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Annoyance and sleep disturbance due to vibrations from trains

Results from the Follow-Up Study 'Wonen langs het spoor' ('Living along the railway line')

RIVM report 2024-0052
E. van Kempen et al.

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(‘Living along the railway line’)

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Colophon

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Synopsis

Annoyance and sleep disturbance due to vibrations from trains

Results from the Follow-Up Survey *Wonen langs het spoor* ('Living along the railway line')

In 2021, around 11% of people in the Netherlands aged 16 and over who lived within 300 metres of a railway line experienced high annoyance due to vibrations from railway traffic. This amounts to an estimated 126,500 people. Furthermore, 13% experienced high sleep disturbance due to such vibrations. The annoyance and sleep disturbance were mainly due to vibrations from passing freight trains. Areas in the vicinity of tunnels, railway bridges and parallel tracks were excluded from this estimation.

The above describes the outcomes of a survey among more than 5,600 people. The survey area has a total population of over 1.1 million, who live in approximately 533,000 houses.

In addition, people who are exposed to higher levels of vibrations or live closer to a railway line are more likely to report high annoyance due to vibrations from freight trains. The association between vibration levels, distance and annoyance is much less pronounced for passenger trains.

In addition to the vibrations, there are social and personal factors that affect the extent to which people experience annoyance or sleep disturbance. An important factor is concern about property devaluation or property damage. Other factors that influence peoples' experience include hearing, feeling or seeing windows, doors or crockery *('rattle').* The extent to which people accept that trains cause vibrations and the expectations that they have about future vibration levels also play a role.

RIVM therefore recommends that in future, policy regarding vibrations caused by trains, social and personal factors be taken into account. While there are several laws that regulate noise from trains, there are few, if any, when it comes to vibrations from trains. The outcomes of this study may serve as input for legislation in this area.

This report is a translation of the RIVM-report "Hinder en slaapverstoring door trillingen van treinen. Resultaten van de Vervolgmeting 'Wonen langs het spoor'". This study was commissioned by the Ministry of Infrastructure and Water Management. It follows up on a survey from 2013 and has confirmed many of the earlier outcomes. The latest survey was based on a model that is better able to predict exposure to vibrations.

Keywords: vibrations, trains, freight trains, passenger trains, exposure-response relationship, exposure measure, noise, co-determinants, annoyance, sleep disturbance, regulation

Publiekssamenvatting

Hinder en slaapverstoring door trillingen van treinen

Resultaten van de Vervolgmeting “Wonen langs het spoor”

In 2021 had ongeveer 11 procent van de Nederlanders van 16 jaar en ouder die binnen 300 meter afstand van het spoor wonen, ernstige hinder van trillingen door treinen. Het gaat naar schatting om 126.500 mensen. Zij hebben last van irritatie, boosheid en onbehagen. ’s Nachts kunnen deze trillingen hun slaap ernstig verstoren (13 procent). Vooral de trillingen van goederentreinen veroorzaken hinder en slaapverstoring. Gebieden in de buurt van tunnels, spoorbruggen en sporen die naast elkaar liggen, zijn in deze schatting niet meegenomen.

Dit blijkt uit een vragenlijstonderzoek onder ruim 5600 mensen. In het onderzoeksgebied wonen ongeveer ruim 1,1 miljoen mensen, verdeeld over ongeveer 533.000 woningen.

Verder rapporteren mensen die aan hogere trillingsniveaus blootstaan of dichter bij het spoor wonen, vaker ernstige hinder door trillingen van goederentreinen. Dit verband tussen trillingsniveaus, afstand en ervaren hinder is veel minder duidelijk voor reizigerstreinen.

Naast de trillingen hebben sociale en persoonlijke factoren invloed op de mate waarin mensen hinder ervaren of in hun slaap worden gestoord. Mensen zijn vooral bezorgd dat de waarde van de woning daalt door de trillingen of dat deze schade aan de woning veroorzaken.

Hun beleving wordt ook beïnvloed als zij ramen, deuren of serviesgoed horen, voelen of zien trillen (“rattle”). Daarnaast is de mate waarin zij accepteren dat treinen trillingen veroorzaken van invloed, en welke verwachtingen zij voor de toekomst over de trillingen hebben. Het RIVM beveelt daarom aan bij toekomstig beleid over trillingen door treinen met sociale en persoonlijke factoren rekening te houden. Voor geluid van treinverkeer bestaat wetgeving, voor trillingen door treinen niet of nauwelijks. De resultaten van dit onderzoek geven hier input voor.

Deze rapportage is een vertaling van het rapport “Hinder en slaapverstoring door trillingen van treinen. Resultaten van de Vervolgmeting ‘Wonen langs het spoor’”. Het is een onderzoek dat is uitgevoerd in opdracht van het ministerie van Infrastructuur en Waterstaat (IenW). Het is een vervolg op een onderzoek uit 2013 en bevestigt veel van de eerdere resultaten. Voor het nieuwe onderzoek is een model gebruikt dat beter de blootstelling aan trillingen kan inschatten.

Kernwoorden: trillingen, treinen, goederentreinen, reizigerstreinen, blootstellingrespons-relatie, blootstellingsmaat, geluid, co-determinanten, hinder, slaapverstoring, regelgeving

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Summary

Background

The Netherlands has one of the busiest railway systems in Europe. Policies aimed at enhancing accessibility and achieving the 2050 climate targets will further intensify the use of the country's railway network. The impact of this not only concerns existing dwellings, but also dwellings as yet to be built in the vicinity of railways.

