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Vibrations in the living environment

Factors related to vibration perception and annoyance

TNO Prevention and Health

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EXECUTIVE SUMMARY

The TNO-PG database with socio-acoustic surveys

In this report an analysis is presented of data on vibration annoyance that are available in a database, which has been established by TNO-PG. The database is an archive of surveys about annoyance caused by environmental *noise*. However, in many of the surveys questions were also asked about the perception of *vibrations* and annoyance due to *vibrations* which, in many instances, accompany noise exposure in the living environment. Although the database contains information about metrics related to environmental *noise*, it does not have any information about *vibration* metrics. Therefore, it is not possible to determine relationships between vibration metrics and vibration annoyance from the data. In the report, vibration annoyance is related to other variables that will be specified below. The indicators specified in the report can be used, with limited accuracy, for an estimation of vibration annoyance in descriptive environmental studies, such as the Netherlands 'Environmental Outlook'.

The analysis concerns vibrations from three types of transportation: aircraft, road and railway traffic.

Questions to be answered

The following questions are studied in the report:

1. Is there a relationship between vibration annoyance, the perception of vibrations and a metric that quantifies *noise* exposure?
2. Is there a relationship between vibration annoyance and noise annoyance?
3. Which situational and individual variables affect the perception of vibrations and annoyance due to vibrations in the living environment?

Datasets

A *dataset* is derived from a socio-acoustic survey and contains the data with respect to one type of transportation. If a survey considers more than one type of transportation, more than one dataset has been derived from that survey. Each dataset is a matrix containing for each respondent in the dataset a value (sometimes missing) for each variable. All in all 28 datasets in the TNO-PG database contain questions about vibration perception and/or vibration annoyance. These datasets comprise in total data on more than 36000 respondents (22400 questioned about vibrations from aircraft, 6500 about vibrations from road traffic and 7200 about vibrations from railraod traffic). However, in many datasets information about some of the variables are missing.

Response variables

Two response variables with regard to vibrations are considered:

- Annoyance due to vibrations. For a group of respondents this variable is specified by the mean (standardized) vibration annoyance score (VIBANNOY). Standardization of the annoyance scores implies that irrespective of the actual annoyance question, the standardized score of a respondent is equal to what his score would have been on a scale of 0 (not at all annoyed) to 100 (extremely annoyed). The annoyance distribution of a group of respondents is also specified by the percentages of respondents with standardized vibration annoyance scores exceeding one of the three cut off points: 72 (indicated by %HAvib: percentage respondents highly annoyed by vibrations), 50 (%Avib: percentage respondents at least annoyed by vibrations) and 28 (%LAvib: percentage respondents at least a little annoyed by vibrations);
- Perception of vibrations. For a group of respondents this variable is specified by the mean (standardized) perception score (PREVIB). Standardization of the perception scores has been carried out along the lines specified for VIBANNOY. The scores also vary between 0 and 100.

For comparison purposes, also the 'best' *noise* annoyance score of each of the respondents has been used in the analyses. For groups of respondents, the noise annoyance distribution is specified by the mean standardized noise annoyance score (NOISANNOY) and the percentages highly noise annoyed respondents (%HAnoise) , at least noise annoyed respondents (%Anoise) and at least a little noise annoyed respondents (%LAnoise).

Variables to which the response variables are related

Noise exposure variables and *other physical variables* for which a possible relationship with the response variables has been considered, are:

1. Equivalent *sound* level* over 24 hours of the noise produced by a type of transportation, determined outside (at a specified distance of) the dwellings of the respondents. In the equivalent sound level over 24 hours no adjustments have been applied with respect to the time of occurrence of the

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[*] The equivalent sound level over a period of time T is the exponential average of all sound levels occuring during T. The exponential averaging implies that in the equivalent sound level more weight is given to higher sound levels than to lower ones.

sounds during the 24 hours. The equivalent sound level over 24 hours due to a specific noise source, such as aircraft, road- and railway traffic, takes into account the number and levels of the noise events in a specific way;

2. Arithmetic average of the SEL[**] values of the *noise* events over 24 hours;
3. Number of events per 24 hours;
4. Distance of the dwelling of the respondent from the road or railway under consideration. No information is available about distance in the datasets on aircraft;
5. Percentage heavy traffic: in the case of road traffic lorries and in the case of railway traffic goods trains.

Other *situational* and *individual* variables examined concern:

1. Whether or not sound insulation measures have been applied to the dwelling of the respondent;
2. Whether the respondent is owner or rentar of the dwelling;
3. Sex of the respondent;
4. Whether or not the respondent is using the type of transportation;
5. Startle of the respondent by the type of transportation;
6. Fear of the respondent with regard to the type of transportation.

Unfortunately information about the soil structure at the various locations of the dwellings is not available.

Vibration annoyance and vibration perception scores

Noise exposure metrics and other physical variables

All datasets show increasing vibration annoyance and vibration perception scores with increasing equivalent sound levels over 24 hours. Almost all datasets also show that these scores increase with average SEL value and with number of events per 24 hours. However, the correlation coefficients[***] (and therefore the explained variances in the data) of vibration annoyance score with average SEL value and with number of events per 24 hours are in almost all datasets (much) smaller than the

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[**] The SEL-value of a noise event is the equivalent sound level of the noise event over the period during which the noise event exists, normalized to one second. E.g. if the equivalent sound level of a noise event lasting 10s is 90 dB(A), the SEL value of this noise event is 90 + 10 lg10 = 90 + 10 = 100 dB(A). If the event would have lasted for 100s, and would have the same equivalent sound level, the SEL value would have been 90 + 10 lg 100 = 90 + 20 = 110 dB(A).

[***] The strenght of a relationship between two variables can be quantified by the correlation coefficient R. R^2 represents that part of the variance in the data that is explained by the relationship. E.g. if R=0.60 for the relationship of vibration annoyance score and equivalent sound level over 24 hours, then $R^2 = 0.36$. Then 36% of the variance in vibration annoyance score is explained by variations in the equivalent sound level over 24 hours.

correlation coefficients of vibration annoyance score with equivalent sound level over 24 hours. Therefore preference should be given to the use, if possible, of the equivalent sound level over 24 hours as an indicator to estimate vibration annoyance and vibration perception, since this parameter allows a 'better' estimation of these scores than the other two variables.
The (linear) relationships of vibration annoyance score with equivalent sound level over 24 hours are given in figure 11 of the main text. The three relationships are about the same for the three types of transportation. The relationship for the three types of transportation together is:

$$\text{VIBANNOY} \approx 0.83L - 20 \qquad \text{for} \;\; L > 40\ \text{dB(A)}$$

with L the equivalent sound level over 24 hours.
If the equivalent sound level is known it can be used as indicator for VIBANNOY by using the formula given above.

The three types of transportation have different relationships for vibration perception (see figure 12 of the main text). At the lower equivalent sound levels over 24 hours the vibration perception score for road traffic is much lower than for railway traffic and aircraft. At the higher equivalent sound levels the vibration perception score is about equal for the three modes of transportation: at 75 dB(A) the vibration perception scores are all three about 50. At that equivalent sound level the mean vibration annoyance score is about 40.

If $L_{Aeq,24h}$ is used as independent variable, inclusion of percentage heavy traffic as independent variable in the analysis hardly increases the explained variance.

Correlation coefficients show that *noise* annoyance scores are more accurately estimated from the equivalent *sound* level over 24 hours than *vibration* annoyance and perception scores for each of the types of transportation. The variance in the noise annoyance scores explained by the equivalent sound level over 24 hours is in the case of aircraft about 2 times the explained variance for vibration annoyance and perception scores. In the case of road traffic this factor is about 1.3 and in the case of railway traffic about 1.2. Therefore the equivalent *sound* level predicts noise annoyance score and vibration annoyance score in the case of road and railway traffic about equally well.

All datasets show, as should be expected, a decrease in vibration annoyance and vibration perception score with increasing distance of the dwelling to the source. The correlation between vibration annoyance and distance is, on average, (much) less than the correlation between vibration annoyance and equivalent sound level over 24 hours. Correlation coefficients of vibration annoyance scores and distance are, in the case of the road traffic datasets, so small that it seems inappropriate to use distance as an indicator to estimate vibration annoyance scores. The road traffic datasets are a mixture of datasets on highways, (free flow and non-free flow) arterial roads, and local roads. In the case of railway traffic, the correlation coefficients are much higher than in the case of road traffic. If distance would be the only known physical or noise parameter, this variable would, in the case of railway traffic, allow a rough estimate of mean vibration annoyance score. In the case of road traffic the explained variance increases considerably if percentage lorries is added to distance as independent variable. Presumably, due to the extra weight of lorries, usually driving at about the same speed as passenger cars, more vibration at higher levels are induced by lorries than by passenger cars. The explained variance does hardly increase if percentage goods trains is added to distance as independent variable. Presumably the slower speed of goods trains counterbalances the extra weight of these trains compared to that of passenger trains in causing vibrations.

The main conclusion is that the equivalent sound level over 24 hours is a 'better' indicator for vibration annoyance and vibration perception scores than any (combination of) the other noise metrics and physical variables (average SEL, number of vehicles, distance and PCHEAVY) studied.

Situational and individual variables

Gender of the respondents, whether they are employed or not in conjunction with the type of transportation, whether they own their dwelling or not and whether or not sound insulating measures have been taken, have, on average, no effect on vibration annoyance scores. This las conclusion is not surprising, since sound insulating measures usually have no effect on the transmission of vibrations.

There appears to be a relatively high correlation between vibration perception and annoyance scores and fear and startle scores. These correlations may reflect a causal relationship (fear/startle does cause increase in vibration annoyance) on the one hand and/or an attitudinal aspect (individuals have a tendency to choose about the same position on a scale, irrespective of their actual feelings) on the other hand. With the data at hand it is not possible to give a conclusion with respect to these possible explanations.

Noise annoyance score as an indicator for vibration annoyance score

It has been shown that the relationships for each of the three types of transportation between mean noise annoyance score and mean vibration annoyance score are about the same. If the three types of transportation are taken together, the relationship between the mean vibration annoyance score and the mean noise annoyance score can be specified as:

$$\text{VIBANNOY} \approx 0.6\ \text{NOISANNOY}$$

Using this equation noise annoyance score can be used as indicator for vibration annoyance score in descriptive environmental studies.

Percentages vibration annoyed respondents

Equivalent sound level over 24 hours

Relationships have been determined between the equivalent sound level over 24 hours and the percentages highly vibration annoyed, at least vibration annoyed and at least a little vibration annoyed respondents for each of the three types of transportation separately.

A multilevel linear regression analysis has been carried out with %HAvib, %Avib and %LAvib as dependent variables and $L_{Aeq,24h}$ as independent variable. Each dataset represented a separate level. %HAvib, %Avib and %LAvib are zero for values of $L_{Aeq,24h}$ below 40 to 50 dB(A) (depending on function and percentage vibration annoyed) and are at the higher values of $L_{Aeq,24h}$ largest for aircraft, followed by road traffic and smallest for railway traffic.

Percentages noise annoyed respondents

The percentages vibration annoyed respondents have been related to the corresponding percentages noise annoyed respondents for the three types of transportation together. Where appropriate, e.g. in the case of estimations in descriptive environmental studies, percentages noise annoyed persons can be used as indicator for percentages vibration annoyed persons by using the following equation (see also figure 22 of the main text):

$\%HAvib = 0.5\ \%Hanoise$ if $\%HAnoise \leq 50$;

$\%Avib = 0.5\ \%Anoise$ if $\%Anoise \leq 50$;

$\%LAvib = 0.5\ \%LAnoise$ if $\%LAnoise \leq 50$;

and

$\%HAvib = \%HAnoise - 25$ if $\%HAnoise > 50$;

$\%Avib = \%Anoise - 25$ if $\%Anoise > 50$;

%LAvib = %LAnoise- 25 if %LAnoise >50.

Answers to the questions

Three questions have been raised, which can be answered shortly as follows:

1. Is there a relationship between vibration annoyance, the perception of vibrations and a metric that quantifies *noise* exposure? Yes, $L_{Aeq,24h}$ is such a metric. It can be used as indicator in environmental descriptive studies;
2. Is there a relationship between vibration annoyance and noise annoyance? A correlation between vibration and noise annoyance could be quantified with reasonable accuracy;
3. Which situational and individual variables affect the perception of vibrations and annoyance due to vibrations in the living environment? Startle and fear are highly correlated to vibration perception and annoyance. However, the data do not permit to determine to which extent this correlation reflects a causal relationship. Other variables studied have no relationship with vibration perception and annoyance. Data on soil structure could not be included in the analysis.

1. INTRODUCTION

This report concerns vibration annoyance in the living environment. It has been produced as a part of a project on this subject, which has been commissioned by the Ministry of Housing, Spatial Planning and the Environment to TNO-PG. In this report an analysis is presented of data on vibration annoyance in a database established by TNO-PG. Detailed information about the database is given in Miedema and Vos (1996, report PG 96.070). The database is an archive of original studies about annoyance caused by environmental *noise*. However, in many of the studies questions were also asked about the perception of and annoyance due to *vibrations* related to the noise sources.

The database contains detailed information about metrics related to environmental *noise*. This information has been used to establish relationships between noise exposure metrics and noise annoyance (Miedema and Vos, 1998, submitted for publication). The database does, however, not contain any information about *vibration* metrics. Therefore, it is not possible to determine relationships between vibration metrics and vibration annoyance from the data. In the report, vibration annoyance is related to other variables. The results can be used, with limited accuracy, for an estimation of vibration annoyance in descriptive environmental studies, such as the Netherlands 'Environmental Outlook'.

The following questions are studied in the report:

1. Is there a relationship between vibration annoyance, the perception of vibrations and a metric that quantifies *noise* exposure?
2. Is there a relationship between vibration annoyance and noise annoyance?
3. Which situational and individual variables affect the perception of vibrations and annoyance due to vibrations in the living environment?

Most of the data in the database concern transportation sources. The data on sources other than transportation (building sites, hammering, weapons) constitute a relatively small heterogeneous mixture of sources and therefore were not used.

The structure of the report is as follows. In chapter 2 an overview is given of the available data. Chapter 3 specifies the response variables and chapter 4 the variables to which the response variables will be related. Chapter 5 discusses the analyses with regard to the mean vibration annoyance and mean vibration perception scores, and chapter 6 the analyses with regard to the percentages vibration annoyed respondents. In chapter 7 a conclusion is given. References are given after chapter 7. All tables are given in annex A and all figures in annex B.

2. DATA

The terminology referred to in Miedema and Vos (1996) about sets of data in the database is used in this report. A *survey* refers to all data generated by one study. A *dataset* is derived from a survey and contains the data with respect to one type of transportation (aircraft, road traffic, railway traffic). A dataset is a matrix containing for each respondent in the dataset a value (sometimes missing) for each variable. Some surveys concern more than one type of transportation. From those surveys more than one dataset has been derived.

