in the sleeping room for the period from 22.00-06.00 h.

Annex B TABLES

Table 1 Correlation coefficients for the relationships between vibration annoyance variables and vibrations metrics for participants with equivalent sound levels over 24 hours of at most 39 dB(A)

	KB_x	KBR_x	KBEQ_x	VDV_x	KBL_x	KBRL_x	KBEQL_x	VDVL_x
RTE	0.27	0.25	0.25	0.28	0.35	0.33	0.31	0.34
Q17.1	0.30	0.27	0.29	0.30	0.36	0.34	0.35	0.35
RNE	0.15	0.18	0.21	0.18	0.15	0.15	0.17	0.16
Q17.2	0.13	0.15	0.17	0.16	0.10	0.09	0.11	0.11

	VCKB25	VCKB50	VCKB1	VCKB2	VCKBL25	VCKBL50	VCKBL1	VCKBL2
Q13.3	0.31	0.30	0.30	0.29	0.29	0.28	0.27	0.26
Q 18	0.38	0.38	0.37	0.35	0.42	0.41	0.40	0.38

	VCKBR25	VCKBR50	VCKBR1	VCKBR2	VCKBRL25	VCKBRL50	VCKBRL1	VCKBRL2
Q13.3	0.31	0.31	0.31	0.30	0.28	0.27	0.25	0.24
Q18	0.35	0.34	0.34	0.33	0.38	0.37	0.36	0.35

	VCKBEQ25	VCKBEQ50	VCKBEQ1	VCKBEQ2	VCKBEQL25	VCKBEQL50	VCKBEQL1	VCKBEQL2
Q13.3	0.31	0.31	0.31	0.30	0.29	0.28	0.27	0.26
Q18	0.36	0.35	0.35	0.34	0.39	0.38	0.38	0.36

	VCVDV25	VCVDV50	VCVDV1	VCVDV2	VCVDVL25	VCVDVL50	VCVDVL1	VCVDVL2
Q13.3	0.30	0.30	0.29	0.28	0.28	0.27	0.26	0.25
Q18	0.37	0.37	0.36	0.35	0.40	0.40	0.39	0.37

Table 2 Correlation coefficients for the relationships between vibration annoyance variables and vibrations metrics for participants with equivalent sound levels over 24 hours of at more than 39 dB(A)

	KB_x	KBR_x	KBEQ_x	VDV_x	KBL_x	KBRL_x	KBEQL_x	VDVL_x
RTE	-0.05	-0.03	-0.01	-0.04	0.02	0.01	0.01	0.00
Q17.1	-0.08	-0.08	-0.07	-0.07	0.04	0.02	0.01	0.03
RNE	0.03	0.01	0.02	0.02	0.06	0.03	0.06	0.05
Q17.2	0.07	0.01	0.01	0.03	0.08	0.04	0.05	0.06

	VCKB25	VCKB50	VCKB1	VCKB2	VCKBL25	VCKBL50	VCKBL1	VCKBL2
Q13.3	-0.01	0.00	0.02	0.04	0.07	0.08	0.09	0.10
Q18	0.03	0.03	0.04	0.05	0.09	0.09	0.09	0.10

	VCKBR25	VCKBR50	VCKBR1	VCKBR2	VCKBRL25	VCKBRL50	VCKBRL1	VCKBRL2
Q13.3	-0.02	-.0.01	0.00	0.01	0.04	0.05	0.05	0.10
Q18	0.02	0.02	0.03	0.03	0.08	0.08	0.08	0.10

	VCKBEQ25	VCKBEQ50	VCKBEQ1	VCKBEQ2	VCKBEQL25	VCKBEQL50	VCKBEQL1	VCKBEQL2
Q13.3	-0.01	0.00	0.01	0.02	0.06	0.06	0.07	0.07
Q18	0.02	0.02	0.02	0.02	0.08	0.08	0.08	0.08

	VCVDV25	VCVDV50	VCVDV1	VCVDV2	VCVDVL25	VCVDVL50	VCVDVL1	VCVDVL2
Q13.3	-0.02	-0.01	0.01	0.02	0.06	0.06	0.07	0.08
Q18	0.02	0.02	0.03	0.03	0.08	0.08	0.08	0.08

Table 3 Correlation coefficients for the relationships between vibration annoyance variables and vibrations metrics.