Like other means of transport and installations, trains not only produce noise but can also cause vibrations in buildings. As far as railway traffic noise is concerned, protection of the environment is laid down in legislation. However, there is much less legislation, if any, for railway-induced vibrations. For some time now, both societal and political actors have been calling for policies and regulation on the issue of vibrations.

Current knowledge on the effects of railway-induced vibrations on human health is limited. To reduce this knowledge gap, in 2013 RIVM conducted a survey, 'Living along the railway line' (In Dutch: *Wonen langs het spoor*), among 4,927 persons aged 16 and over living within 300 metres of a railway line. The survey was intended to provide a national picture of responses to railway-induced vibrations among residents living nearby railway lines. Based on the outcomes of this survey, RIVM estimated that approximately 20% of people in the Dutch population aged 16 and over who live within 300 metres of a railway line experience high annoyance due to railway-induced vibrations. Freight trains were found to produce the most annoyance. Similar results were found for sleep disturbance. The RIVM used the data from the survey to establish dose-response relationships (DR relationships) for high annoyance and high sleep disturbance in relation to exposure to railway-induced vibrations.

In response to commitments made by the State Secretary of Infrastructure and Water Management to the House of Representatives in 2018, and as a follow-up to the 2013 measurement, RIVM was asked to conduct a new measurement. This assignment was translated into two sub-studies:

a) a Repeated Measurement study into the effects of railway-induced vibrations among respondents in the ‘Living along the railway line’ study in 2013, and
b) a Follow-Up Study among a new sample of persons aged 16 and over who live within 300 metres of a railway line.

The Repeated Measurement study took place in 2019 and the outcomes were reported in 2021[1]. The purpose of that survey was to study developments in people's responses to vibrations from railway traffic in terms of annoyance, sleep disturbance and self-reported health effects over the 2013-2019 period (monitoring). For the second sub-study, in

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[1] Van Kamp et al., ‘Repeated measurement Living along the railroad track (2013-2019)’, Bilthoven: RIVM, 2021

autumn 2021 RIVM conducted a study (hereinafter referred to as the Follow-Up Study) among a new sample of persons aged 16 and over who live within 300 metres of a railway line, which included a questionnaire on the effects of vibrations from railway traffic. Participants in the 2019 Repeated Measurement study were also invited as supplementary respondents. The present report concerns the Follow-Up Study only. It is a translation of the RIVM-report "Hinder en slaapverstoring door trillingen van treinen. Resultaten van de Vervolgmeting 'Wonen langs het spoor'" published in 2023.

Study goals

The Follow-Up Study seeks to answer the following research questions:

a) What is the extent of (high) annoyance and (high) sleep disturbance due to railway-induced vibrations among the Dutch population (prevalence)?
b) Which vibration exposure indicator is the most suitable for predicting annoyance and/or sleep disturbance due to railway-induced vibrations?
c) What dose-response (DR) relationships can be established between (high) annoyance and (high) sleep disturbance due railway-induced vibrations from railway traffic and exposure to these vibrations from different railway sources (passenger trains versus freight trains)?
d) How do physical, contextual and personal factors influence high annoyance and high sleep disturbance due to railway-induced vibrations?

Where possible, outcomes were compared with results from the 2013 measurement. Since the results of the Repeated Measurement study cannot not serve as a basis for statements about the situation in the Netherlands, this report does *not* include a comparison with the results from the 2019 Repeated Measurement study.

What has been studied?

To answer the above questions, we conducted a cross-sectional study using an online questionnaire. We assessed the participants' exposure to railway-induced vibrations by means of the OURS calculation model[2]. As in 2013, we also carried out a non-response study.

Participants

We invited a total of 17,189 persons to participate in the main study, and divided them into two groups:

Group I: This is a representative sample of 16,000 persons aged 16 and over living within 300 metres of a railway line. To identify this group, we made a selection of all addresses which are i) located within 300 metres of a railway line in use, and ii) used for residential purposes.

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[2] OURS = Ontwikkeling Uniform Rekenmodel Spoortrillingen (development of a uniform calculation model for railway-induced vibrations) This model, which was commissioned by the Ministry of Infrastructure and Water Management, makes it possible to calculate expected vibration levels (Kok et al., Gebruik rekenmodel spoortrillingen. Bilthoven: RIVM, 2020).

In total, this selection included more than 848,000 addresses. We then eliminated the following addresses:

a) all addresses where we suspected that the possibility of reliably estimating railway-induced vibrations using the OURS model might be compromised. This concerned all addresses in the vicinity of railway bridges, sunken tracks and major stations with many parallel tracks;
b) all addresses whose residents had already been invited to participate in the 2013 survey[3].

From the remaining 532,730 addresses we selected a random sample of 16,000 addresses, as we did in 2013, stratifying by distance to the nearest railway line and year of construction.

Group II: This group consists of 1,189 participants in the 2019 Repeated Measurement study who had given us permission to invite them again.

The questionnaire

We used an online questionnaire to collect data about the perception of railway-induced vibrations, the effects of those vibrations and their possible determinants. These questions were largely based on the questionnaire used in 2013. The survey was held from September to November 2021.