Only those datasets in the TNO database are used for analysis that include information on vibration perception or vibration annoyance of the respondents. A specification of the datasets is given in table 1 (in annex A at the end of the report). Each dataset is labelled by its code from Fields' catalogue of noise annoyance surveys (Fields, 1994), if the survey concerns one type of transport. Those datasets which come from surveys with two or more types of transport are each labelled by the Fields' code followed by the type of transport (2: road traffic; 3 or 4: railway traffic, with 3: trains and 4: trams). With respect to the six railway traffic datasets: dataset NET-2764 is the only dataset that solely concerns trams. Four of the other railway surveys concern trains and GER-192 includes the data of 135 respondents about trams and of 1513 respondents about trains. These 1648 data (labelled GER-1923) have been treated as one dataset in the main analyses. This will be justified in the report by a comparison of some results from GER-1923 for trains and trams separately. In the report the datasets are denoted by the numbers in Fields'code without the reference to the country in which the survey was carried out.

28 datasets were analysed, consisting in total of data on more than 36000 respondents (counting 2238 respondents more than once, if they appear in more than one dataset).

3. RESPONSE VARIABLES

The datasets contain information on two aspects of vibrations in the living environment of the respondents:

- Perception of vibrations;
- Annoyance due to vibrations.

In the questionnaires of the various surveys questions about vibration perception and annoyance have a varying number of response categories. These response categories have been standardized (see Miedema and Vos, 1996). Dependent upon the response of a respondent and upon the number of response categories of a question, a response score has been assigned to a respondent. Such a score corresponds to the score for the midpoint of the response category the respondent selected[*].

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

- the mean of the standardized vibration annoyance scores of the respondents in the group, denoted by VIBANNOY;
- the percentage of standardized vibration annoyance scores exceeding a cut off point. For a detailed description of the way how to arrive at 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 respondents highly annoyed by vibrations), 50 (percentage denoted by %Avib, percentage respondents at least annoyed by vibrations) and 28 (percentage denoted by %LAvib, percentage respondents at least a little annoyed by vibrations).

To describe the vibration perception distribution in a group of respondents, the mean of the standardized vibration perception scores of the respondents is used. This parameter of a group of respondents is indicated by PREVIB. Standardization of the perception scores has been carried out along the lines specified for VIBANNOY. The scores also vary between 0 and 100.

For comparison purposes, also the 'best' *noise* annoyance score of each of the respondents has been used in the analyses (for the specification of 'best', see Miedema and Vos, 1996). On a population level, the mean of the standardized noise annoyance scores (indicated by NOISANNOY) and the percentage highly noise annoyed respondents (%HAnoise), the percentage at least noise annoyed respondents (%Anoise) and the percentage at least a little noise annoyed respondents (%LAnoise) will be used in the report.

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[*] A category midpoint score is determined as follows: $\text{score}_{\text{category } i} = 100(i - ½)/m$ where m is the number of categories and i = 1,...., m the rank number of the category, starting with the lowest response category.

4. OTHER VARIABLES

The noise exposure of a respondent is characterized by:

1. Equivalent sound level over 24 hours (denoted by $L_{Aeq,24h}$), determined outside the dwelling of the respondent;
2. Average SEL value of the noise events during 24 hours[**].

Physical aspects that are assumed to have an effect on vibration perception and annoyance are:

1. Number (n) of events per 24 hours. In the report 10 times the logarithm of the number is used (10 lg number). Note that $L_{Aeq,24h}$ is the sum of average SEL, 10 lg number and a constant;
2. Distance of the dwelling of the respondent from the source. In the report 10 times the logarithm of the distance is used (10 lg distance);
3. Percentage heavy traffic (PCHEAVY). For road traffic percentage heavy traffic is the percentage lorries. The specification of 'lorry' has not been given in all surveys. For railway traffic percentage heavy traffic is the percentage goods trains.

Other aspects that might be correlated with perception of and annoyance due to vibrations and which could be examined in this report concern:

1. Whether or not sound insulation measures have been applied to the dwelling of the respondent;
2. Whether the respondent is owner or renter of the dwelling;
3. Sex of the respondent;
4. Whether or not the respondent is using the type of transportation or not;
5. Startle by the type of transportation. The standardized startle score[***] is used;
6. Fear for the type of transportation. The standardized fear score[****] is used.

NOISANNOY is, like the standardized startle and fear score, also a variable that might be correlated with vibration annoyance and perception.

[**] The average SEL value is calculated as follows. Let the number of noise events (passages of airplanes, road vehicles, trains or trams) be n per 24 hours. Then $SEL = L_{Aeq,24h} - 10lgn + 49.4$.

[***] The standardized startle score has been obtained from the responses of the respondents to a question on startle, in the same way as VIBANNOY and PREVIB have been obtained from the questions about vibration annoyance and vibration perception, respectively.

[****] The standardized fear score has been obtained from the responses of the respondents to a question on fear, in the same way as VIBANNOY and PREVIB have been obtained from the questions about vibration annoyance and vibration perception, respectively.

5. VIBRATION ANNOYANCE SCORE AND VIBRATION PERCEPTION SCORE

5.1 Introduction

In this chapter an analysis is given of the data about the vibration annoyance and vibration perception scores. In paragraph 5.2 the mean vibration annoyance and perception scores are presented as a function of the two noise exposure metrics and the three physical variables specified in chapter 4. Effects of individual and situational variables on vibration perception and annoyance are discussed in paragraph 5.3. Paragraph 5.4 discusses the possible relationship between vibration annoyance score and noise annoyance score.

5.2 Vibration annoyance and perception scores as a function of noise and other physical variables

Introduction

In Miedema and Vos (1996) it was shown that large differences in the relationships of noise annoyance and noise metrics exist between surveys. The same turns out to be applicable to vibration annoyance and vibration perception, as will become clear further in this report. Due to these large 'between survey' differences, analyses are first carried out per individual dataset.

Unfortunately various datasets do not have information on all five variables. For instance, only in 4 road traffic datasets and in 5 railway traffic datasets information is available on the distance of the dwelling of the respondent to the source of vibrations and none of the aircraft datasets contains information about distances. Three road traffic and 4 railway traffic datasets have PCHEAVY as independent variable.

Where possible a multiple regression analysis is carried out with VIBANNOY and PREVIB as dependent variable. In the analysis $L_{Aeq,24h}$, SEL and 10lg number will not be used simultaneously in the analysis, since $L_{Aeq,24h}$ has an intrinsic relationship with SEL and 10 lg number. Further the correlation between the various independent variables has been determined in order to be able to decide whether variables will be used simultaneously as independent variables in the analysis. Two variables which have a too high correlation coefficient (as a rule of thumb larger than 0.70 or smaller than -0.70) should not be used in an analysis simultaneously. For all but one of the datasets the correlation coefficient of $L_{Aeq,24h}$ and 10 lg distance is much smaller than -0.50 (in the exception of dataset 072 the coefficient is equal to -0.49). Therefore it has been decided not to use $L_{Aeq,24h}$ and 10 lg distance simultaneously in the analysis. For all 7 datasets that contain PCHEAVY as variable the correlation coefficient of PCHEAVY and $L_{Aeq,24h}$ is low enough to consider $L_{Aeq,24h}$ and PCHEAVY together in a multiple regression analysis. The correlations between PCHEAVY and 10 lg distance also allow these two variables to be used together in a multiple regression analysis.

Singular regression analysis per dataset

A singular linear regression analysis has been carried out with the vibration annoyance score (VIBANNOY) as dependent variable. $L_{Aeq,24h}$, average SEL, 10 lg number and 10 lg distance are the (separate) independent variables. Table 2 gives for each dataset, if data are available, for each of the independent variables the regression coefficient (slope) (B) of the best fitting straight line of VIBANNOY on the variable. This slope shows whether the relationship between variables is positive or negative. The correlation coefficient (R) (100 times the quadratic value of R is the percentage of the variance in VIBANNOY explained by the variable considered) for the relationship with VIBANNOY is also given in table 2. Together with the values of B the table includes the level of significance (in brackets) of B, for those datasets where this level exceeds 0.025 (level of significance for a two-sided test). If the level of significance exceeds 0.025, the hypothesis that VIBANNOY is not dependent upon the variable cannot be rejected.

Table 2 shows that the slopes of all best fitting straight lines of VIBANNOY on $L_{Aeq,24h}$ are positive and that the level of significance for all datasets is less than 0.025 (in nearly all cases this level turned out to be even less than 0.001).

The average SEL also has a positive relationship with VIBANNOY, except in the road traffic dataset 120. Apparently, for this dataset the positive relationship of VIBANNOY with $L_{Aeq,24h}$ (the metric which includes the contributions of all road vehicles) changes into a negative relationship with SEL (the metric that is representative for one ‘average’ road vehicle and that is in principle independent of number of road vehicles per 24 hours). This dataset does have the largest range in numbers of vehicles per 24 hours (from about 200 to 200000 per 24 hours). Therefore average SEL stands for situations with very high traffic density (which appear to have the highest values of $L_{Aeq,24h}$) and for situations with very low traffic density (apparently with low values of $L_{Aeq,24h}$). The results for this dataset clearly show that average SEL is not an appropriate metric to relate annoyance to.

The next columns of table 2 show that VIBANNOY increases with increasing (10 times the logarithm of) the number of events per 24 hours for most of the datasets, with the exception of dataset 240. (In this dataset for 38% of the respondents the number of airplanes is 48.9 per 24 hours and for 62% of the respondents the number is 86.7 per 24 hours. Ten times the logarithm of the numbers therefore does have a very small range in this dataset and other factors determine to a larger degree vibration annoyance in the two subgroups).

The correlation coefficients (and therefore the explained variances in the data) of average SEL and of 10 lg number with VIBANNOY are in almost all datasets much smaller than the correlation coefficients of VIBANNOY with $L_{Aeq,24h}$. Therefore, average SEL and 10 lg number are not included in the following analyses, and only $L_{Aeq,24h}$ (which is equal to the sum of average SEL, 10 lg number and a constant) will be used as independent variable.

The last column of table 2 shows that there is a negative relationship between vibration annoyance and distance of the dwelling from the source. All regression coefficients are negative and the probability that the regression coefficient is not statistically significant different from 0 is in all cases less than 0.001. The correlation coefficient of vibration annoyance with distance is, however, on average smaller than the correlation coefficients of VIBANNOY and $L_{Aeq,24h}$.

In table 3 the results are given of the linear regression analysis of PREVIB on $L_{Aeq,24h}$ and on 10 lg distance of the dwelling from the source. The same trends are visible as observed in table 2 with VIBANNOY as dependent variable: there is in each dataset a positive regression coefficient for PREVIB on $L_{Aeq,24h}$ and a negative regression coefficient for PREVIB on 10 lg distance. The slopes and the correlation coefficients for PREVIB are, however, on average smaller than in the case of VIBANNOY.

In the figures 1 to 6 best fitting straight lines, for each of the datasets separately, have been plotted for vibration annoyance score, vibration perception score and, to be able to compare the results with vibration scores, also for *noise* annoyance score (for the 'best' noise annoyance measure) as a function of $L_{Aeq,24h}$. Each line covers the range over which data on $L_{Aeq,24h}$ are available in the dataset. The results are clustered for aircraft in the first three figures and for both road and railway traffic in the figures 4 to 6. Obviously all three effect parameters do increase with increasing $L_{Aeq,24h}$ for each of the datasets, with the exception of dataset 3613 and noise annoyance score. (Dataset 3613 contains 71 respondents only. It is unclear why noise annoyance decreases with $L_{Aeq,24h}$ in this dataset).

The spread between the lines is considerable. For the highest and lowest lines effects differ by about a factor 2. This holds not only for vibration annoyance and perception scores, but also for noise annoyance scores. Note the outlying position of the straight line for dataset 153 in the case of vibration annoyance score. Dataset 153 is the only dataset for which vibration annoyance is a dichotomous variable. For all other datasets the question whether a respondent is annoyed by vibrations is on at least a four point scale.

The scoring procedure for dichotomous variables usually results in relatively high mean scores[*****]. Therefore, with respect to vibration annoyance, dataset 153 will be omitted from further analysis. With regard to vibration perception (also a dichotomous function in survey 153), dataset 153 will be used, since many of the datasets use a dichotomous vibration perception variable. With respect to noise annoyance, this variable is in dataset 153 on a five point scale.

In the figures 7 to 9 vibration annoyance score, vibration perception score and noise annoyance score is given as a linear function of 10 lg distance for road and railway traffic (data for aircraft are lacking). Just as with the regression lines of the scores with $L_{Aeq,24h}$, the spread between the straight lines for the various datasets is considerable.

In the Introduction it was mentioned that survey 192 contains (apart from the dataset on road traffic) a dataset on train traffic and a dataset on tram traffic, with trams passing on straight tracks. In figure 10 the vibration annoyance score for both datasets has been plotted as a function of $L_{Aeq,24h}$ and of 10 lg distance. Since the values of $L_{Aeq,24h}$ in the tram dataset have a small range of 3 dB(A) and since the range of 10 lg distance is also small (0.5), the results for trams are given as datapoints. The figure shows that the vibration annoyance scores for both means of transport are about the same in this dataset. Whether the trams are included or not, the slope of the regression lines remain nearly unchanged (slope of VIBANNOY with $L_{Aeq,24h}$ changes from 1.50 to 1.51 and the slope with 10 lg distance from - 3.86 to - 3.80) .

Multiple regression analysis per dataset

For each of the seven datasets with data on PCHEAVY, adjusted R has been determined with PCHEAVY and $L_{Aeq,24h}$ as independent variables, and VIBANNOY and PREVIB as dependent variables. Table 4 gives adjusted R, and the first order regression coefficients B (slopes) of the relationships between $L_{Aeq,24h}$ and PCHEAVY with VIBANNOY and PREVIB, the significance of the (normalized) first order regression coefficients if the level of significance exceeds 0.025.