	KB_x	KBR_x	KBEQ_x	VDV_x	KBL_x	KBRL_x	KBEQL_x	VDVL_x
RTE	-0.09	0.11	0.12	0.11	0.22	0.21	0.20	0.21
Q17.1	0.08	0.09	0.12	0.11	0.23	0.21	0.21	0.22
RNE	0.08	0.08	0.09	0.08	0.11	0.10	0.12	0.11
Q17.2	0.08	0.06	0.06	0.07	0.09	0.07	0.08	0.08

	VCKB25	VCKB50	VCKB1	VCKB2	VCKBL25	VCKBL50	VCKBL1	VCKBL2
Q13.3	0.14	0.15	0.16	0.17	0.24	0.24	0.24	0.24
Q 18	0.18	0.18	0.18	0.19	0.30	0.30	0.29	0.28

	VCKBR25	VCKBR50	VCKBR1	VCKBR2	VCKBRL25	VCKBRL50	VCKBRL1	VCKBRL2
Q13.3	0.15	0.16	0.16	0.17	0.22	0.21	0.21	0.20
Q18	0.18	0.18	0.18	0.18	0.28	0.27	0.26	0.25

	VCKBEQ25	VCKBEQ50	VCKBEQ1	VCKBEQ2	VCKBEQL25	VCKBEQL50	VCKBEQL1	VCKBEQL2
Q13.3	0.17	0.17	0.17	0.17	0.23	0.22	0.22	0.21
Q18	0.19	0.19	0.19	0.18	0.28	0.27	0.27	0.26

	VCVDV25	VCVDV50	VCVDV1	VCVDV2	VCVDVL25	VCVDVL50	VCVDVL1	VCVDVL2
Q13.3	0.15	0.16	0.16	0.17	0.23	0.23	0.23	0.22
Q18	0.19	0.19	0.19	0.18	0.29	0.28	0.28	0.27

Table 4 Information about the linear regression line with VCKBL25 as independent variable and annoyance scores of question 13.3 (vibration annoyance question), 18 (vibration annoyance thermometer), 11 (noise annoyance thermometer) and 9.1 (annoyance due to the presence of the railway). B is the slope of the best fitting straight line, constant the constant in the equation, and R the correlation coefficient for the relationship between the dependent and independent variable.

score of question	VCKBL25		
	B	constant	R
	all participants		
13.3	18.97	61.3	0.24
18	21.95	51.1	0.29
11	19.74	68.0	0.26
9.1	19.02	66.6	0.26
	VCKBL25 ≤ -0.571		
13.3	21.3	61.9	0.19
18	23.6	50.5	0.22
11	28.8	75.0	0.23
9.1	29.9	75.5	0.26
	VCKBL25 > -0.571		
13.3	- 13.9	51.7	0.09
18	- 18.5	39.6	0.13
11	- 12.6	58.1	0.09
9.1	- 11.1	57.2	0.08

Table 5 Information about the linear regression line with VCKBL25 and percentage perceptible vibrations (VIBNUM) as independent variable, and annoyance scores of question 13.3 (vibration annoyance question), 18 (vibration annoyance thermometer), 11 (noise annoyance thermometer) and 9.1 (annoyance due to the presence of the railway). B is the slope of the best fitting straight line (between brackets the level of significance if this level is over 0.025), constant the constant in the equation and R the correlation coefficient for the relationship between the dependent and independent variable.