Exposure to vibrations from railway traffic

We used the OURS calculation model (version 2.1), train speed and frequency data from 2019 and railway position data from 2021 to estimate exposure to railway-induced vibrations for the addresses of all participants in this Follow-Up Study. The OURS model enabled us to express the exposure to railway-induced vibrations from for each participant in the Follow-Up Study by three different indicators: one that concerns maximum exposure (V_{max}[4]) and two indicators that concern average exposure (V_{per}[5] and RMS[6]). In performing these calculations, we distinguished between different sources of railway-induced vibration (total railway traffic, freight trains and passenger trains) and different parts of the day (daytime hours, evening, night or 24-hour period). The sensitivity of the human body to vibrations not only depends on the vibration level, but also on their frequency and direction. In other words, the frequency and direction of the vibrations can cause them to be perceived to be stronger or weaker even if the vibration level remains unchanged. This can be taken into account by differentiating the weighting of vibrations depending on their frequency range and direction. One common method to weight down vibration indicators is described in ISO 2631. For the purpose of the Follow-Up Study, all vibration exposure levels were calculated with and without directional

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[3] Van Kamp et al., Living along the railroad track: health effects of vibrations due to trains, Bilthoven: RIVM, 2015.

[4] V_{max} is the highest effective vibration level during the assessment period, on the understanding that the 2% of trains with the highest vibration levels were excluded as outliers.

[5] V_{per} is the average vibration level during the exposure period, weighted according to exposure duration.

[6] The RMS or frequency-weighted root-mean-square is an exposure indicator (often an average) used for vibrations over longer periods of time or to express the magnitude of vibration events.

frequency weighting in accordance with ISO 2631. In addition, for every participant we calculated the distance to the railway line from the nearest façade of the participant's home address.

Exposure to noise produced by railway traffic and other physical environmental characteristics

For each participant we also calculated their exposure to noise produced by railway traffic. We used the standard calculation method II of the Calculation and Measurement Regulations for Noise, and expressed the exposure as an annual average L_{den} and L_{night} valid for the highest exposed facade. For this purpose, we used train speeds and intensities from 2019.
Finally, we linked various physical and social environmental characteristics to the participants' addresses, such as the degree of urbanisation.

The non-response study

Participation in a survey may be influenced by factors directly associated with the subject of the survey. The non-response study consisted of two parts:

a) A random sample was made from a list of addresses of persons who had not filled in the questionnaire of the Follow-Up Study. We then sent an invitation to take part in the non-response study to each address in the sample. The study involved a brief online questionnaire (with eight questions). To investigate the possibility of selective non-response bias, we compared the participants in the non-response study with the participants in group I who did complete the questionnaire of the Follow-Up Study.
b) We had already collected information about the participants in group II in 2013 and 2019. For the purpose of the non-response study, therefore, we used the data from 2013 and 2019 to compare persons from group II who had completed the questionnaire of the Follow-Up Study with the persons in group II who had not.

Response

A total of 5,611 questionnaires were returned, which equals 33.0% of the usable sample. The response rate in group I was 30.2%. This is slightly lower but still comparable to the response rate of 32% achieved for the previous survey performed in 2013. The response rate in group II was 69.1%.

Comparisons between groups of participants and non-participants suggest that unintended selection may have occurred. For example, annoyance scores among participants were higher than among the group of non-respondents. This means that the participants are not entirely representative of the total sample, potentially resulting in a slight bias of the outcomes.

Answering the research questions using the key findings

The study area of the Follow-Up Study has an estimated population of over 1.1 million, who live in approximately 533,000 houses. Zones in the vicinity of railway bridges, tunnels and major stations with many parallel tracks, have been excluded.

What is the extent of high annoyance due to exposure to vibrations from railway traffic in the Netherlands?

Based on the outcomes of the Follow-Up Study, we estimated that approximately 11% of the Dutch population aged 16 and over who live within 300 metres of a railway line experience high annoyance due to railway-induced vibrations. Zones in the vicinity of railway bridges, tunnels and major railway stations with many parallel tracks, were excluded. These zones have an estimation population of 126,500.

As regards the different sources of railway-induced vibrations, we found that vibrations from freight trains continue to cause by far the most annoyance. Based on the outcomes of the Follow-Up Study, we estimated that in 2021, approximately 22.6% of the Dutch population living within 300 metres of a railway line experienced high annoyance due to vibrations from freight trains. Zones in the vicinity of railway bridges, tunnels and major stations with many parallel tracks were excluded from this estimation. An estimated 8% of the Dutch population living within 300 metres of a railway line experiences high annoyance due to vibrations produced by passenger trains, which is low compared with the high annoyance from vibrations produced by freight trains.

The results of the Follow-Up Study confirm the results of the 2013 study. In that year, freight trains likewise were by far the most important source of annoyance, with an estimated prevalence of 22.7% at the time. And just as in the Follow-Up Study, the prevalence of high annoyance due to vibrations from passenger trains in the 2013 survey was low compared with the prevalence of high annoyance due to freight trains. The percentage of high annoyance due to vibrations produced by passenger trains was an estimated 3% in 2013.

As regards the amount of annoyance caused by vibrations from other sources, there is a difference between the results of the Follow-Up Study and the 2013 study. In contrast to the situation in 2013, the Follow-Up Study showed that in 2021 railway traffic was no longer the principal source of vibration-induced annoyance among the Dutch population aged 16 and over who live within 300 metres of a railway line. Instead, vibrations caused by road traffic and construction activity were the main sources of annoyance.

What is the extent of high sleep disturbance due to exposure to vibrations from railway traffic in the Netherlands?

Based on the outcomes of the Follow-Up Study, we estimated that in 2021 approximately 13% of Dutch population aged 16 and over who live within 300 metres of a railway line experience high sleep disturbance due to railway-induced vibrations. Zones in the vicinity of railway bridges, tunnels and major stations with many parallel tracks were excluded from this estimation.