For each of the seven datasets the slope of VIBANNOY and of PREVIB on $L_{Aeq,24h}$ is positive. For each of the three road traffic datasets the slopes of VIBANNOY on PCHEAVY are positive, and the one for PREVIB also. This implies that with increasing percentage of heavy traffic VIBANNOY does increase at equal values of $L_{Aeq,24h}$. However, only for dataset 1922 the slope is statistically different from 0. For one

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[*****] The question in the questionnaire of survey 153 was: are you ever annoyed by vibrations from trains? Standardization of the responses implies for a dichotomous function that if a respondent answers no, his standardized vibration annoyance score is 25. If the respondent answers yes, his standardized vibration annoyance score is set at 75. In dataset 153 270 out of the 671 respondents do not perceive vibrations, 224 do perceive vibrations, but are not annoyed and 177 perceive vibrations and are annoyed. This results in a mean vibration annoyance score of 38.2. On a 4 point scale, the score for 'no' is 20, and for 'yes' it varies between 40, 60 and 80 and the average score of the respondents that are annoyed by vibrations will therefore usually not be 75 on a 4 point scale.

railway traffic dataset (116) the slopes of VIBANNOY and of PREVIB on PCHEAVY are positive (but not statistically significant) and for the other two datasets the slopes are negative (statistically significant). This last finding implies that at a given $L_{Aeq,24h}$, vibration annoyance decreases with increasing percentage goods trains. Possibly $L_{Aeq,24h}$ (which includes a contribution of noise from goods trains) overestimates the contribution of goods trains on vibration annoyance. The adjusted R if PCHEAVY as well as $L_{Aeq,24h}$ are used in the multiple regression analysis are in most datasets about equal to the correlation coefficients if $L_{Aeq,24h}$ is used as the only independent variable (compare table 4, column VIBANNOY, adjusted R with table 2, third column). Differences between adjusted R and correlation coefficients differ by at most 0.02. **Therefore, inclusion of PCHEAVY as independent variable in the analysis hardly increases the explained variance if $L_{Aeq,24h}$ is already included as independent variable.**

In table 5 the results are given if PCHEAVY and 10 lg distance are used in the multiple regression analysis. Adjusted R in the case of a multiple regression in which 10 lg distance and PCHEAVY are included as independent variables is for railway traffic at most 0.02 larger than if 10 lg distance is the only independent variable (compare table 5 with table 2 and 3). In the case of road traffic, adjusted R with VIBANNOY as dependent variable in the two datasets considered increases from 0.14 to 0.20 and from 0.39 to 0.48. Adjusted R with PREVIB as dependent variable increases from 0.12 to 0.23. **Therefore in the case of road traffic the explained variance increases considerably if PCHEAVY is added to 10 lg distance as independent variable. This is not the case for railway traffic.** This may be explained by presumed differences in speed between heavy and other vehicles. In the case of road traffic differences in the speed of lorries and of passenger cars are usually small. The much higher weight of the lorry will therefore set the soil into vibration to a much larger degree. Goods trains usually have a much smaller speed than passenger trains. Therefore the lower speed is at least paretically counterbalancing the extra weight in causing vibrations.

Below, the correlation coefficients of VIBANNOY and PREVIB on $L_{Aeq,24h}$ from the singular regression analysis are compared with adjusted R determined in the multiple regression analysis with PCHEAVY and 10 lg distance as independent variables:

dataset	type	dependent variable	R for $L_{Aeq,24h}$	adjusted R for PCHEAVY and 10 lg distance
72	road	VIBANNOY	0.40	0.20
1922	road	VIBANNOY	0.46	0.39
116	rail	VIBANNOY	0.30	0.33
1923	rail	VIBANNOY	0.51	0.38
365	rail	VIIBANNOY	0.14	0.12
72	road	PREVIB	0.12	0.23
116	rail	PREVIB	0.44	0.49
153	rail	PREVIB	0.25	0.22
365	rail	PREVIB	0.10	0.12

From the information above it is concluded that $L_{Aeq,24h}$ is a 'better'indicator for VIBANNOY than combinations of PCHEAVY and 10 lg distance.

If 10 lg number is included as the third independent variable (PCHEAVY and 10 lg distance being the other two) in the multiple regression analysis, adjusted R is only 0.01 higher than calculated if PCHEAVY and 10 lg distance are the only two variables.

Analysis per type of transportation

Figures 1 to 9 show a large variation between datasets. The best way to take this variation into account if the data of the various datasets are combined is by using a multi-level model (Miedema and Vos, 1998, presented for publication). Such a multi-level model will be applied in chapter 6 on percentages annoyed respondents. With regard to the vibration annoyance and perception scores, data will be aggregated by simply considering the data per type of transportation. In this respect it should be remembered that the results of the analysis have a limited usefulness.

In table 6, for each type of transportation separately, information is given on the best fitting straight lines of VIBANNOY and PREVIB with $L_{Aeq,24h}$ and with 10 lg distance, if the data of all respondents are taken together. In figure 11 the vibration annoyance score and in figure 12 the vibration perception score has been plotted as a function of $L_{Aeq,24h}$. There is not much difference between the relationships of vibration annoyance score with $L_{Aeq,24h}$ for the three types of transportation. Therefore the first order regression line for all respondents together (dataset 153 excluded) is also given in figure 11.

This function has the following equation:

$$\text{VIBANNOY} = 0.83\ L_{Aeq,24h} - 20.$$

With regard to perception of vibrations as a function of $L_{Aeq,24h}$, the best fitting straight lines for the three modes of transportation seem to deviate considerable. At the lower equivalent sound levels the vibration perception score for road traffic is much lower than for railway and aircraft traffic. At the higher equivalent sound levels the vibration perception score is about equal for the three modes of transportation: at 75 dB(A) the vibration perception score are all three about 50. At that equivalent sound level the mean vibration annoyance score is about 40.

In the figures 13 and 14 vibration annoyance and perception score has been plotted as a function of 10 lg distance for road and railway traffic. Table 6 shows that for road traffic the correlation coefficients of the two scores with $L_{Aeq,24h}$ are much larger than for these scores with 10 lg distance. In fact, the correlation coefficients for road traffic are so small that it seems inappropriate to use distance as a parameter to estimate vibration scores. Note in table 2 that only 2 road traffic datasets contain information about VIBANNOY and distance. This conclusion is therefore based on a limited number of observations. By far the most data in these two dataset concern highway and free flowing arterial road traffic. Only about 4% of the data concern local roads. It has been further explored whether the number of road vehicles might have an effect on the low correlation between VIBANNOY and distance for road traffic noise. Although the correlation coefficients of the relationship between 10 lg distance and 10 lg number is for the datasets separately 0.00, this correlation coefficient for the combined datasets is 0.07. The calculated regression coefficient of the relationship of 10 lg number and 10 lg distance of 0.15 implies an increase of a factor 1.5 in number if distance increases with a factor 10. This implies that situations have been selected in which larger distances from the road correspond with larger number of vehicles. It seems reasonable that this selection decreases the correlation between VIBANNOY and distance from the road. In the case of railway traffic, the correlation coefficients of the two scores with 10 lg distance are nearly three times higher than in the case of road traffic. However, taking into account that the correlation coefficients of the scores with $L_{Aeq,24h}$ are larger than with 10 lg distance, preference should be given to $L_{Aeq,24h}$ in estimating vibration annoyance and vibration perception scores for railway traffic.

The lower part of table 4 gives the results of the multiple regression analysis, if the data for road traffic are considered together and if the data for railway traffic are considered together. For road traffic there are positive relationships of VIBANNOY and PREVIB with $L_{Aeq,24h}$ and with percentage heavy traffic. For railway traffic there are positive relationships of VIBANNOY and PREVIB with $L_{Aeq,24h}$ and negative relationships with percentage heavy traffic.

Results of the multiple regression analysis with PCHEAVY and 10 lg distance as independent variables and VIBANNOY and PREVIB as dependent variables are given at the end of table 5. For road as well as railway traffic the relationships of VIBANNOY and PREVIB with 10 lg distance are negative. For road traffic the relationships of VIBANNOY and PREVIB with PCHEAVY are positive and for railway traffic negative. The result that VIBANNOY has a negative relationship with percentage heavy traffic in the case of railway traffic is not in agreement with an earlier publication on this subject (Miedema, 1993). Miedema found that for PCHEAVY less than 10%, vibration annoyance score was less than for higher percentages in situations with equal number of trains and equal distances from the railway track. The analysis by Miedema has been based on the same three railway datasets that were used in the present analysis with PCHEAVY as independent variable. Differences in the analysis by Miedema and the present analysis are:

. Miedema used distance as independent variable instead of 10 lg distance;

. Miedema used number of trains in 24 hours instead of 10 lg number per 24 hours;

. Miedema used distance, PCHEAVY and number per 24 hours simultaneously in the analysis. In the present analysis 10 lg n cannot be used as independent variable together with PCHEAVY since the correlation coefficient of these two variables is -0.59. Therefore a multiple regression analysis in which 10 lg distance, 10 lg n and PCHEAVY are all three included simultaneously is not permitted. This implies that the results in the Miedema report, in which all three variables have been entered in the analysis simultaneously cannot be duplicated in this report;

. Miedema excluded the data on trams in dataset 1923.

To compare some of the results presented by Miedema with the present results, for the three railway traffic datasets together the data have been divided in two classes with PCHEAVY less and over 10% (the lower class has 688 and the upper class 4540 respondents). For both classes a multiple regression analysis has been carried out with VIBANNOY as dependent variable and 10 lg distance and PCHEAVY as independent variables. The slopes of the regression lines are both statistically significant different from 0. Figure 15 gives a result. VIBANNOY is plotted against PCHEAVY for the two distances 30 and 100 m. Also the regression lines are given for the group not divided in two classes. After the division in two classes, VIBANNOY increases with PCHEAVY increasing from 0 to 10%, and then decreases (in the Miedema results the regression line remains constant for PCHEAVY over 10%. The increase in VIBANNOY for the lower percentages heavy traffic is about the same as given in figure 15). Since it cannot be easily understood why VIBANNOY first increases and then decreases with increasing PCHEAVY a possible interaction with $L_{Aeq,24h}$ has been examined. For the lower PCHEAVY class the median value of $L_{Aeq,24h}$ is 58.2 dB(A) and for the higher class 53.7 dB(A). This decrease in equivalent sound level fully explains the decrease in VIBANNOY with increasing PCHEAVY. Within the lowest PCHEAVY class there is a slight statistically insignificant increase in $L_{Aeq,24h}$ with increasing PCHEAVY. Therefore $L_{Aeq,24h}$ does not explain the increase of VIBANNOY with PCHEAVY in the lower PCHEAVY class.

5.3 Vibration annoyance score and vibration perception score as a function of other variables

In this chapter the effects on vibration annoyance and vibration perception scores by the six variables given in chapter 4 are considered. First each variable is considered separately and those variables that are highly correlated with vibration annoyance or perception scores will be used in a multiple regression analysis. Table 7 gives the results per dataset about the regression lines with VIBANNOY as dependent variable and each of the six variables as independent variable. The slopes of all best fitting straight lines of VIBANNOY on the standardized startle and fear scores are positive and statistically significant, with exception of dataset 239 for fear. For four out of five aircraft datasets the correlation coefficient with startle as independent variable is larger than that with $L_{Aeq,24h}$ as independent variable. This also holds for fear in the case of datasets 024 and 032, but not in the case of the other datasets. The correlation between vibration annoyance score and scores for startle and fear may be influenced by a cause effect relationship (fear/startle does cause increase in vibration annoyance) on the one hand and an intrinsic relationship between these variables (individuals have a tendency to choose about the same position on a scale, irrespective of their actual feelings) on the other hand. Without any data on vibration magnitudes these two factors cannot be distinguished.

Table 7 shows that the results with respect to dependency of respondents on the type of transportation for employment, whether respondents own their dwelling or whether sound insulating measures have been taken, are different from dataset to dataset. In some datasets the slope of the best fitting straight lines are positive and in other datasets they are negative. An analysis of all data per type of transportation also shows that there are no statistically significant effects. Note the very large regression coefficient for dataset 153 in the case of sound insulation measures. This large value is caused by the fact that the 5 respondents for which the dwelling was acoustically isolated, all stated that they were vibration annoyed (for a dichotomous variable this results in an individual vibration annoyance score equal to 75). For the other 666 respondents the mean vibration annoyance score was equal to 37.9. Taking into account the very few respondents on which this result is based and the fact that vibration annoyance is a dichotomous variable in this dataset, no general conclusions are possible about the effect of sound insolation of dwellings on vibration annoyance. Note in figure 6 that the noise annoyance scores in dataset 153 are relatively low.

Table 7 also shows the results of the correlation between VIBANNOY and gender. A positive slope ($B > 0$) means that women have a lower vibration annoyance score than men. The slopes of the best fitting straight lines are positive and negative and statistically not significant. The results if the data are analysed by type of transportation are also not statistically significant. Therefore there is no effect of gender on vibration annoyance score.

From the results presented in table 7 it is concluded that startle and fear may have a relationship with vibration annoyance, and the other four variables have not. To further explore a possible relationship of VIBANNOY with fear and startle, a multiple regression analysis has been performed with fear, startle, $L_{Aeq,24h}$ and10 lg distance as independent variables. Also PREVIB and NOISANNOY have been entered as dependent variable in the analysis. In table 8, adjusted R is given for each of the datasets separately with VIBANNOY, PREVIB and NOISANNOY as dependent variables and $L_{Aeq,24h}$, distance, fear and startle as independent variables. The table shows that the multiple R of startle and $L_{Aeq,24h}$ as independent variables and VIBANNOY as dependent variable is in 7 out of the 8 datasets (the exception is dataset 239) much larger than the correlation coefficient with $L_{Aeq,24h}$ as independent variable only. This implies that startle itself, and not through a covariance with $L_{Aeq,24h}$, does have a relationship with vibration annoyance score. The same holds, to a somewhat lesser extend, also for VIBANNOY and fear. The trends for PREVIB and NOISANNOY are the same as for VIBANNOY. Note the high value of adjusted R for dataset 022 if $L_{Aeq,24h}$ and startle are taken as independent variables and NOISANNOY as dependent variable. $L_{Aeq,24h}$ explains only 20% of the variance and both factors together explain 64% of the variance in NOISANNOY. It should be remembered, however, that this high correlation does not necessarily reflect a cause effect relationship between startle and noise annoyance.

5.4 Vibration annoyance score and noise annoyance score

For each of the three modes of transportation the (linear) relationships between VIBANNOY and NOISANNOY has been determined. The slopes of the three regression lines are between 0.50 and 0.60. In all three cases the (statistically significant) constant in the equation of VIBANNOY against NOISANNOY is less than 3. A constant of less than 3 implies that if the noise annoyance score is 0, the vibration annoyance score is less than 3. For two reasons equations are presented without a constant:

- The vibration and noise annoyance scores have been standardized such that these scores are never equal to 0. In the database the lowest scores are at least 5. The equations therefore are applicable for scores over 5 only. At higher scores, the difference between the values of VIBANNOY estimated from NOISANNOY in using equations with or without a constant is very small;
- NOISANNOY can be used as an indicater in situations where the noise annoyance score is known. In situations without any traffic NOISANNOY will be taken as 0. If NOISANNOY is then taken as indicator for VIBANNOY, the estimate of VIBANNOY should also be 0 and not have a small positive value.