score of question	VCKBL25			VIBNUM		
	B	constant	R	B	constant	R
			all participants			
13.3	18.97	61.3	0.24	0.051	41.4	0.17
18	21.95	51.1	0.29	0.060	28.0	0.21
11	19.74	68.0	0.26	0.060	46.2	0.20
9.1	19.02	66.6	0.26	0.051	46.8	0.17
			VIBNUM ≤ 160 per 24 hours			
13.3	16.64	58.2	0.20	0.128	33.5	0.21
18	21.10	49.4	0.27	0.184	16.1	0.31
11	17.68	64.5	0.20	0.180	34.2	0.27
9.1	18.26	65.0	0.22	0.197	33.0	0.31
			VIBNUM > 160 per 24 hours			
13.3	19.94	62.5	0.16	- 0.004 (0.90)	54.7	0.01
18	18.57	50.5	0.16	- 0.008 (0.79)	44.4	0.02
11	14.41	67.3	0.14	- 0.027 (0.37)	67.4	0.06
9.1	16.14	66.2	0.15	- 0.027 (0.36)	65.6	0.06
			VCKBL25 ≤ -0.571			
13.3	21.3	61.9	0.19	0.02 (0.38)	40.7	0.06
18	23.6	50.5	0.22	0.02 (0.27)	27.1	0.08
11	28.8	75.0	0.23	0.04 (0.09)	44.6	0.12
9.1	29.9	75.5	0.26	0.04 (0.08)	44.2	0.13
			VCKBL25 > -0.571			
13.3	- 13.9	51.7	0.09	0.01 (0.67)	54.2	0.03
18	- 18.5	39.6	0.13	0.01 (0.56)	43.0	0.04
11	- 12.6	58.1	0.09	0.02 (0.30)	57.5	0.07
9.1	- 11.1	57.2	0.08	0.01 (0.68)	59.0	0.02

Table 6 Percentage annoyed participants due to vibrations (vib) noise and the presence of the railway (rail) for all participants and for two noise exposure classes (L24 ≤ 39 dB(A) and L24 > 39 dB(A).

	% HA		% A		%LA	
	B	CONSTANT	B	CONSTANT	B	CONSTANT
ALL PARTICIPANTS						
vib	13.61	20.93	30.39	49.50	38.95	82.84
noise	20.17	47.58	31.90	80.08	23.15	95.75
rail	23.96	45.64	29.75	76.54	23.56	96,95
L24 ≤ 39 dB(A)						
vib	12.38	18.72	11.54	38.62	9.63	66.65
noise	13.63	46.90	2.92	69.06	6.41	87.93
rail	24.17	46.59	0.93	63.52	7.20	88.01
L24 > 39 dB(A)						
vib	19.62	27.14	50.11	64.71	64.06	102.52
noise	24.46	47.78	47.30	86.79	31.04	100.58
rail	24.14	45.07	52.14	89.92	30.04	103.07

Table 7 Information about the participants in Zeichart (1998) classified according to their outdoors noise exposure and indoors vibration exposure. In Zeichart (1998) *outdoors* noise exposure values have been calculated. In Zeichart et al. (1993) *indoors* values have been used.

vibration exposure class (daytime)	noise exposure class (daytime)		
	low	medium	high
low	KBR = 0.023 Leq = 50 dB(A) n = 117	KBR = 0.027 Leq = 64 dB(A) n = 117	KBR = 0.034 Leq = 71 dB(A) n = 117
medium	KBR = 0.057 Leq = 52 dB(A) n = 42	KBR = 0.058 Leq = 64 dB(A) n = 49	KBR = 0.057 Leq = 72 dB(A) n = 43
high	KBR = 0.12 Leq = 51 dB(A) n = 39	KBR = 0.12 Leq = 64 dB(A) n = 39	KBR = 0.16 Leq = 72 dB(A) n = 120
vibration exposure class (nighttime)	**noise exposure class (nighttime)**		
	low	medium	high
low	KBR = 0.016 Leq = 47 dB(A) n = 124	KBR = 0.019 Leq = 61 dB(A) n = 39	KBR = 0.022 Leq = 69 dB(A) n = 40
medium	KBR = 0.042 Leq = 48 dB(A) n = 68	KBR = 0.045 Leq = 60 dB(A) n = 36	KBR = 0.045 Leq = 69 dB(A) n = 50
high	KBR = 0.10 Leq = 50 dB(A) n = 36	KBR = 0.10 Leq = 60 dB(A) n = 36	KBR = 0.13 Leq = 72 dB(A) n = 117