Railway traffic is the principal source of vibration-induced sleep disturbance among the Dutch population aged 16 and over who live within 300 metres of a railway line. This outcome is in contrast with the findings for high annoyance, where road traffic proved to be the main source of high annoyance.

As regards the different sources of railway-induced vibrations types, we found that vibrations from freight trains cause the most sleep disturbance. Based on the outcomes of the survey of the Follow-Up Study, we estimated that in 2021, more than 18% of the Dutch population who lived within 300 metres of a railway line experienced high sleep disturbance due to vibrations from freight trains. An estimated 6% of this population experiences high sleep disturbance due to vibrations from passenger trains, which is low compared to the sleep disturbance caused by freight trains.

The results of the Follow-Up Study confirm the results of the 2013 study: in that year, freight trains likewise were by far the most important source of sleep disturbance. Freight trains were estimated at the time to be responsible for high sleep disturbance in over 16% of the Dutch population living within 300 metres of a railway line. And just as in the Follow-Up Study, the prevalence of high sleep disturbance due to vibrations from passenger trains in the 2013 survey was low compared with the prevalence of high sleep disturbance due to freight trains. Vibrations produced by passenger trains were estimated at the time to cause high sleep disturbance in 3.5% of the Dutch population living within 300 metres of a railway line.

Which vibration exposure indicator is the most suitable for predicting annoyance and/or sleep disturbance due to railway-induced vibrations?

To determine which of the different exposure indicators is the most suitable for predicting annoyance and sleep disturbance due to railway-induced vibrations, we performed the following investigations:

a. We tested which model is the most suitable for predicting the annoyance and/or sleep disturbance based on the underlying data. For that purpose we considered the model fit (the extent to which the model fits with the underlying data) and the accuracy of the model's predictions.
b. In addition, we looked at the correlations between the various exposure indicators.

We found strong correlations between the different indicators used to express exposure to railway-induced vibrations (V_{per}, V_{max}, RMS and distance to nearest railway line). In addition, the differences between the indicators studied were also small as regards accuracy of prediction models based on the different indicators. This means that a prediction of the percentage of the population experiencing high annoyance or high sleep disturbance based on any of the tested exposure indicators (such as V_{max}) is about as accurate as a prediction based on any of the other exposure indicators.

However, when we consider the fit of the models with the underlying data, a number of differences between the models do emerge. For example, the models based on exposure indicators *without* ISO weighting were found to have a better model fit with the underlying data than the models *with* ISO weighting. Indeed, the ISO weighting appears to reduce the predictive strength of the models.

The differences in fit between V_{max}, V_{per} and RMS (all *without* ISO weighting) are small for both high annoyance and high sleep disturbance. Only for high annoyance due to vibrations from freight trains does distance from the railway line give a significantly better fit than the other indicators studied. Strikingly though, the accuracy in that case is lower.

The results of the Follow-Up Study do not yield a single indicator for exposure to railway-induced vibrations that clearly stands out from the others.

What dose-response relationships can be established for (high) annoyance and (high) sleep disturbance due to railway-induced vibrations from and exposure to vibrations from different railway sources (passenger trains versus freight trains)?

For both total railway traffic and freight trains, we found a clear dose-response (DR) relationship between the vibration exposure levels calculated with OURS (expressed in V_{max}, RMS or V_{per}) and the percentage of persons experiencing high annoyance due to vibrations from these sources. The analyses showed that the percentage of persons experiencing high annoyance due to vibrations from total railway traffic and/or freight trains increases as the exposure to vibrations increases. These relationships were far less pronounced for high annoyance and vibration exposure from passenger trains.

In addition, we found DR relationships between the vibration exposure levels calculated with OURS (expressed as V_{max}, RMS_{night} or $V_{per,night}$) and the percentage of persons experiencing high sleep disturbance due to vibrations from both total railway traffic and freight trains. As with annoyance, these DR relationships were strongest for freight trains. The DR relationships between exposure to vibrations from passenger trains and high sleep disturbance were weak.

The relationship between exposure and response is not always linear. Therefore, if the method used for establishing the DR relationship can only describe linear relationships, this may result in unreliable DR outcomes. This is why we used two different types of models in our analyses: logistic regression models using either a continuous or categorical exposure. Unlike continuous models, categorical models are also suitable for describing non-linear relationships between exposure and response. The analyses have shown that the type of method used to establish DR relationships matters. In most cases the categorical model proved to be more effective than the linear model in predicting high

annoyance and/or high sleep disturbance due to railway-induced vibrations. Furthermore, the continuous and categorical models produce different DR relationships, especially in the higher exposure ranges. This suggests that the relationship between exposure to railway-induced vibrations and high annoyance and/or high sleep disturbance caused by such vibrations in non-linear.
To ensure comparability between the results of the Follow-Up Study and the results of the 2013 measurement, we used the OURS model to retroactively re-estimate the exposure of the participants in the 2013 study to railway-induced vibrations. At the time, the exposure of the participants in the 2013 study was estimated using the SRM-t model. We have made new estimates for the DR relationships in 2013 based on the new exposures. Comparison of the DR relationships for 2013 and 2021 shows that for equal maximum vibration levels, the probability of high annoyance due to railway-induced vibrations was lower in 2021 than in 2013. When we express exposure to vibrations using RMS or V_{per}, a similar picture emerges.