In table 9 the slopes of the regression lines, without a constant, and the correlation coefficients are given for the three types of transportation separately. Apparently there is not much difference between the three types of transportation. Therefore the regression line is also given for all data together. Note the relatively high correlations between VIBANNOY and NOISANNOY. As already mentioned with respect to the fear and startle scores, it is unknown whether these high correlations are due to a cause effect relationship of these two variables (noise annoyance does cause an increase in vibration annoyance) or due to intrinsic factors (people choose for each of the variables relatively the same side of the scale). Apparently the relationship between VIBANNOY and NOISANNOY does not differ much for the various types of transportation. If the three types of transportation are taken together, the relationship between the mean vibration annoyance score and the mean noise annoyance score can be specified as:

$$\text{VIBANNOY} \approx 0.6 \text{ NOISE ANNOY}$$

This implies that for a noise annoyance score of 10, the vibration annoyance score is 6. If the noise annoyance score is 60, then the vibration annoyance score is 35.

6. VIBRATION ANNOYANCE PERCENTAGES

6.1 Introduction

In chapter 3 three cut off points for determining a percentage vibration annoyed respondents have been specified: 72 (resulting percentage denoted by %HAvib, percentage respondents highly annoyed by vibrations), 50 (percentage denoted by %Avib, percentage respondents at least annoyed by vibrations) and 28 (percentage denoted by %LAvib, percentage respondents at least a little annoyed by vibrations). In paragraph 6.2 these percentages will be given as a function of $L_{Aeq,24h}$.

In chapter 3 also the three percentages noise annoyed respondents have been specified: percentage highly noise annoyed respondents (%HAnoise), percentage at least noise annoyed respondents (%Anoise) and percentage at least a little noise annoyed respondents(%LAnoise). In paragraph 6.3 the relationships between the corresponding percentages vibration and noise annoyed respondents will be explored.

6.2 Percentages as a function of $L_{Aeq,24h}$

In chapter 5 it has been shown that a substantial variation exists in the mean vibration annoyance score of the various datasets, even if the $L_{Aeq,24h}$ values are about equal (see the figures 1 and 4). This is also the case for the three percentages vibration annoyed respondents. Therefore, a multilevel (linear regression) analysis has been carried out with %HAvib, %Avib and %LAvib as dependent variables and $L_{Aeq,24h}$ as independent variable. Each dataset represents a separate level. In the figures 16, 17 and 18 the results have been plotted for each of the types of transportation separately. The equations of the linear regression lines are given in table 10.

6.3 Percentages vibration annoyed as a function of percentages noise annoyed

In determining the relationships between the percentages vibration annoyed and percentages noise annoyed for each of the three types of transportation together, in the fitting procedures it has been considered to use linear and quadratic functions. If quadratic functions of %HAvib and %LAvib are used, the values of adjusted R are larger than for linear functions. Adjusted R is about the same for linear and quadratic functions of %Avib. Therefore, quadratic functions of %HAvib and %LAvib and linear functions of %Avib are used for the relationships with percentages noise annoyed. It turned out that the relationships for the three types of transportation are not statistically different. Therefore have been determined using all datasets together, irrespective of the type of transportation. In figure 19 %HAvib has been plotted against %HAnoise, figure 20 gives %Avib against %Anoise and figure 21 %LAvib against %LAnoise. The following equations apply:

$$\%HAvib = -\ 0.0090\ (\%HAnoise)^2 + 0.85\ (\%HAnoise);$$

$$\%Avib = 0.53\ (\%Anoise) + 1.4;$$

$$\%LAvib = 0.0091\ (\%LAnoise)^2 - 0.25\ (\%LAnoise) + 14.0.$$

The three functions are plotted together in figure 22. The three functions can be summarized by the following two visually determined equations:

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

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

with X is H, missing or L.

7. CONCLUSION

In the Introduction three questions have been raised, which can be answered shortly as follows:

1. Is there a relationship between vibration annoyance, the perception of vibrations and a metric that quantifies *noise* exposure? Yes, with certain limitations $L_{Aeq,24h}$ is such a metric.
2. Is there a relationship between vibration annoyance and noise annoyance? A correlation between vibration and noise annoyance could be quantified with reasonable accuracy..
3. Which situational and individual variables affect the perception of vibrations and annoyance due to vibrations in the living environment? Startle and fear are highly correlated to vibration perception and annoyance. However, the data do not permit to determine to which extent this correlation reflects a cause effect relationship Other variables have no relationship with vibration perception and annoyance.

Ad 1.

The correlation coefficients R in table 8 (8th column) show that, on average, *noise* annoyance scores are more accurately estimated from the equivalent *sound* level over 24 hours than *vibration* annoyance and perception scores. From the correlation coefficients of the datasets an average correlation coefficient of VIBANNOY has been determined per type of transportation. The square of this average correlation coefficient is a measure of the variance in VIBANNOY explained by the equivalent sound level over 24 hours. This variance in noise annoyance score explained by the equivalent sound level over 24 hours is, on average, for aircraft 2 times the variance explained for vibration annoyance score. In the case of road traffic this factor is about 1.3 and for railway traffic about 1.2. Therefore the equivalent sound level over 24 hours predicts vibration annoyance score in the case of road and railway traffic only slightly less well as noise annoyance score. The equivalent sound level over 24 hours predicts vibration annoyance score considerable less well than noise annoyance score in the case of aircraft.

The vibration annoyance score can be estimated from $L_{Aeq,24h}$ (L) by using the following equation:

$$\mathrm{VIBANNOY} = 0.83L - 20 \qquad \text{for } L > 40 \text{ dB(A)}$$

Percentages vibration annoyance can be estimated from:

aircraft:	$\%\mathrm{HAvib} = 0.49L - 17.2$
road traffic:	$\%\mathrm{HAvib} = 0.66L - 27.2$
railway traffic:	$\%\mathrm{HAvib} = 0.37L - 14.4$

aircraft: $\%Avib = 0.71L - 20.5$
road traffic: $\%Avib = 1.17L - 49.2$
railway traffic: $\%Avib = 0.85L - 35.5$

aircraft: $\%LAvib = 1.17L - 33.7$
road traffic: $\%LAvib = 1.98L - 73.8$
railway traffic: $\%LAvib = 1.58L - 64.7$

Ad 2.

The following equations have been given to estimate measures of vibration annoyance from measures of noise annoyance:

1. $VIBANNOY \approx 0.6\ NOISANNOY$

2. $\%HAvib = 0.5\ \%HAnoise$ if $\%HAnoise \leq 50$;
$\%Avib = 0.5\ \%Anoise$ if $\%Anoise \leq 50$;
$\%LAvib = 0.5\ \%LAnoise$ if $\%LAnoise \leq 50$;
and
$\%HAvib = \%HAnoise - 25$ if $\%HAnoise > 50$;
$\%Avib = \%Anoise - 25$ if $\%Anoise > 50$;
$\%Lavib = \%LAnoise - 25$ if $\%LAnoise > 50$.

Ad 3.

Gender, dependency of respondents on the type of transportation for employment, whether respondents own their dwelling or whether sound insulating measures have been taken have no effect on vibration annoyance score.

Correlations between vibration perception and annoyance scores and startle and fear scores are relatively high. However, these correlations may be influenced by a cause al relationship (fear/startle does cause increase in vibration annoyance) on the one hand and/or attitudes of the respondents (individuals have a tendency to choose about the same position on a scale, irrespective of their actual feelings) on the other hand. The data do not allow any decisions on this matter.

Unfortunately the datasets did not contain any information about the soil structure.

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Annex A

Table 1 Datasetson aircraft included in analyses in this report,

Fields' code	Name of the survey	Number of respondents (for this source)
Aircraft Noise		
AUL-210	Australian Five Airport Survey (1980)	3284
FRA-239	French Combined Aircraft/Road Traffic Survey (1984)	570
NET-240	Schiphol Combined Aircraft/Road Traffic Survey (1984)	573
NOR-311	Oslo Airport Survey (1989)	1529
NOR-328	Bodo Military Aircraft Exercise Study (1991)	497
NOR-366	Vaernes Military Aircraft Exercise Study (1990)	389
UKD-024	Heathrow Aircraft Noise Survey (1967)	4515
UKD-242	Heathrow Combined Aircraft/Road Traffic Survey (1982)	1988
UKD-238	Glasgow Combined Aircraft/Road Traffic Survey (1984)	607
USA-082	LAX Airport Noise Study (1973)	681
USA-022	U.S.A. Four-Airport Survey (phase I of Tracor Survey) (1967)	3235
USA-032	U.S.A. Three-Airport Survey (phase II of Tracor Survey) (1969)	2771
USA-044	U.S.A. Small City Airports (small City Tracor Survey) (1970)	1792
Road Traffic Noise	Total Aircraft (13 surveys)	22437
AUS-329	5-Area Tirol Traffic Noise Survey (1989)	826
CAN-120	Western Ontario University Traffic Noise Survey (1975)	751
GER-192	German Road/Railway Noise Comparison Study (1978/1981)	1648
GER-373	Retingen Road Traffic/Aircraft Survey (1987)	438
NET-106	Dordrecht Home Sound Insultation Study (1974)	419
NET-258	Amsterdam Home Sound Insultation Study (1975)	363
NET-361	Netherlands Environmental Pollution Annoyance Survey (1983)	880
TRK-367	Istanbul Trans-Europe Motorway Survey (1995)	154
UKD-072	English Road Traffic Survey (1972)	1942
Railway Noise	Total Road Traffic (9 Surveys)	6521
GER-192	German Road/Railway Noise Comparison Study (1978/1981)	1648
NET-276	Netherlands Tram and Road Traffic Noise Survey (1983)	519
NET-153	Netherlands Railway Noise Survey (1977)	671
NET-361	Netherlands Environmental Pollution Annoyance Survey (1993)	71
SWE-365	Swedish 15-site Railway Study (1992)	2833
UKD-116	British National Railway Noise Survey (1975/1976)	1431
	Total Railway (6 surveys)	7173

Table 2 Information on the regression of the vibration annoyance score with various variables. B is the slope of the best fitting straight line, R is the correlation coefficient. If cells are empty, the vibration annoyance score and/or the data on the variable are missing in the dataset. Together with the values of B the table includes the the level of significance (in brackets) of B, for those datasets where this level exceeds 0.025 (level of significance for a two-sided test).

dataset	$L_{Aeq,24h}$ in dB(A)		Average SEL over 24 hours in dB(A)		10 lg (number of events)		10 lg (distance) (distance in m)	
	B	R	B	R	B	R	B	R
					aircraft			
022								
024	0.55	0.17	0.97	0.16	0.59	0.13		
032	1.60	0.43	1.81	0.42	3.49	0.27		
044								
082	0.52	0.19	0.52	0.19				
210								
238	1.47	0.29	1.65	0.29	11.10	0.30		
239	0.37	0.19	0.41	0.20	0.90 (0.90)	0.04		
240	0.93	0.22	0.96	0.23	-1.27 (0.12)	0.06		
242	1.74	0.32	1.85	0.33	0.09 (0.61)	0.01		
311								
328								
366								
					road traffic			
072	0.87	0.40	0.48	0.12	0.93	0.38	-0.74	0.14
106								
120	1.50	0.32	-0.44	0.08	0.91	0.27		
1922	1.22	0.45	0.82	0.28	1.36	0.21	-1.17	0.19
258								
329								
3612	0.97	0.27						
367								
373								
					railway traffic			
116	0.68	0.30	0.73	0.28	0.94	0.15	-2.24	0.33
153								
1923	1.50	0.50	0.82	0.28	-1.06	0.12	-3.86	0.38
2764	0.48	0.13	0.41	0.07	0.69	0.10	-1.11	0.27
3613	1.61	0.38			0.16	0.03		
365	0.23	0.13	0.20	0.11			-0.41	0.10

Table 3 Information on the regression of the vibration perception score with various variables. B is the slope of the best fitting straight line, R is the correlation coefficient. If cells are empty, the vibration perception score and/or the data on the variable are missing in the dataset. Together with the values of B the table includes the the level of significance (in brackets) of B, for those datasets where this level exceeds 0.025 (level of significance for a two-sided test).

dataset	$L_{Aeq,24h}$ in dB(A)		10 lg (number of events)		10 lg (distance) (distance in m)		standardized startle score		standardized fear score	
	B	R	B	R	B	R	B	R	B	R
aircraft										
022	0.92	0.37	0.80	0.17			0.71	0.76	0.52	0.52
024	0.45	0.15	0.47	0.11			7.35	0.28	0.38	0.31
032	1.60	0.43	3.49	0.27					0.43	0.48
044	0.83	0.31	1.13	0.19					0.37	0.38
082	0.52	0.21							0.26	0.26
210	0.68	0.20	0.17 (0.05)	0.04					0.39	0.55
238	1.32	0.30	9.31	0.28			0.28	0.31	0.17	0.20
239	1.50	0.58	10.03	0.38			0.36	0.14	0.28	0.31
240	0.84	0.20	-0.45 (0.59)	0.02			0.41	0.32		
242	1.62	0.33	0.23 (0.17)	0.03			0.32	0.26		
311	0.96	0.38							0.22	0.24
328	0.67	0.25								
366	1.05	0.41								
road traffic										
072	1.30	0.52	1.49	0.52	-0.76	0.12			0.18	0.17
106	2.25	0.45			-5.05	0.40				
120										
1922										
258	0.40 (0.37)	0.05			-0.73 (0.03)	0.11				
329	0.66	0.31								
3612	0.36	0.10								
367	1.04	0.51			-2.74	0.49				
373	0.12 (0.16)	0.07								
railway traffic										
116	1.00	0.43	1.44	0.23	-3.41	0.40	0.35	0.25	0.44	0.26
153	0.68	0.24	1.35	0.10	-2.27	0.22				
1923										

table 3

2764	0.21 (0.25)	0.05	0.05 (0.90)	0.01	-2.37	0.13
3613	0.97	0.26				
365	0.37	0.10	-0.11 (0.47)	0.01	-0.74	0.10

Table 4 Upper part of the table: for datasets with information on PCHEAVYthe results of a multiple regression analysis with $L_{Aeq,24h}$ and PCHEAVY as independent variables and VIBANNOY and PREVIB as dependent variables: the adjusted R, the regression coefficients (slopes) and the significance of these (normalized) coefficients if the level of significance exceeds 0.025. Lower part of the table: these data for road and railway traffic.