Table 8 Results for the analysis of variance with combined measures of daytime and nighttime vibration annoyance scores as dependent variable in the upper part of the table and combined measures of daytime and nighttime noise annoyance scores as dependent variable in the lower part of the table. F is the F ratio and p the significance level of F.

annoyance variable	main effect V		main effect N		interaction effect V*N	
	F	p	F	p	F	p
daytime vibration annoyance	4.11	0.0001	3.38	0.0001	1.16	0.25
nighttime vibration annoyance	1.75	0.14	3.25	0.01	1.04	0.40

	main effect N		main effect V		interaction effect N*V	
	F	p	F	p	F	p
daytime noise annoyance	9.81	0.0001	2.19	0.007	1.73	0.01
nighttime noise annoyance	2.55	0.04	0.63	0.64	1.00	0.43

Table 9 Results for the analysis of variance with the overall annoyance due to the presence of the railway (question 9) as dependent variable and vibration and noise exposure as independent variables. F is the F ratio and p the significance level of F.

main effect N		main effect V		interaction effect N*V		explained variance		
F	p	F	p	F	p	N	V	N*V
16.3	0.0001	9.68	0.0001	3.00	0.02	8%	5%	3%

Annex C Figures

Figure 1 Annoyance scores as a function of VCKBL25 for two classes of number of perceptible vibrations per 24 hours.

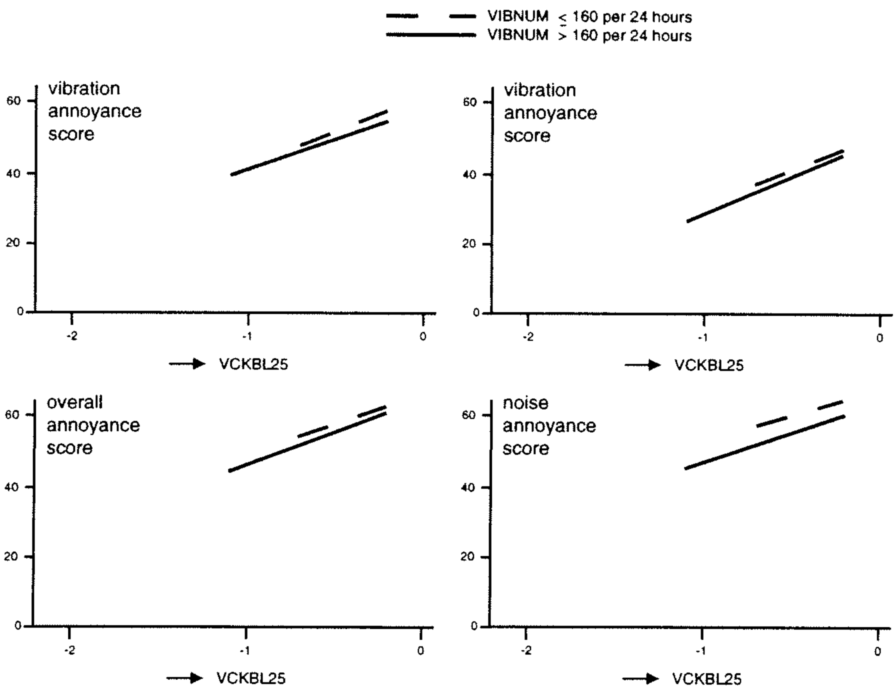


Figure 2 Vibration annoyance score as a function of VCKBL25 for all participants and participants in 2 and 4 VCKBL25 classes (left figure) and all participants and paricipants in 2 VIBNUM classes (right figure).