However, the findings are different for high sleep disturbance: comparison of the 2013 and 2021 DR relationships for maximum exposure to vibrations from total railway traffic and for high sleep disturbance due to railway-induced vibrations has shown that for equal maximum vibration levels, the probability of high sleep disturbance was *higher* in 2021 than in 2013. When we express exposure to vibrations using RMS or V_{per}, a similar picture emerges.

How do physical, contextual and personal factors influence high annoyance and high sleep disturbance due to vibrations from railway traffic?

The analyses showed that, in addition to exposure to railway-induced vibrations, annoyance and sleep disturbance caused by railway noise seemed to be the main factors influencing the reported levels of annoyance and sleep disturbance caused by railway-induced vibrations.

In addition, social and personal factors play an important role. These factors are related to concerns about the decrease in the property value and/or property damage, hearing, feeling or seeing windows, doors or crockery (‘rattle’), acceptance of vibrations and expectations regarding railway-induced vibrations in the future.

Socio-demographic factors such as age, gender, level of education and degree of urbanisation were found to have little influence on the reported levels of annoyance and sleep disturbance due to vibrations from the different railway sources. Urbanisation only appeared to influence the reported levels of high sleep disturbance due to vibrations from total railway traffic.

Exposure to the noise produced by railway traffic (L_{den} or L_{night}) was also found to be associated with high annoyance due to railway-induced vibrations. However, this was only the case if no adjustments were made for high annoyance due to the noise produced by railway traffic. Similar results were found for high sleep disturbance due to railway-induced vibrations.

Specifically with regard to high sleep disturbance due to railway-induced vibrations, it makes a difference whether the windows are open or closed in summer and/or winter.

Caveats

There are a number of important caveats concerning the results of the this study.

The additional study among non-respondents has shown that their non-response was not arbitrary. For example, it was found that annoyance scores among participants were higher than among the group of non-respondents. This means that the participants of the main study are not entirely representative of the total sample, potentially resulting in a slight bias of the outcomes. Unfortunately, due to the low response rate in the non-response study (19%) the influence of selective non-response on the reported percentage for high annoyance in the Follow-Up Study cannot be reliably quantified.

We conducted the Follow-Up Study in the fall of 2021, in the middle of the COVID-19 pandemic. During that pandemic, the government took a large number of measures that were intended to curb the spread of the coronavirus. Especially in 2020, this affected the frequencies of passenger trains and the numbers of freight trains on the various routes and railway sections. When the measures were relaxed starting from late April 2021, the Dutch railway operator (NS) gradually increased train frequencies again, returning to operating a full timetable by August 2021. Freight transport by rail also recovered quite robustly in 2021. This is why we believe that the levels of railway-induced vibrations from changed very little during the study as a result of the COVID-19 pandemic. Moreover, the results suggest that most of the participants in the Follow-Up Study shared this belief: a large majority said that in their experience, the COVID-19 pandemic did not cause any change in the vibrations or the noise produced by railway traffic.

However, the pandemic did increase people's dependence on their immediate environment: not only did they work from home more frequently, they also became more frequent users of facilities in their own local neighbourhoods, such as parks and squares. People also travelled by train less frequently as they spent more time working from home. These developments may have affected the reported levels of annoyance and sleep disturbance. A nationwide perception survey has found that during the COVID-19 pandemic, people experienced annoyance due to noise and vibrations from other sources than before the pandemic. This also appears to have been the case in the Follow-Up Study, which showed that in 2021 railway traffic was no longer the dominant source of vibration-induced annoyance among the Dutch population aged 16 and over who live within 300 metres of a railway line. Instead, vibrations caused by road traffic and construction activity were the main source of annoyance within this population.

Given that the COVID-19 pandemic occurred before and during the field work phase of the Follow-Up Study, there may have been a so-called change situation. Research into the impact of environmental noise on annoyance has shown that when there are changes in noise levels, people tend to respond more strongly, or less strongly, than could be expected based on the applicable DR relationships. It has not been possible to study the extent to which the COVID-19 pandemic affected the relationship between exposure to vibrations and high annoyance or sleep disturbance due to railway traffic.

In addition, the results of the Follow-Up Study are not fully comparable to the results of the 2013 measurement. Addresses in the vicinity of railway bridges, sunken tracks and stations with many parallel tracks were excluded from the Follow-Up Study, but where included in the 2013 measurement. We analysed the extent to which this sampling difference influenced the prevalence of high annoyance due to railway-induced vibrations reported in 2013. This analysis showed that this influence is likely to have been small. We do know, however, that the addresses of participants in the 2013 survey outside the exclusion zones were on average closer to a railway line than the addresses of participants within the exclusion zones. We therefore expect vibration exposure among the former group to be slightly higher than the exposure levels among participants with addresses within an exclusion zone. The DR relationships derived on the basis of the 2013 research data are likely to be somewhat steeper, therefore, after excluding participants within the exclusion zones.

The exposure of participants in the Follow-Up Study to railway-induced vibrations was estimated using the OURS model. Compared with the SRM-t model, which was used for the 2013 survey, the OURS model is more suitable for estimating exposure to railway-induced vibrations. The vibration levels estimated using the OURS model appear to correspond more closely to the range of values measured. The model offered the added advantage of being capable of calculating more exposure indicators. One good example of that is the calculation of exposure indicators with and without ISO 2631 weighting. In addition, the OURS model was capable of estimating average exposure levels (expressed as V_{per} or RMS) for different parts of the day. This is not possible with the SRM-t model.