dataset	VIBANNOY			PREVIB		
72 (road)	B	significance B	adjusted R	B	significance B	adjusted R
$L_{Aeq,24h}$	0.84		0.40	1.24		0.52
PCHEAVY	0.11	0.11		0.20		
range PCHEAVY	4 - 18%			4 - 18%		
120 (road)						
$L_{Aeq,24h}$	1.46		0.32			
PCHEAVY	0.24	0.52				
range PCHEAVY	1.5 - 9%					
1922 (road)						
$L_{Aeq,24h}$	1.35		0.46			
PCHEAVY	0.84					
range PCHEAVY	5 - 17%					
116 (rail)						
$L_{Aeq,24h}$	0.68		0.30	1.00		0.44
PCHEAVY	0.02	0.44		0.01	0.61	
range PCHEAVY	1 - 53%			1 - 53%		
153 (rail)						
$L_{Aeq,24h}$				0.68		0.25
PCHEAVY				0.03	0.75	
range PCHEAVY				4 - 37%		
1923 (rail)						
$L_{Aeq,24h}$	1.20		0.31			
PCHEAVY	- 0.12					
range PCHEAVY	3 - 51%					
365 (rail)						
$L_{Aeq,24h}$	0.23		0.14	0.36		0.10
PCHEAVY	- 0.10			- 0.11	0.15	

Table 4

range PRHEAVY	31 - 45%		31 - 45%	
road	three datasets		one dataset	
$L_{Aeq,24h}$	1.02	0.37	1.24	0.52
PCHEAVY	0.34		0.20	
range PRHEAVY	1.5 - 18%		4 - 18%	
rail	four datasets		two datasets	
$L_{Aeq,24h}$	0.80	0.34	0.67	0.28
PCHEAVY	- 0.13		-0.22	
range PRHEAVY	1 - 53%		1 - 53%	

Table 5 Upper part of the table: for datasets with information on PCHEAVYthe results of a multiple regression analysis with 10 lg distance and PCHEAVY as independent variables and VIBANNOY and PREVIB as dependent variables: the adjusted R, the regression coefficients (slopes) and the significance of these (normalized) coefficients if the level of significance exceeds 0.025. Lower part of the table: these data for road and railway traffic.

dataset	VIBANNOY		PREVIB	
72 (road)	B	adjusted R	B	adjusted R
10 lg distance	- 0.65	0.20	- 0.60	0.23
PCHEAVY	0.34		0.57	
1922 (road)				
10 lg distance	- 1.12	0.48		
PCHEAVY	1.64			
116 (rail)				
10 lg distance	- 2.25	0.33	- 3.42	0.49
PCHEAVY	0.02		0.02	
153 (rail)				
10 lg distance			- 2.31	0.22
PCHEAVY			- 0.07	
1923 (rail)				
10 lg distance	- 3.80	0.38		
PCHEAVY	0.12			
365 (rail)				
10 lg distance	- 0.42	0.12	- 0.76	0.11
PCHEAVY	- 0.14		- 0.18	
		road		
10 lg distance	- 0.83	0.29 (1706)	- 0.60	0.24 (1030)
PCHEAVY	0.70		0.57	
		rail		
10 lg distance	- 2.32	0.41 (5228)	- 2.38	0.37 (4933)
PCHEAVY	- 0.05		- 0.11	

Table 6 Information on the first order regression lines of VIBANNOY and PREVIB as a function of $L_{Aeq,24h}$ and 10 lg distance.

Effect	data on $L_{Aeq,24h}$				data on 10 lg distance			
	number	regression coefficient	constant	correlation coefficient	number	regression coefficient	constant	correlation coefficient
				aircraft				
VIBANNOY	8922	0.60	-5.39	0.20		-	-	-
PREVIB	22431	0.50	11.66	0.19		-	-	-
				road traffic				
VIBANNOY	4630	1.11	-35.6	0.38	1830	-0.67	35.71	0.11
PREVIB	4121	1.02	-24.4	0.37	1966	-0.32	44.64	0.06
				railway traffic				
VIBANNOY	7140	0.66	-13.4	0.50	6770	-1.66	54.7	0.31
PREVIB	5492	0.55	11.12	0.19	5412	-1.04	61.50	0.17
				road + railway traffic				
VIBANNOY					8600	-1.03	43.0	0.25
PREVIB					7378	-0.49	49.8	0.10
				transportation				
VIBANNOY	20692	0.83	-19.7	0.32				

Table 7 Information on the regression of the vibration annoyance score with various variables. B is the slope of the best fitting straight line, R is the correlation coefficient. If cells are empty, the vibration annoyance score and/or the data on the variable are missing in the dataset. Together with the values of B the table includes the the level of significance (in brackets) of B, for those datasets where this level exceeds 0.025 (level of significance for a two-sided test).

dataset	employ		gender		owner		sound insulation		standardized startle score		standardized fear score	
	B	R	B	R	B	R	B	R	B	R	B	R
						aircraft						
022												
024	0.92 (0.53)	0.01	-0.92 (0.23)	0.02	6.13	0.12			11.00	0.39	0.45	0.34
032	-2.92 (0.10)	0.03	1.86 (0.11)	0.03	3.09	0.04	4.58	0.06			0.44	0.48
044												
082			0.55 (0.80)	0.01							0.34	0.30
210												
238	-5.31 (0.61)	0.02	-1.70 (0.94)	0.01	-2.40 (0.41)	0.03	2.32 (0.27)	0.05	0.41	0.40	0.24	0.25
239	5.16 (0.06)	0.08	-2.12 (0.17)	0.06	-2.91 (0.08)	0.07	-0.86 (0.41)	0.04	0.33	0.18	0.02 (0.29)	0.04

Table 7

240	-3.34 (0.33)	0.04	-2.05 (0.30)	0.04	-3.02 (0.13)	0.06	-6.36	0.13	0.47	0.37		
242	-5.05	0.05	-2.28 (0.07)	0.04			1.04 (0.10)	0.04	0.50	0.36		
311												
328												
366												
					road traffic							
072			2.10 (0.12)	0.05			1.12 (0.27)	0.01			0.61	0.37
106	0.19	0.21										
120	1.31 (0.60)	0.02	2.70 (0.22)	0.05	12.4	0.20					0.26	0.29
1922	-0.64 (0.68)	0.01	0.48 (0.57)	0.01	-0.39 (0.65)	0.01	-1.90	0.06	0.58	0.45		
258												
329			-0.39 (0.76)	0.01			5.57	0.25				
3612			0.80 (0.63)	0.02								
367												
373												
					railway traffic							
116	-3.25 (0.07)	0.05	-1.95 (0.14)	0.04	4.30	0.09	8.31	0.12	0.60	0.43	0.61	0.37
153	-7.02 (0.37)	0.03	-1.99 (0.30)	0.04	3.08	0.07	13.50	0.10				
1923	-0.51 (0.86)	0.00	0.36 (0.75)	0.02	0.68 (0.75)	0.03			0.50	0.38		
2764			-0.40 (0.82)	0.01	0.55 (0.78)	0.01	-1.20 (0.61)	0.02				
3613			0.15 (0.73)	0.01								
365			0.60 (0.72)	0.03			-0.65 (0.24)					

Table 8 Multiple R of the vibration annoyance score (VIBANNOY), perception of vibrations (PREVIB) and noise annoyance (NOISANNOY) if various variables are entered in the multiple regression analysis and R for the variables seperately.

dataset	startle and $L_{Aeq,24h}$	fear and $L_{Aeq,24h}$	startle and distance	fear and distance	startle	fear	$L_{Aeq,24h}$	10 lg distance
				aircraft				
022								
VIBANNOY								
PREVIB	0.70	0.56			0.76	0.52	0.37	
NOISANNOY	0.80	0.58			0.78	0.46	0.45	
024								
VIBANNOY	0.42	0.38			0.39	0.34	0.17	
PREVIB	0.32	0.34			0.28	0.31	0.15	
NOISANNOY	0.42	0.42			0.37	0.37	0.23	
032								
VIBANNOY		0.56				0.48	0.43	
PREVIB		0.56				0.48	0.43	
NOISANNOY		0.54				0.46	0.43	
044								
VIBANNOY								
PREVIB		0.45				0.38	0.31	
NOISANNOY		0.50				0.43	0.34	
082								
VIBANNOY		0.35				0.30	0.19	
PREVIB		0.32				0.26	0.21	
NOISANNOY		0.38				0.31	0.25	
210								
VIBANNOY								
PREVIB		0.57				0.55	0.20	
NOISANNOY		0.75				0.72	0.33	
238								
VIBANNOY	0.45	0.35			0.40	0.25	0.29	
PREVIB	0.39	0.34			0.31	0.20	0.30	
NOISANNOY	0.58	0.57			0.38	0.32	0.52	
table 8								
239								
VIBANNOY	0.19	0.25			0.18	0.04	0.19	
PREVIB	0.60	0.58			0.14	0.31	0.58	
NOISANNOY	0.70	0.66			0.10	0.39	0.66	
240								
VIBANNOY	0.42				0.37		0.22	
PREVIB								
NOISANNOY	0.41				0.30		0.30	
242								
VIBANNOY	0.46				0.36		0.32	
PREVIB								
NOISANNOY	0.42				0.29		0.34	
311								
VIBANNOY								
PREVIB		0.43				0.24	0.38	
NOISANNOY		0.54				0.36	0.45	
328								
VIBANNOY								
PREVIB							0.25	
NOISANNOY							0.43	

Table 8

366								
VIBANNOY								
PREVIB							0.41	
NOISANNOY							0.38	
road traffic								
072								
VIBANNOY		0.44		0.24		0.37	0.40	0.14
PREVIB		0.53		0.20		0.17	0.52	0.12
NOISANNOY		0.56		0.26		0.22	0.53	0.14
106								
VIBANNOY								
PREVIB							0.45	0.40
NOISANNOY							0.38	0.36
120								
VIBANNOY		0.41				0.29	0.32	
PREVIB								
NOISANNOY		0.42				0.24	0.36	
1922								
VIBANNOY	0.58		0.50		0.45		0.45	0.39
PREVIB								
NOISANNOY	0.66		0.51		0.49		0.45	0.22
258								
VIBANNOY								
PREVIB							0.05	0.11
NOISANNOY							0.22	0.28
329								
VIBANNOY								
PREVIB							0.31	
NOISANNOY							0.42	
3612								
VIBANNOY							0.27	
PREVIB								
NOISANNOY							0.15	
367								
VIBANNOY								
PREVIB							0.51	0.49
NOISANNOY							0.70	0.67
373								
VIBANNOY								
PREVIB							0.07	
NOISANNOY							0.24	
railway traffic								
116								
VIBANNOY	0.49	0.42	0.49	0.43	0.43	0.37	0.30	0.33
PREVIB	0.46	0.46	0.49	0.47	0.25	0.26	0.43	0.49
NOISANNOY	0.54	0.41	0.52	0.40	0.48	0.33	0.32	0.27
153								
VIBANNOY							0.21	0.22
PREVIB							0.24	0.18
NOISANNOY							0.29	0.19
1923								
VIBANNOY	0.54		0.56		0.38		0.50	0.38
PREVIB								
NOISANNOY	0.59		0.62		0.50		0.52	0.48

Table 8		
2764		
VIBANNOY	0.13	0.27
PREVIB	0.05	0.13
NOISANNOY	0,13	0.00
3613		
VIBANNOY	0.38	
PREVIB		
NOISANNOY	0.18	
365		
VIBANNOY	0.13	0.10
PREVIB	0.10	0.10
NOISANNOY	0.39	0.37

Table 9 Information about the regression lines of VIBANNOY on NOISANNOY for the three types of transportation seperately and for the three types of transportation together. B is the slope of the regression line and R the correlation coefficent.

Type of transportation	B	R
aircraft	0.57	0.81
road traffic	0.60	0.79
railway traffic	0.59	0.76
transportation	0.58	0.80

Table 10 Information about the regression lines of %HAvib, %Avib and %LAvib as dependent variables and $L_{Aeq,24h}$ as independent variable. for the three types of transportation. $L_{Aeq,24h}$ has been abbreviated to L.

Percentage vibration annoyed	Type of transportaition	Equation
%HAvib	aircraft road traffic railway traffic:	%HAvib = 0.92L - 45.9 %HAvib = 0.81L - 36.9 %HAvib = 0.48L - 20.6
%Avib	aircraft: road traffic: railway traffic:	%Avib = 1.38L - 63.8 %Avib = 1.37L - 59.9 %Avib = 0.93L - 39.4
%LAvib	aircraft road traffic railway traffic	%LAvib = 1.67L - 67.4 %LAvib = 1.89L - 73.8 %LAvib = 1.43L - 58.3

ANNEX B

Figure 1 Vibration annoyance score for aircraft datasets as a function of $L_{Aeq,24h}$. Parameters are the codes of the datasets.

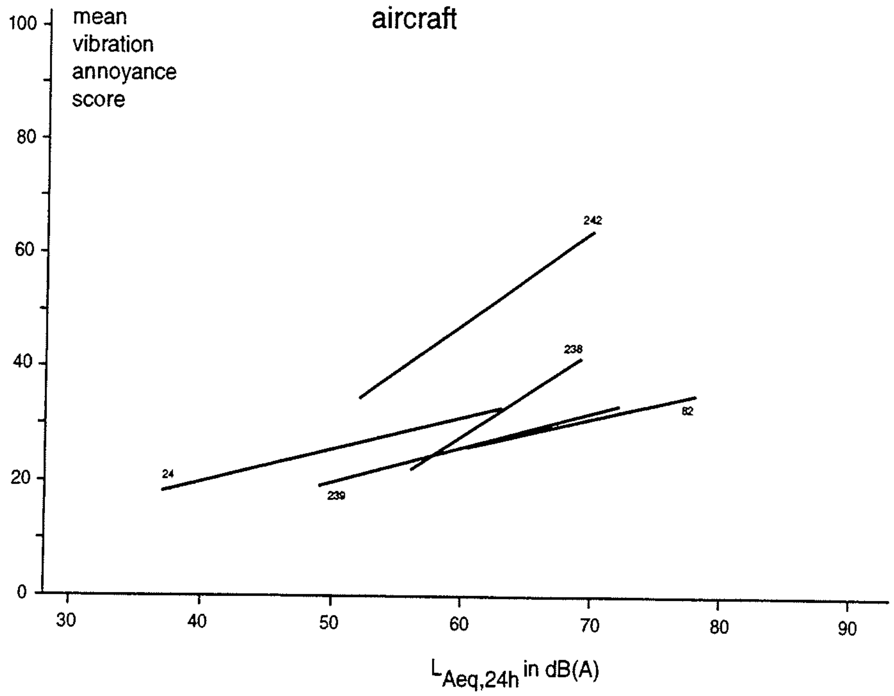


Figure 2 Vibration perception score for aircraft datasets as a function of $L_{Aeq,24h}$. Parameters are the codes of the datasets.