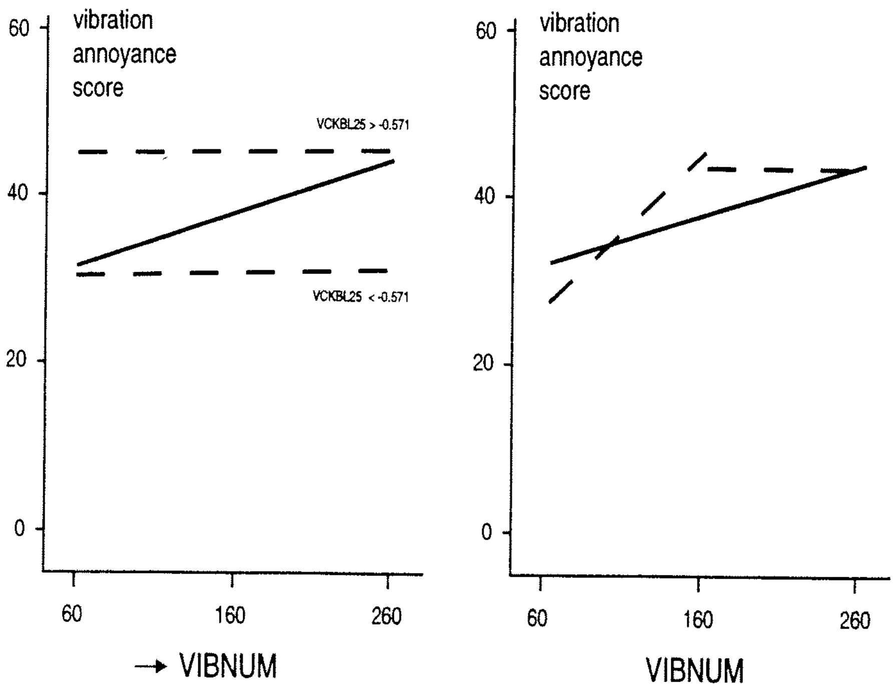


Figure 3 Vibration annoyance score as a function of VIBNUM for all participants and participants in 2 VCKBL25 classes (left figure) and all participants and paricipants in 2 VIBNUM classes (right figure).

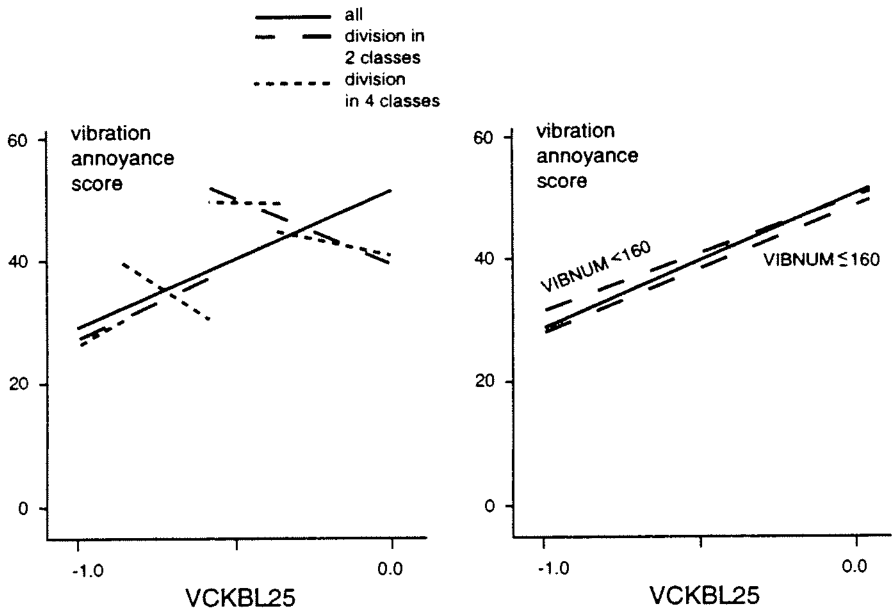


Figure 4 Percentage highly annoyed participants as a function of VCKBL25. Left figure vibration annoyance, middle figure overall annoyance and right figure noise annoyance. Datapoints and best fitting straight lines with 95% confidence intervals.