Conclusions

Based on the Follow-Up Study, it has been estimated that around 11% of the Dutch population aged 16 and over who live within 300 metres of a railway line (excluding zones near railway bridges, tunnels and major stations with many parallel tracks) experience high annoyance due to railway-induced vibrations. This amounts to an estimated 126,500 persons. As regards high sleep disturbance due to railway-induced vibrations, the estimate is just under 13%.

Most of the annoyance and sleep disturbance is caused by freight trains and to a lesser extent by passenger trains: 22.6% and 18% of persons aged 16 and over report high annoyance and high sleep disturbance, respectively, due to freight trains. The extent of high annoyance and sleep disturbance due to vibrations from passenger trains is estimated at 8% and 6%, respectively.

Under current regulations (Policy Rules on Annoyance due to Train-Related Vibrations (Bts) and SBR), no ISO 2631 weighting is applied. The Follow-Up Study has shown that vibration measures *without* directional frequency weighting in accordance with ISO 2631 more reliably predict both annoyance and sleep disturbance due to railway-induced vibrations. This confirms the results from previous studies into the influence of directional frequency weighting. It appears to be undesirable, therefore, to apply ISO weighting under any new regulations to be developed.

The Follow-Up Study covered various types of vibration exposure indicators: one indicator for maximum exposure (V_{max}) and indicators for average exposure with due regard for the number of trains and/or train length (e.g. RMS). No single indicator has been found that is clearly preferable to the others. This confirms the results from previous studies into various vibration exposure indicators. In the further development of regulations on the subject of vibrations from railway traffic, therefore, it will have to be determined what the policy focus for exposure should be: the perceptibility of vibrations and their potential as a source of annoyance, or other aspects, such as the effects of night-time exposure.

For both total railway traffic and freight trains, a clear link has been found between vibration exposure levels and the percentage of people experiencing high annoyance due to vibrations from these sources: the percentage of high annoyance due to railway-induced vibrations increases as the level of exposure to these vibrations increases. The relationships were found to be the strongest for freight trains, and were far less pronounced for passenger trains. The picture for sleep disturbance was similar to that for annoyance.

Besides exposure to vibrations, several other factors influence reported levels of high annoyance and sleep disturbance due to railway-induced vibrations. By far the most important of those factors was annoyance due to the noise produced by trains. Sleep disturbance due to the noise from railway traffic was the main predictor of high sleep disturbance due to railway-induced vibrations. In addition, social and personal factors in particular acceptance of vibrations, concerns, expectations and perceiving the rattling of vibrating or moving objects in the home played an important role in both high annoyance and high sleep disturbance due to vibrations.

The results of the Follow-Up Study confirm the results of the 2013 measurement in a number of important respects. In 2013 it was also found that most annoyance is caused by vibrations from freight trains, and to a lesser extent by vibrations from passenger trains. Apart from vibration exposure, social and personal factors in particular were found to influence the amount of reported levels of annoyance and sleep disturbance due to railway-induced vibrations.

And like the Follow-Up Study, for both total railway traffic and freight trains the 2013 measurement found a clear DR relationship between vibration exposure levels and the percentage of people experiencing high annoyance and high sleep disturbance due to vibrations. These relationships were far less pronounced for passenger trains. However, there were also differences: for equal (maximum) vibration levels, the chance of high annoyance due to vibrations from railway traffic in 2021 was lower than in 2013. In contrast, for equal (maximum) vibration levels, the chance of high sleep disturbance due to vibrations from railway traffic in 2021 was *higher* than in 2013.

In principle, all DR relationships derived from the Follow-Up Study can be used to estimate the extent of high annoyance and sleep disturbance due to vibrations from total railway traffic, passing freight trains and passing passenger trains. However, preferably those DR relationships should be used which: i) use distance from the railway line (m) as an indicator for the exposure to railway traffic vibrations, or ii) express vibration exposure in a indicator for which *no* ISO 2631 weighting has been applied. The relationship between exposure to vibrations from railway traffic and high annoyance or sleep disturbance has been found to be, in most cases, non-linear. Where this is the case, therefore, it is preferable to use DR relationships derived on the basis of categorical models.

Recommendations

Based on the Follow-Up Study we have formulated the following recommendations:

Five years from now, consider, in light of the knowledge then available, whether the DR relationships derived in this measurement should be renewed.

DR relationships are important for Dutch environmental policy. Among other things, they can be used for estimating the percentages of the population experiencing high annoyance or high sleep disturbance in a particular area. However, local circumstances are subject to change, and new knowledge may emerge. In order to reduce the time between changes in local circumstances, the emergence of new knowledge and its eventual implementation in laws and regulations, we recommend keeping that knowledge up to date and carrying out new measurements in future.

We need more insight into the potential influence of co-determinants on the association between exposure to railway-induced vibrations and the experienced level of annoyance, the interdependencies between those co-determinants, and the extent to which they can be influenced. That further research should also cover the role of noise.

The results of the Follow-Up Study yielded a number of demographic, contextual and personal factors that could co-determine the relationship between railway-induced vibrations and effects. The present study did not examine the extent to which those co-determinants influence the association between exposure to railway-induced vibrations from railway traffic and annoyance or sleep disturbance caused by such vibrations.

More knowledge about co-determinants can provide areas of focus and intervention tools to help reduce exposure to railway-induced vibrations.

In addition, it could have consequences for the ways in which measures and policies to reduce vibrations are implemented, and for the ways in which local residents are informed about and involved in those measures and policies to ensure their success.

As in the Follow-Up Study, when deriving future DR relationships, use techniques that allow for the fact that such relationships may be non-linear.