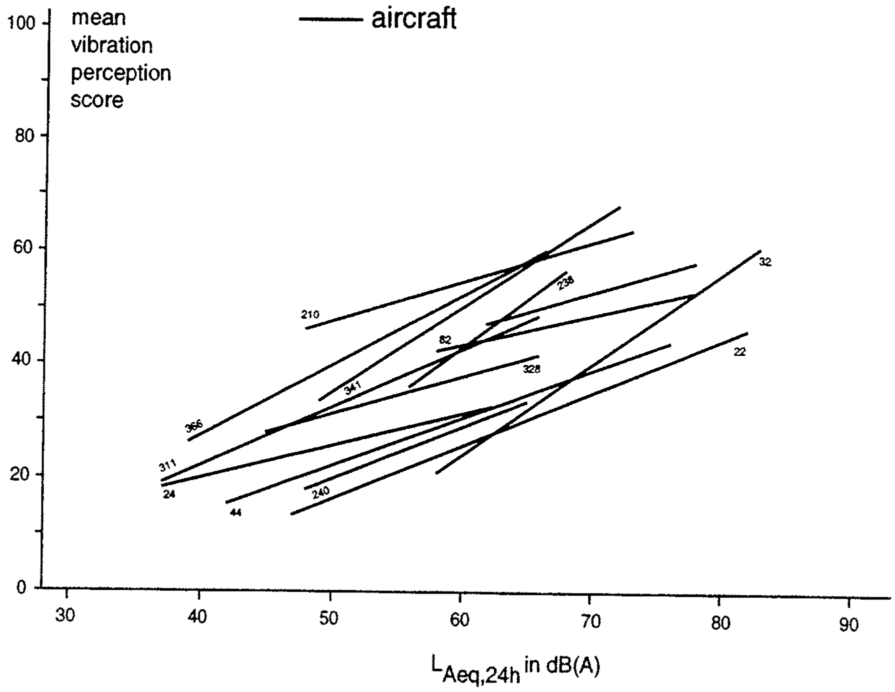


Figure 3 Noise annoyance score for aircraft datasets as a function of $L_{Aeq,24h}$. Parameters are the codes of the datasets.

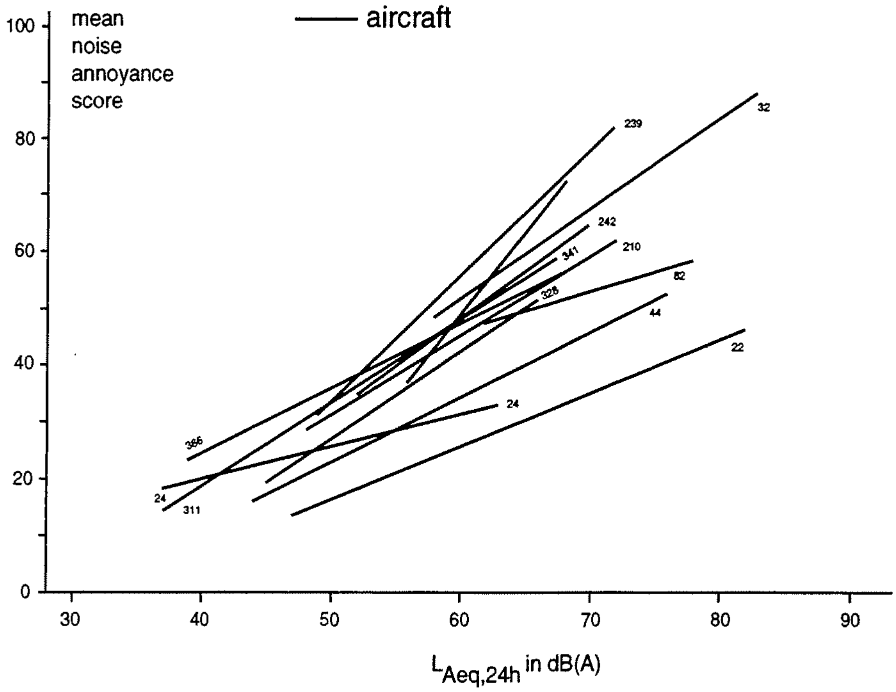


Figure 4 Vibration annoyance score for road and railway datasets as a function of $L_{Aeq,24h}$. Parameters are the codes of the datasets.

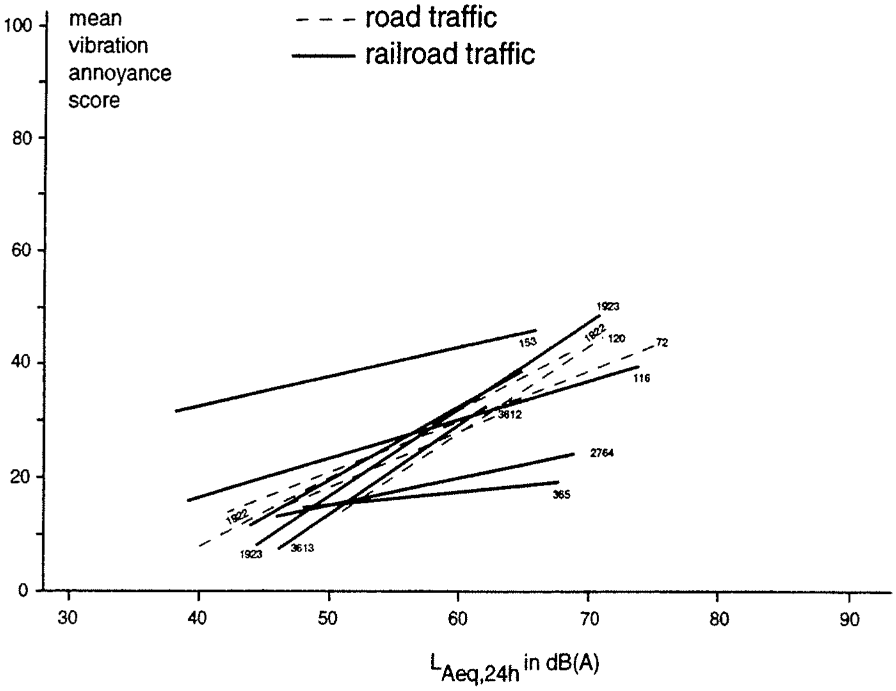


Figure 5 Vibration perception score for road and railway datasets as a function of $L_{Aeq,24h}$. Parameters are the codes of the datasets.

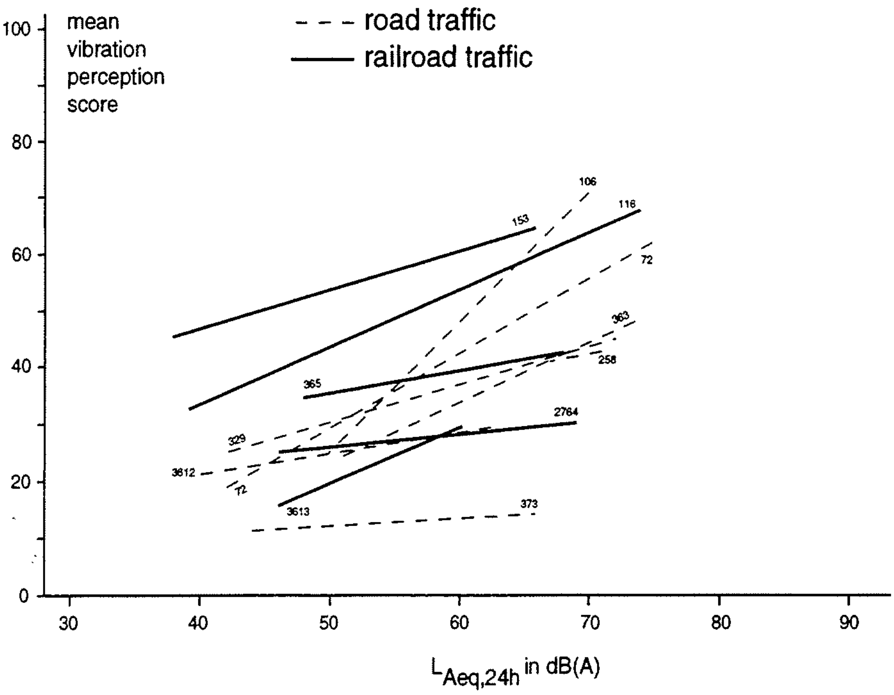


Figure 6 Noise annoyance score for road and railway datasets as a function of $L_{Aeq,24h}$. Parameters are the codes of the datasets.

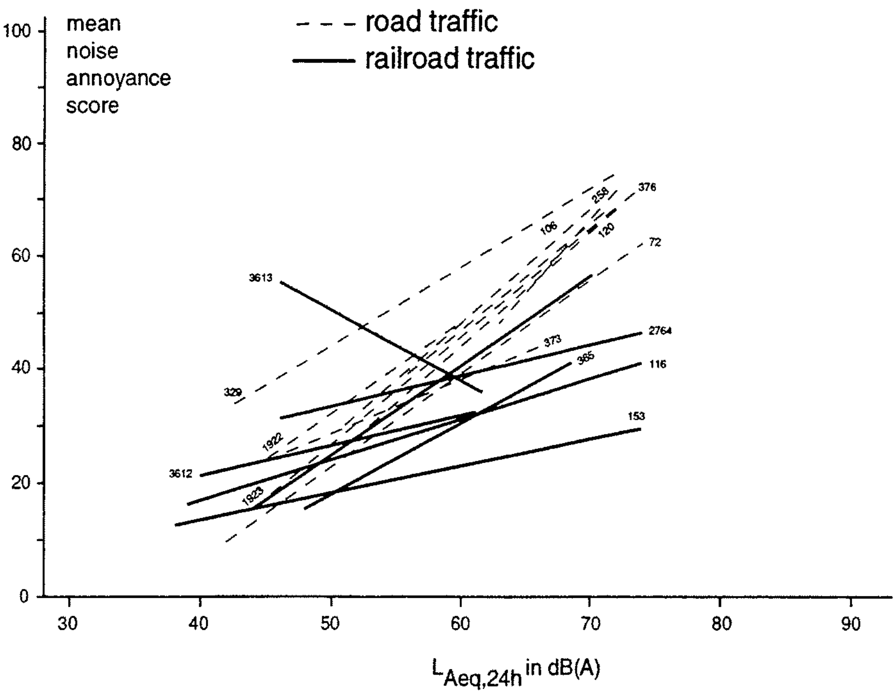


Figure 7 Vibration annoyance score for road and railway datasets as a function of 10 lg distance. Parameters are the codes of the datasets.

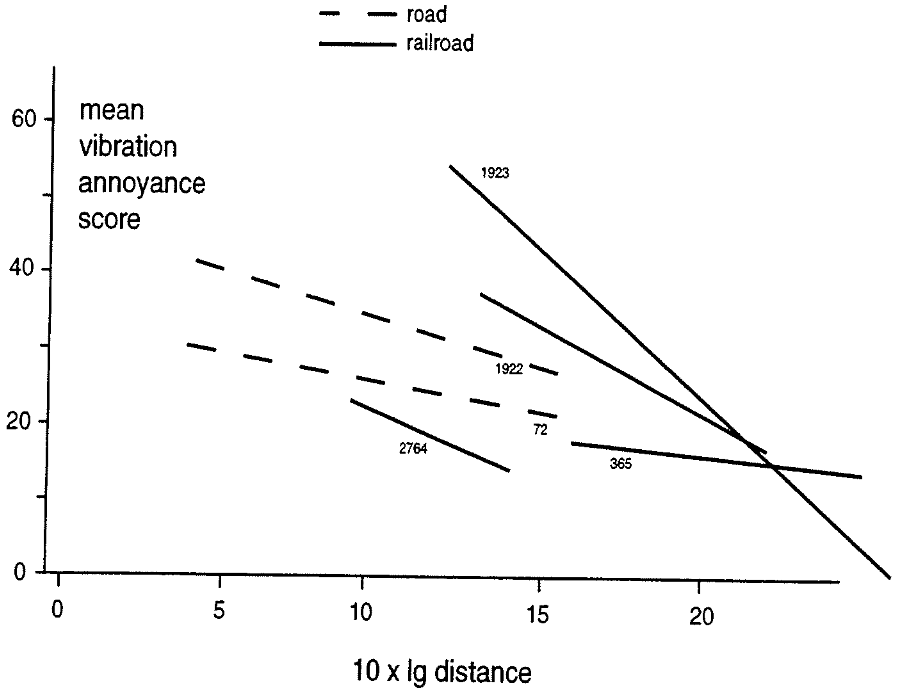


Figure 8 Vibration perception score for road and railway datasets as a function of 10 lg distance. Parameters are the codes of the datasets.

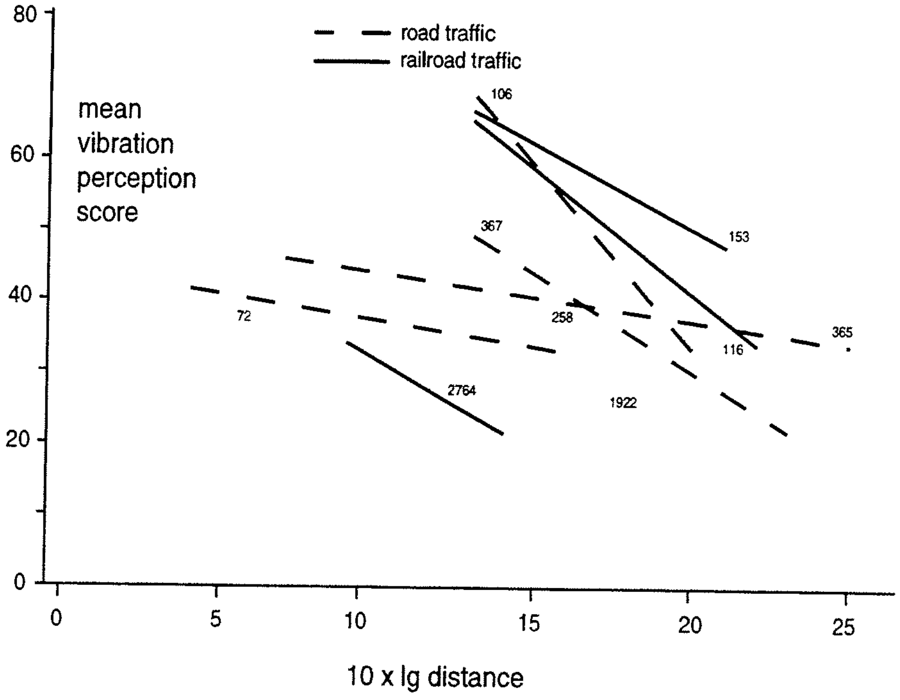


Figure 9 Noise annoyance score for road and railway datasets as a function of 10 lg distance. Parameters are the codes of the datasets.