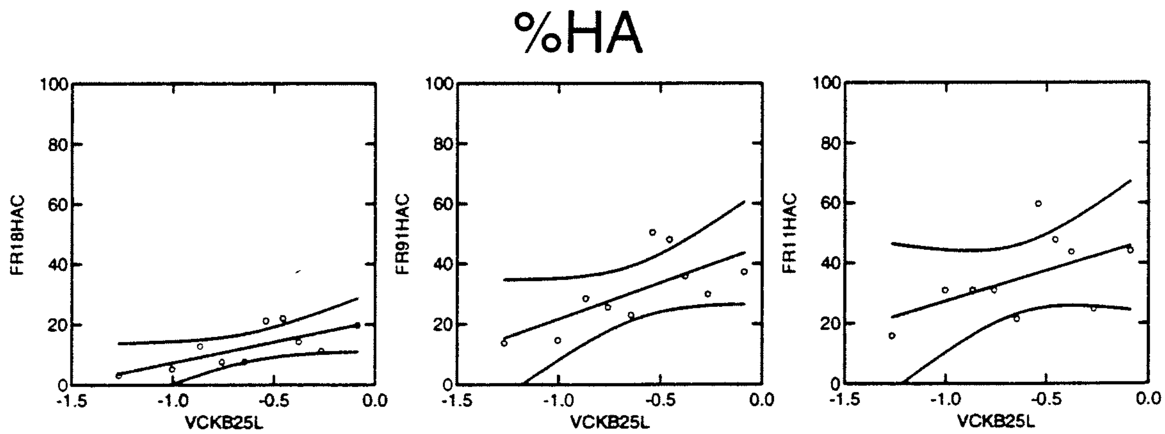


Figure 5 Percentage at least annoyed participants as a function of VCKBL25. Left figure vibration annoyance, middle figure overall annoyance and right figure noise annoyance. Datapoints and best fitting straight lines with 95% confidence intervals.

%A

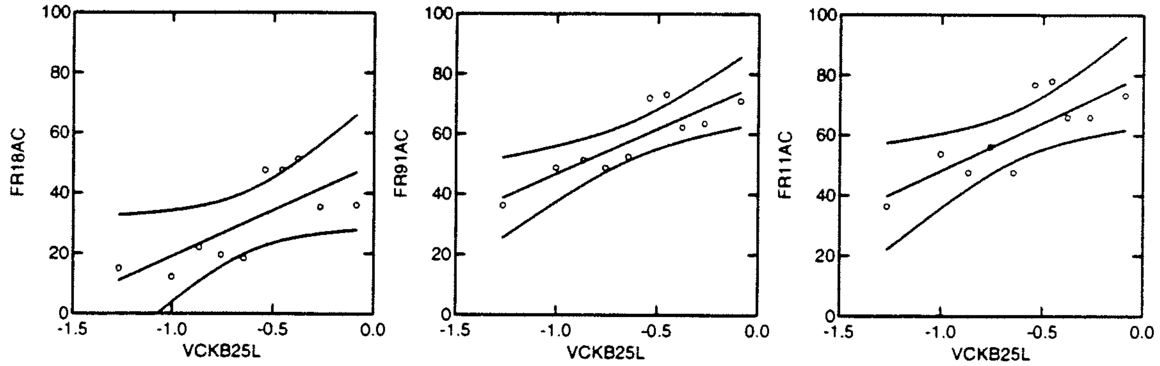


Figure 6 Percentage at least a little annoyed participants as a function of VCKBL25. Left figure vibration annoyance, middle figure overall annoyance and right figure noise annoyance. Datapoints and best fitting straight lines with 95% confidence intervals.