Various different methods have been used to derive the DR relationships. These methods have shown that the relationship between exposure and response is not always linear. So the type of method used to derive DR relationships makes a difference. As in current research, in future research we recommend using techniques for deriving DR relationships that allow for the fact that these relationships are not always linear.

1 Introduction

1.1 Background

The Netherlands has one of the busiest railway networks in Europe. During the decade between 2010 and 2019 the network became busier and busier: railway traffic in the Netherlands increased by approximately 18%, from 17 billion kilometres in 2010 to 20.3 billion kilometres in 2019. Due to the COVID-19 pandemic, the total distance travelled by passengers between 2019 and 2020 fell by around 55%, to 9.1 billion kilometres[5]. However, the Netherlands Institute for Transport Policy Analysis (KiM) expects that by 2025 passengers will be using the railway system as intensively as they did in 2019. KiM also expects a 1% to 7% increase in the total distance travelled by passengers in 2026 relative to 2019. The volume of freight transport by rail increased by approximately 19.5% between 2010 and 2019, and decreased by 6.1% in 2020. However, KiM expects that freight transport by rail will grow by 11% in the 2019-2026 period [5].

In light of the efforts to improve accessibility and achieve the climate targets for 2050, expectations are that the railway network will become even busier in the years ahead: the High-Frequency Rail Transport Programme (PHS) provides for the construction of facilities and the implementation of measures (such as running trains without a timetable) that enable intercity trains and sprinters to operate high-frequency services independently from each other. As a result, travel times will continue to decrease [6].

Further intensification of freight transport by rail is also expected. For example, in 2018 the State Secretary of Infrastructure and Water Management expressed the ambition that freight rail transport should see its volume rise from 42 million tonnes in 2016 to 54-61 million tonnes in 2030. In December 2020, the European Commission published the Green Deal. In order for the EU to be climate neutral by 2050, the Commission aims to achieve a substantial reduction in carbon emissions by 2030 (reduction of 55% compared with 1990) [7]. To achieve that, a considerable part of domestic freight transport that is currently taking place by road will have to be transferred to rail. The drive towards intensification has an impact on existing dwellings along the railway lines.

While the volume of railway traffic will grow, it is expected that the size of the built-up area will also increase. To reduce the housing shortage, some 900,000 houses will have to be built in the Netherlands in the period until 2030 [8]. Some of those new houses will probably be built in the vicinity of railway lines. This may give rise to tension between various ambitions and functions in the field of sustainable rail transport and the need for a healthy and safe residential environment.

Like other means of transport and installations, trains not only emit noise; they can also produce vibrations in buildings. Protection against noise is laid down in environmental legislation. However, there is much less legislation, if any, for vibrations produced by railway traffic (also see Box 1). Current knowledge about the effects of railway-induced vibrations on human health is limited. Another problem is that we do not really know which vibration exposure measure is the most suitable for predicting the health effects of railway-induced vibrations.

1.2 Prior history

For quite a while now, both politicians and society at large have called for regulations covering vibrations near railways. For example, in 2010 Parliament accepted two motions calling for the government to a) formulate legal standards for vibrations from railway traffic, and b) formulate proposals in the short term for a set of enforcement instruments for noise and vibrations in the vicinity of railways. Next, RIVM was asked to carry out a programming study[7] into the effects of railway noise and vibrations on human health and well-being. This request was made in response to commitments made to the House of Representatives by the then State Secretary of Infrastructure and Water Management on 18 January 2011 [9]. The programming study included a literature study to identify the current state of affairs as regards the effects of railway-induced vibrations and low-frequency noise on health and well-being [10]. The review also identified a number of knowledge gaps. For example, the data available at the time were not sufficient to serve as the basis for a reliable estimate of the occurrence of health effects due to railway vibrations [10]. To close this knowledge gap, in 2013 a survey ('Living along the railway line') was held among 4,927 persons aged 16 and over living within 300 metres of a railway line. The main purpose of that survey was to provide a picture for the Netherlands as a whole of how people who live in the vicinity of a railway line respond to vibrations and noise produced by passenger trains and freight trains, both during the day and at night. Based on the outcomes of the survey, it was estimated that approximately 20% of the Dutch population aged 16 and over who live within 300 metres of a railway line experienced high annoyance due to vibrations from railway traffic. By far the most annoyance was caused by vibrations from freight trains; based on the outcomes of the survey, it was estimated that approximately 22% of the Dutch population aged 16 and over who live within 300 metres of a railway line experience high annoyance due to vibrations from passing freight trains. The percentage of people experiencing high annoyance due to vibrations from passenger trains was much smaller, at an estimated 3%. The findings for sleep disturbance produced a similar picture. Over 16% of the Dutch population aged 16 and over who live within 300 metres of a railway line reported high sleep disturbance due to vibrations from passing freight trains. The percentage of people experiencing high sleep disturbance due to vibrations from passenger trains was estimated at just over 3.5%. Dose response (DR) relationships were derived from the survey findings to establish the association between exposure to vibrations and high annoyance and high sleep disturbance [11].

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[7] A programming study is a study that not only covers the knowledge already available, but also identifies existing knowledge gaps and any obstacles. Programming studies also generally include proposals for new research.

The 2013 survey suffered from a number of important limitations, the most significant of which had to do with the method used to estimate exposure to vibrations. In the 2013 survey, vibration exposure was estimated using a calculation method known as the Standard Calculation Method for Vibrations (SRM-t) [12]. This model calculated exposure to vibrations based on data about distance to the railway line, soil type, train type, driving speed and floor construction. However, the model used standard values and local indicators, which may have given rise to misclassification of exposure values. Depending on the direction of the misclassification, this may have led to an underestimation or overestimation of the DR relationship.