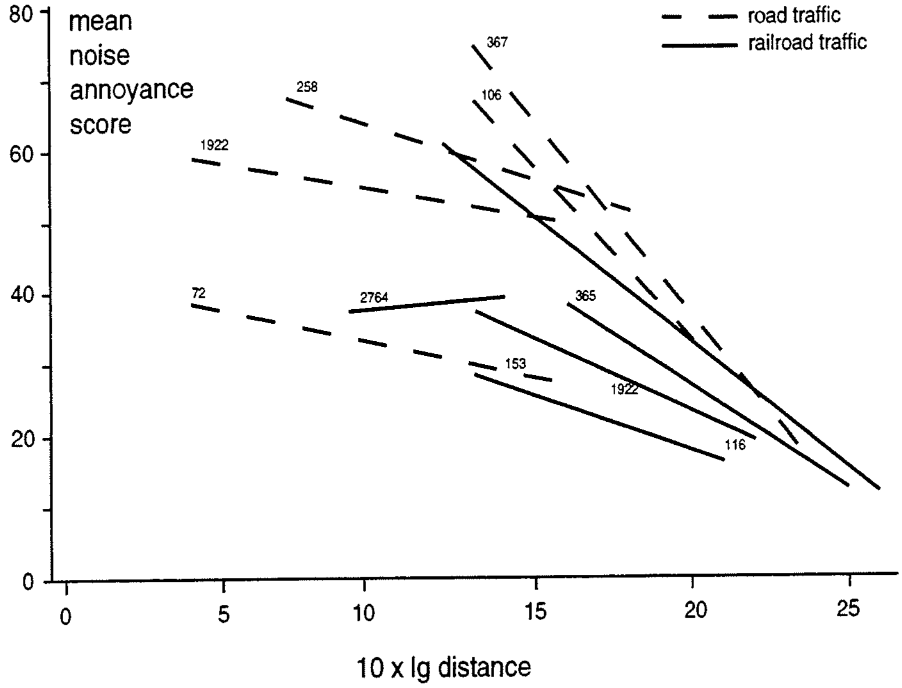


Figure 10 Vibration annoyance score for survey 192 as a function of $L_{Aeq,24h}$ and 10 lg distance for trains and trams separately.

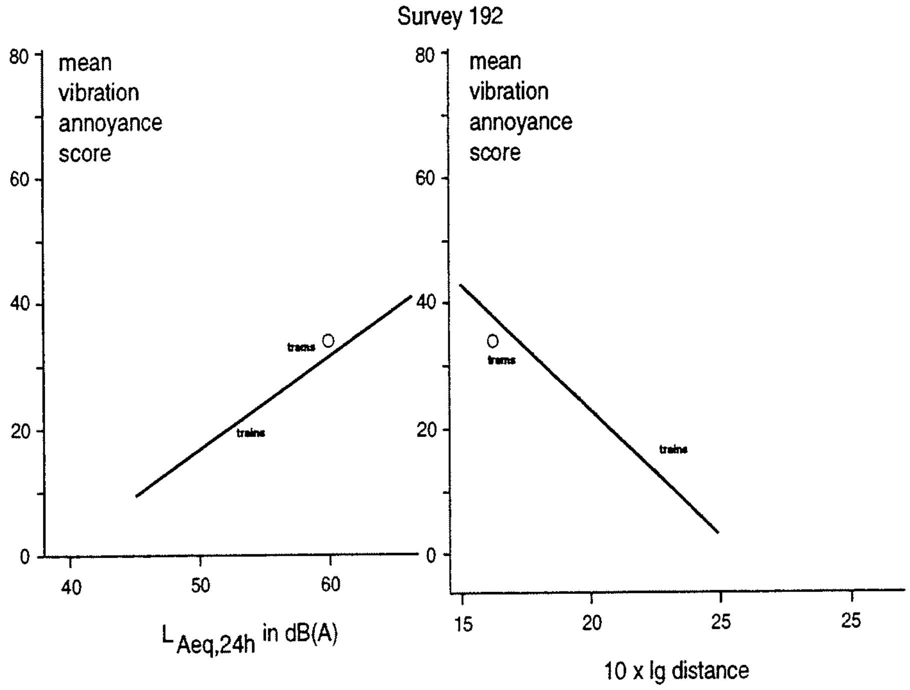


Figure 11 Vibration annoyance score for aircraft, road and railway traffic and for transportation as a function of $L_{Aeq,24h}$.

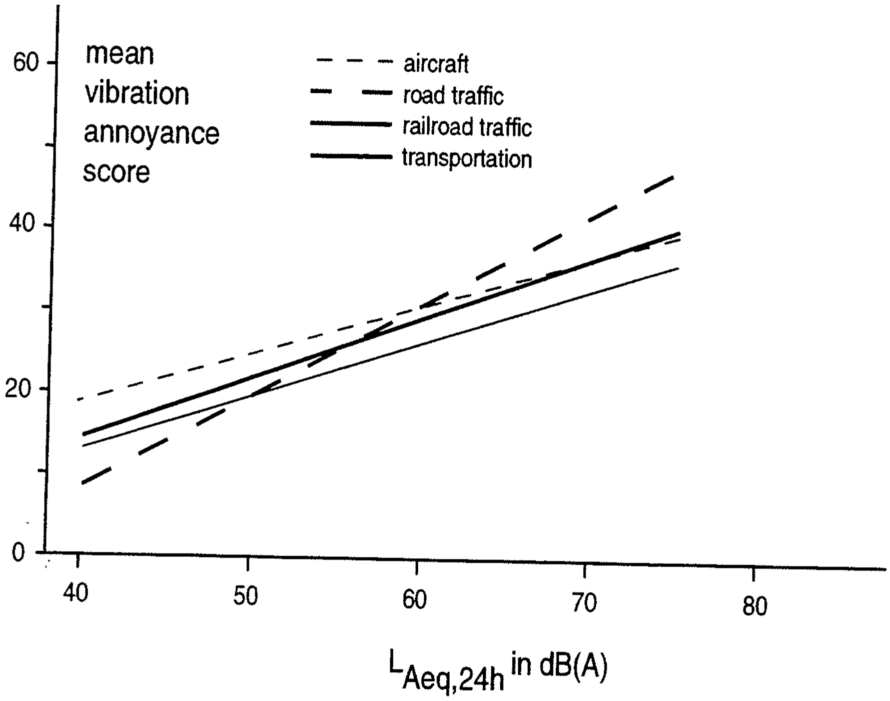


Figure 12 Vibration perception score for aircraft, road and railway traffic as a function of $L_{Aeq,24h}$.

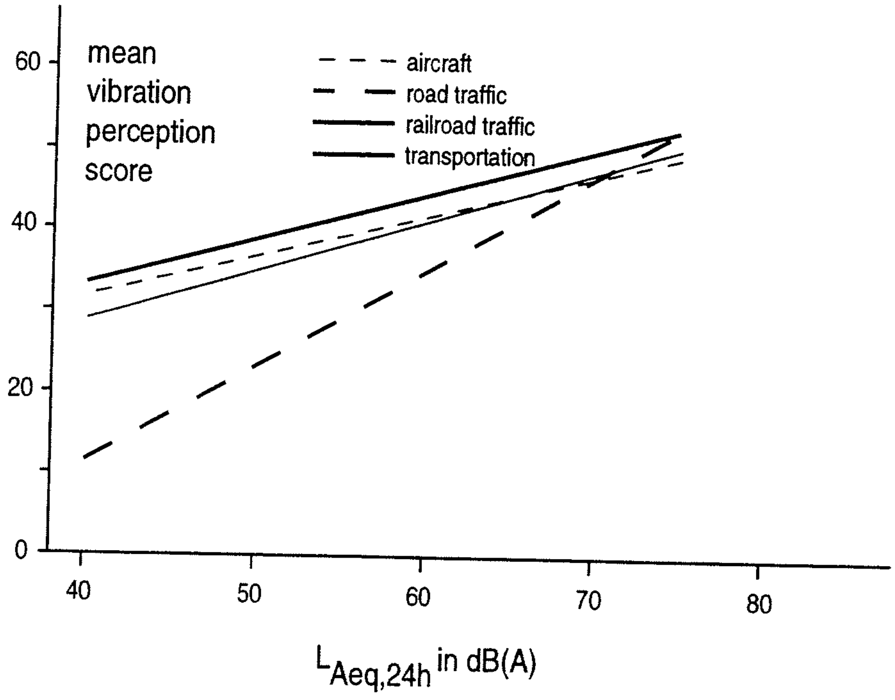


Figure 13 Vibration annoyance score for road and railway datasets as a function of 10 lg distance.

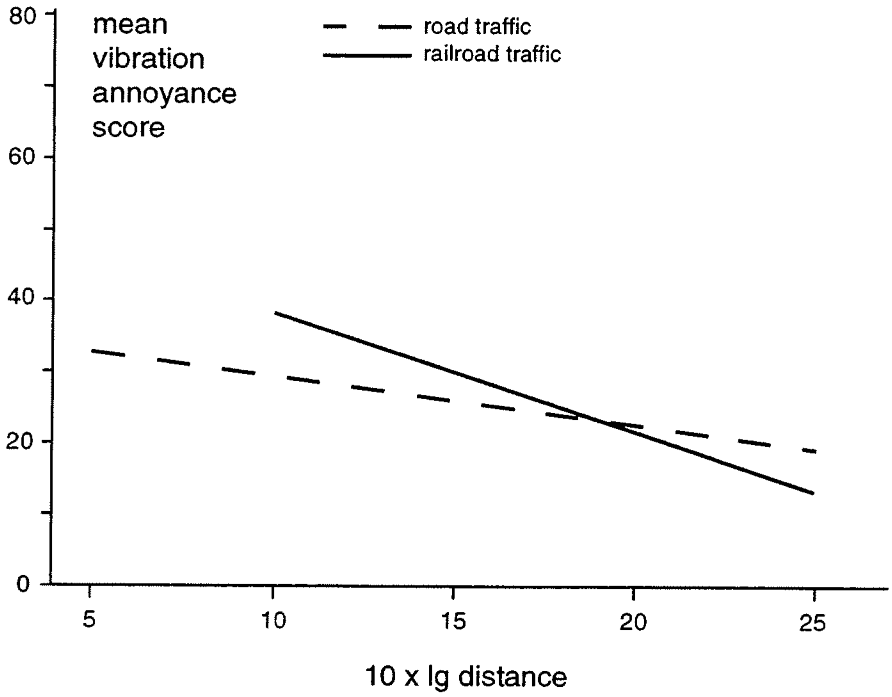


Figure 14 Vibration perception score for road and railway traffic as a function of 10 lg distance.

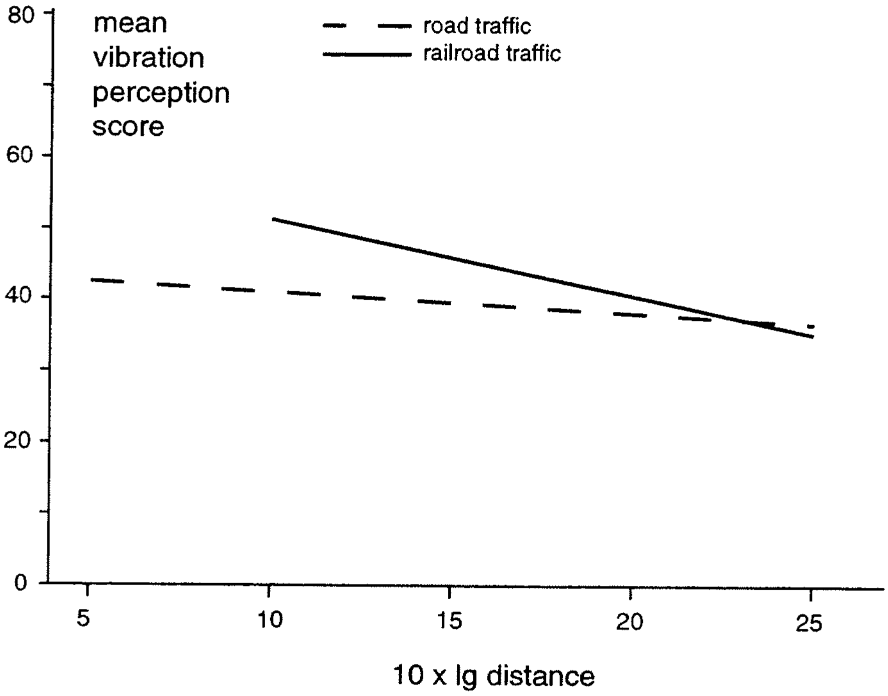


Figure 15 Vibration annoyance score for railway traffic as a function of percentage heavy traffic.

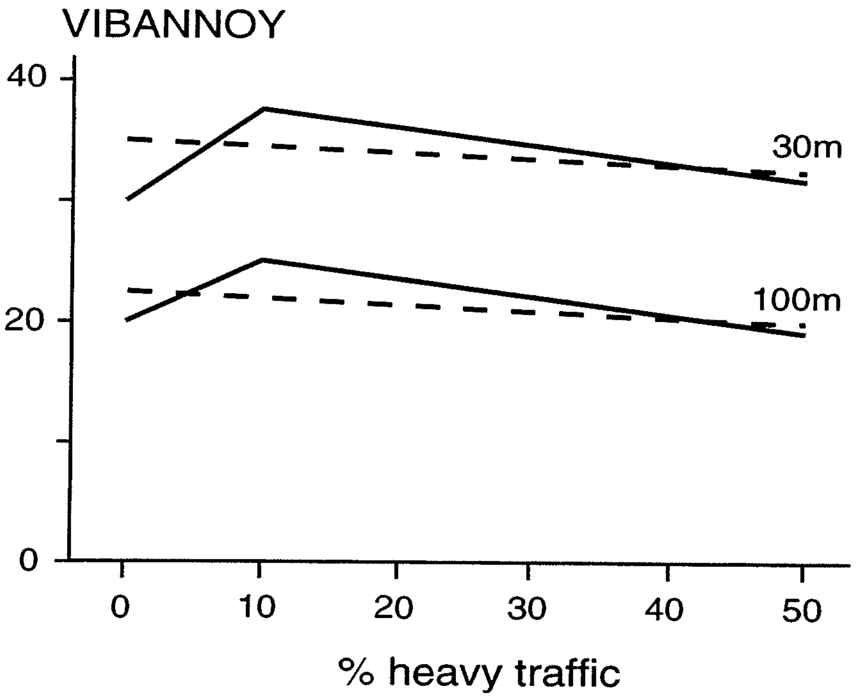


Figure 16 Percentages annoyed respondents (%HAvib, %Avib and %LAvib) due to vibrations from aircraft as a function of $L_{Aeq,24h}$.