%LA

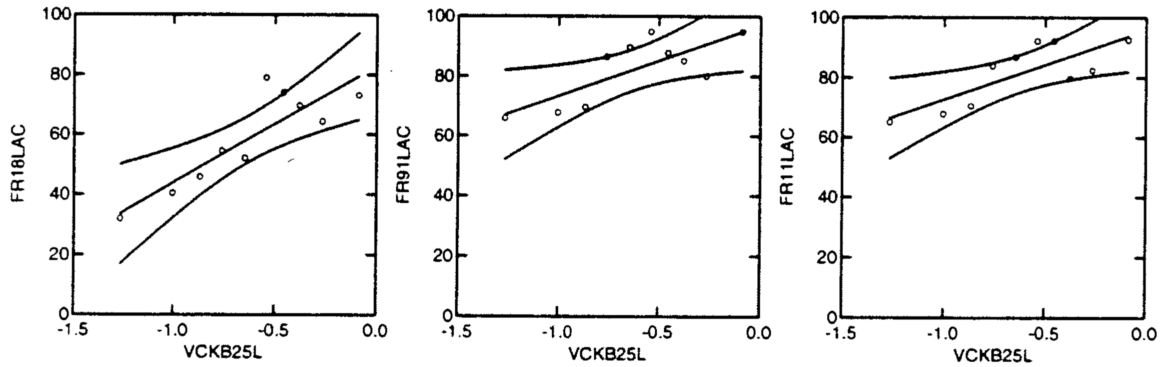
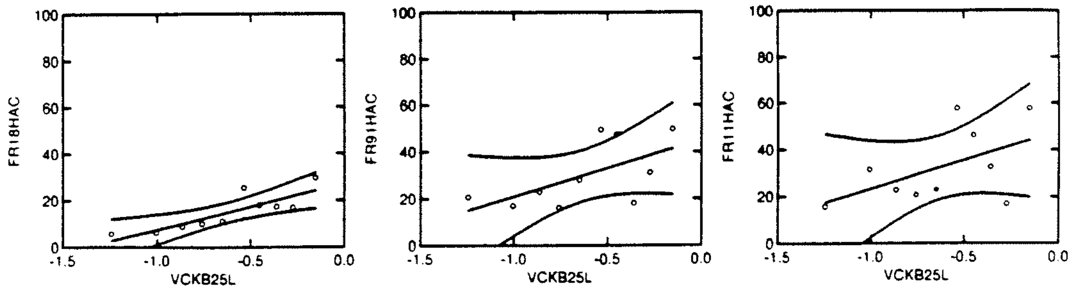


Figure 7 Percentage highly annoyed participants as a function of VCKBL25 for two noise exposure classes: indoors L24 ≤ 39 dB(A) and indoors L24 > 39 dB(A). Left figures vibration annoyance, middle figures overall annoyance and right figures noise annoyance. Datapoints and best fitting straight lines with 95% confidence intervals.

%HA L24<=39 dB(A)



%HA L24>39 dB(A)

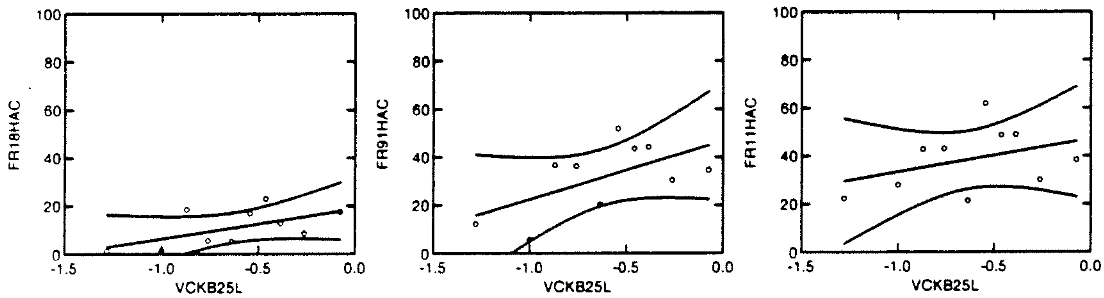
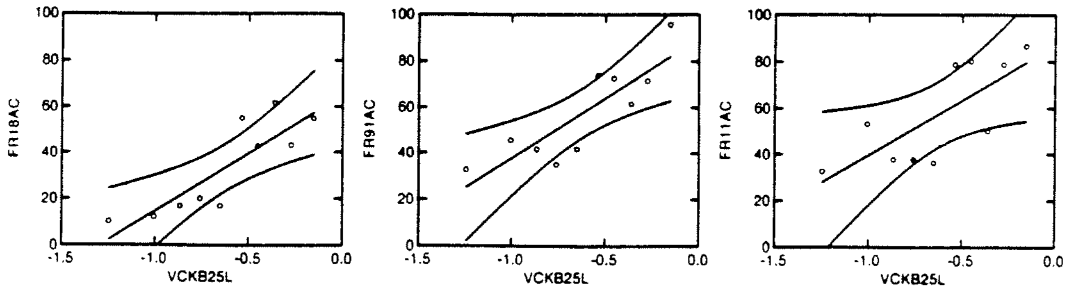


Figure 8 Percentage at least annoyed participants as a function of VCKBL25 for two noise exposure classes: indoors L24 ≤ 39 dB(A) and indoors L24 > 39 dB(A). Left figures vibration annoyance, middle figures overall annoyance and right figures noise annoyance. Datapoints and best fitting straight lines with 95% confidence intervals.