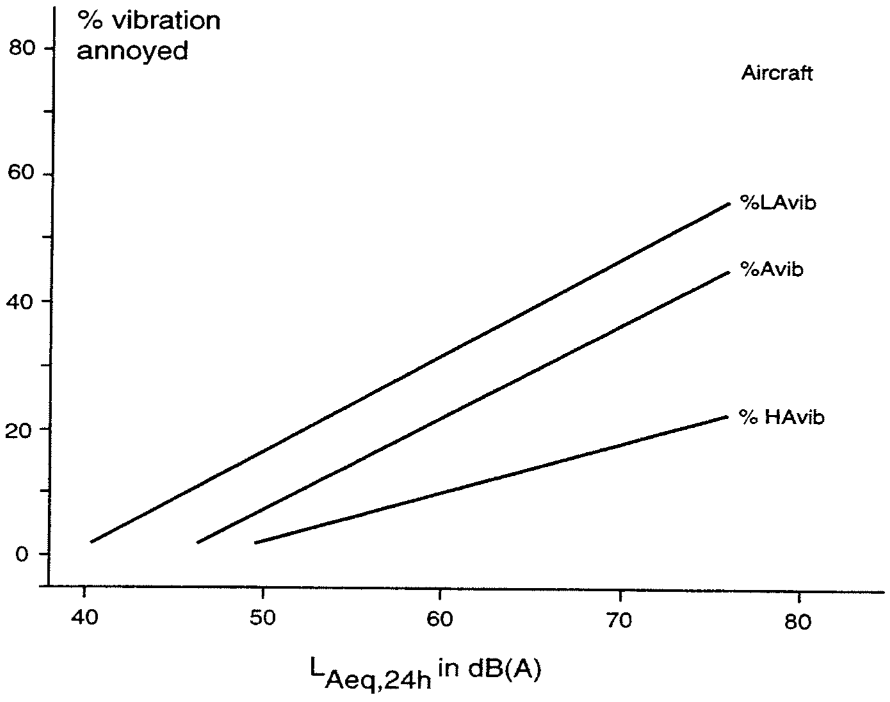


Figure 17 Percentages annoyed respondents (%HAvib, %Avib and %LAvib) due to vibrations from road traffic as a function of $L_{Aeq,24h}$.

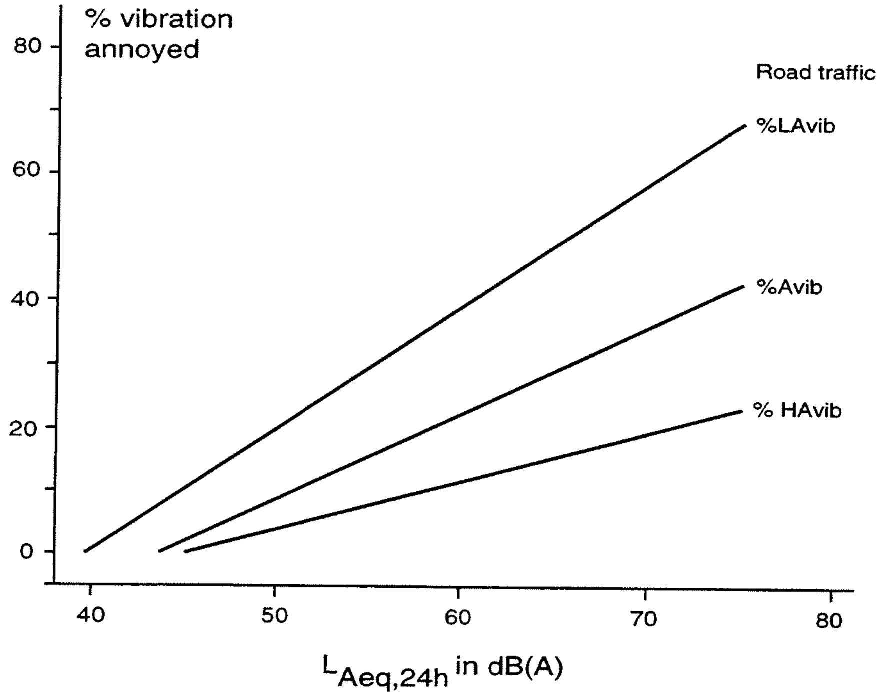


Figure 18 Percentages annoyed respondents (%HAvib, %Avib and %LAvib) due to vibrations from railway traffic as a function of $L_{Aeq,24h}$.

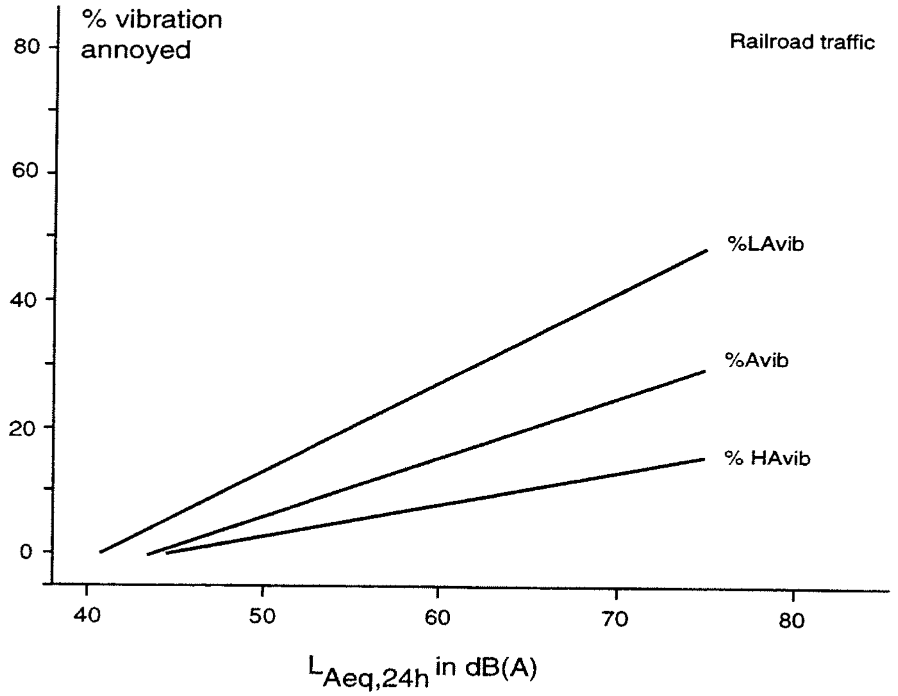


Figure 19 Percentage highly annoyed respondents due to vibrations from transportation as a function of percentage highly noise annoyed respondents.

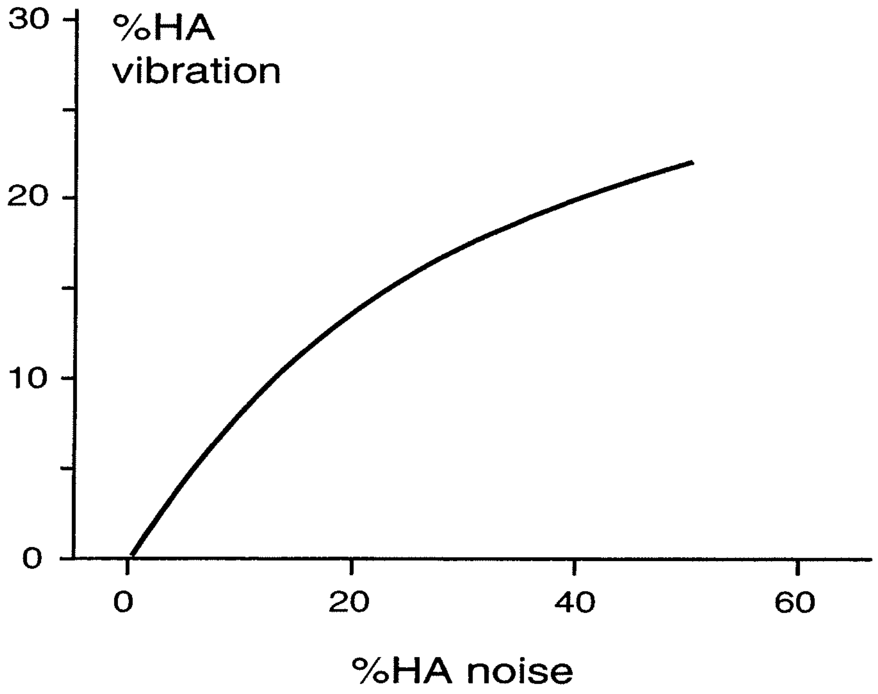


Figure 20 Percentage at least annoyed respondents due to vibrations from transportation as a function of percentage highly noise annoyed respondents.

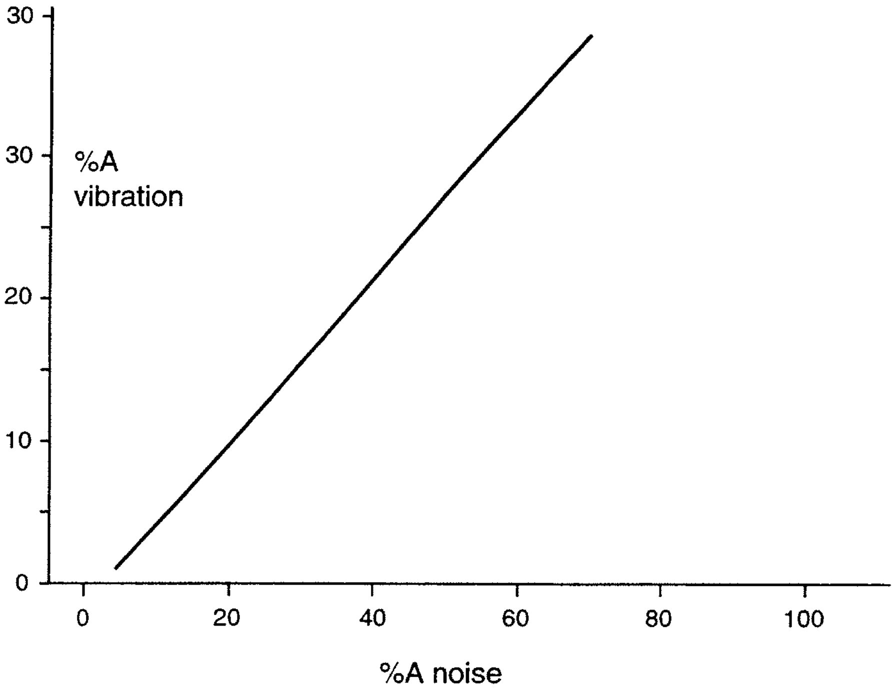


Figure 21 Percentage at least somewhat annoyed respondents due to vibrations from transportation as a function of percentage highly noise annoyed respondents.

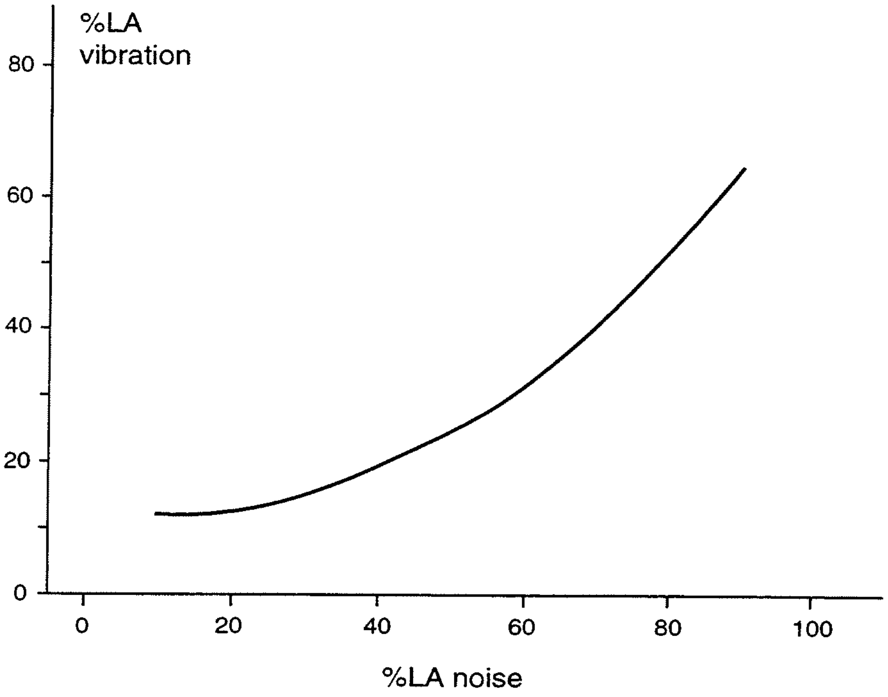
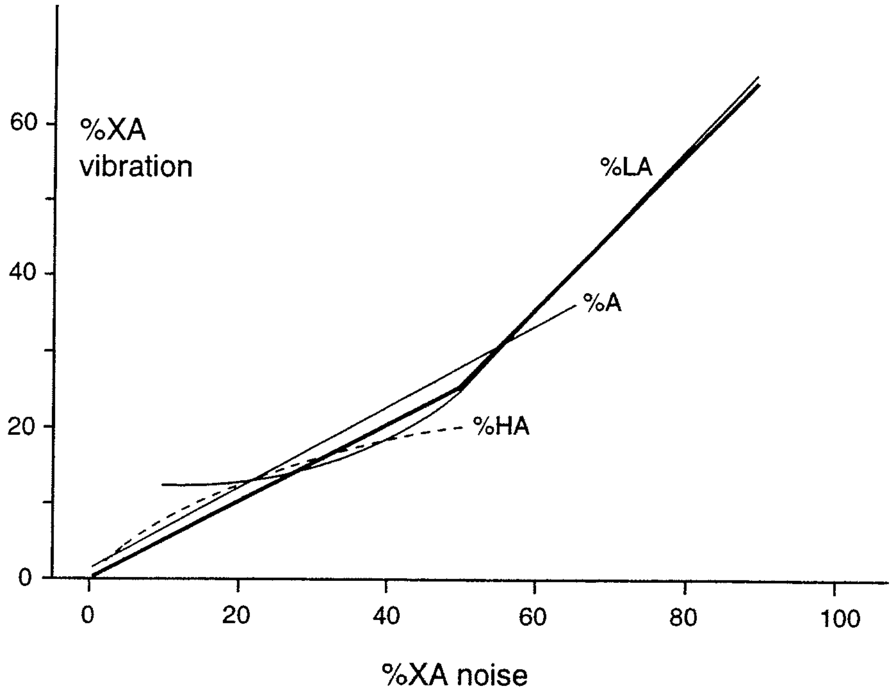


Figure 22 Regression lines of percentage highly annoyed, at least annoyed and at least a little annoyed respondents due to vibrations from transportation as a function of the corresponding percentages noise annoyed respondents.



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