%A L24<=39 dB(A)



%A L24>39 dB(A)

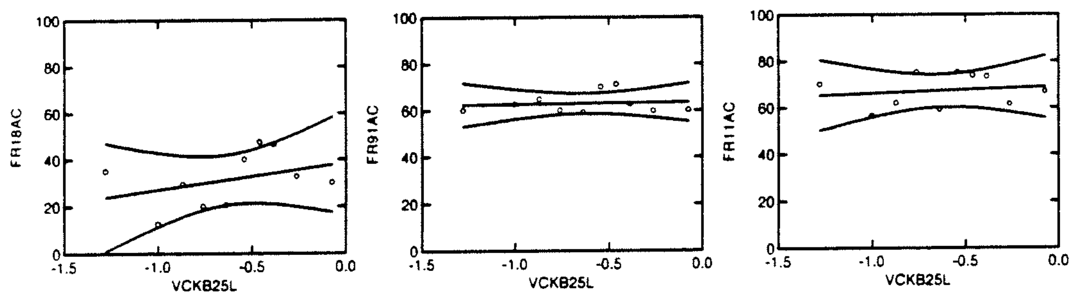
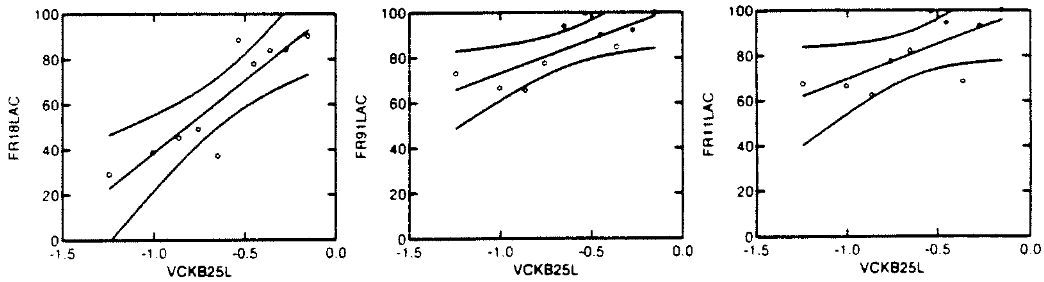
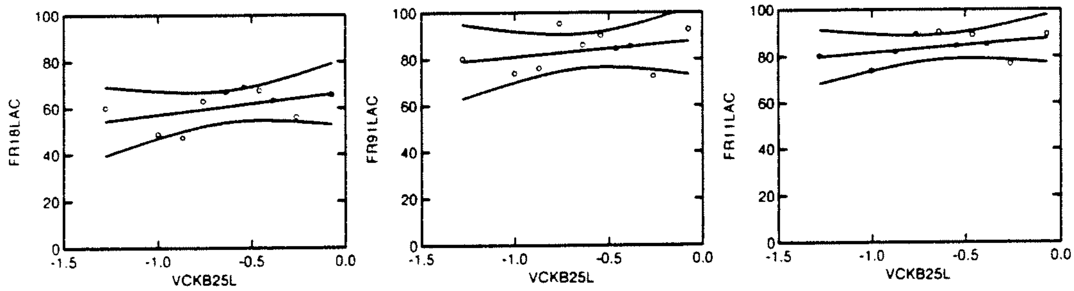


Figure 9 Percentage at least a little annoyed participants as a function of VCKBL25 for two noise exposure classes: indoors L24 $\leq$ 39 dB(A) and indoors L24 > 39 dB(A). Left figures vibration annoyance, middle figures overall annoyance and right figures noise annoyance. Datapoints and best fitting straight lines with 95% confidence intervals.

%LA L24<=39 dB(A)



%LA L24>39 dB(A)



Repro: *TNO-PG*
projectnr.: *40303*