Development of the vibration calculation model
In 2016, in response to a letter from the State Secretary of Infrastructure and Water Management to the House of Representatives [13], RIVM was commissioned to develop a uniform calculation method for vibrations caused by trains [14]. This resulted, in 2020, in the first version of the OURS model (which is short for 'development of a uniform calculation model for railway-induced vibrations'), which can be used to calculate likely vibration levels [15], for instance in preparation for railway construction projects. The model can also be used for research into the scale of exposure to vibrations and the possible effects of that. The model was improved based on implementation and test data gathered from professional users. A new version was developed in November 2021 [16].

Box 1 Existing regulations in the field of railway-induced vibrations

Despite the fact that vibrations are a priority in the drafting of spatial development plans (Section 3.1 of the Spatial Planning Act), at the moment there is hardly any legislation in the Netherlands which seeks to prevent annoyance or damage due to vibrations. There is a guideline from 1993 for measuring and assessing annoyance among people in buildings caused by vibrations from external sources. This guideline, drawn up by Stichting Bouwresearch, is known as the SBR guideline [1]. It provides for the assessment of annoyance due to vibrations based on observation graphs. A distinction is made between the perception threshold (the vibration level at which 50% of the population perceive vibrations) and the annoyance threshold (the level at which people begin to experience vibrations as annoying).
The Policy Rules on Annoyance caused by Vibrations from Trains (Bts) were introduced in 2012[2]. The purpose of the Bts was to lay down rules on how to deal with some aspects of vibration-related annoyance when adopting a Route Decision (*Tracébesluit*, TB) to build or modify a national railway line as referred to in the Transport Infrastructure (Planning Procedures) Act. The Bts contains provisions on maximum permissible vibration levels from railway traffic. This concerns an assessment of vibrations in relation to the annoyance they cause to people in buildings. Following several court decisions, an amended version of the Bts was published in 2014 [3]. Both the SBR guideline (Chapter 10) and the Bts (Articles 5, 6 and 7) contain target values; the Bts additionally includes limit values. The table below presents an

overview of target and limit values for vibrations in residential buildings, in the existing situation.

Table B1 Target and limit values (V_{max} and V_{per})[a] for recurrent vibrations over prolonged periods of time for existing situations in residential buildings

	Period	**Day-time and evening hours**			**Night**		
	Indicator à	**V_{max}**	**V_{max}**	**V_{per}**	**V_{max}**	**V_{max}**	**V_{per}**
SBR	Target value	0.2[b]	0.8[c]	0.1	0,2[b]	0.4[c]	0.1
	Limit value	-	-	-	-	-	-
Bts	Target value	0.2		-	0.2	-	-
	Limit value	0.8	-	0.1	0.4	-	0.1

[a] V_{max} = The highest effective vibration level during the assessment period (one week); V_{per} = The average vibration level during the assessment period, weighted according to duration of exposure; [b] This concerns the lower limit value; if it is reached, V_{per} is ignored; [c] This concerns the upper limit value, which, if achieved, is combined with the V_{per} requirement.

Based on the SBR, the limit value is achieved if i) the value for maximum vibration strength V_{max} in a space is lower than the lower limit value, or if ii) the value for maximum vibration level V_{max} in a space is lower than the lower limit value and average vibration level V_{per} is lower than target value 0.1. In the Bts, the link between V_{max} and V_{per} is abandoned. Depending on whether SBR or Bts is used, the period during which the target value or limit value is exceeded is also important.
The New Construction and Train-generated Vibrations Guideline (Handreiking Nieuwbouw en Spoortrillingen) [4], issued in 2019, assists planners in ensuring timely and concrete consideration of railway-induced vibrations in new construction projects near railway lines. It does not include any new target or limit values. Depending on whether there is a Route Decision, either the SBR guideline or the Bts must be applied.

1.3 Objective and research questions

1.3.1 Objective

In response to questions in Parliament in 2018 and 2019 about the effects of expansion of the railway network, in 2018 State Secretary Van Veldhoven of Infrastructure and Water Management promised the House of Representatives to commission a large-scale survey among local residents on the levels of annoyance and sleep disturbance they experienced [7, 17, 18]. This task was entrusted to RIVM and, in consultation with the Ministry of Infrastructure and Water Management, translated into two sub-studies:

- A Repeated Measurement study of the effects of railway-induced vibrations, in the form of a survey among former respondents in the ‘Living along the railway’ study in 2013 [11], and
- A Follow-Up Study of the effects of railway-induced vibrations, in the form of a survey among a new sample of people aged 16 and over who live within 300 metres of a railway.

The present report presents the results of the Follow-Up Study. It is a translation of the report “Hinder en slaapverstoring door trillingen van treinen. Resultaten van de Vervolgmeting 'Wonen langs het spoor'" that was published in 2023[8]. As in 2013, the purpose of the Follow-Up Study was to provide a picture for the Netherlands as a whole of how people who live in the vicinity of a railway line respond to vibrations and noise produced by passenger trains and freight trains, both during the day and at night. The results of the first sub-study (the Repeated Measurement study) were published in 2021 [19]. The purpose of the Repeated Measurement study was to study developments in responses to vibrations from railway traffic in terms of annoyance, sleep disturbance and self-reported health effects over the 2013-2019 period (monitoring).

1.3.2 *Research questions*

The Follow-up Study seeks to answer the following research questions:

- What is the extent of (high) annoyance and (high) sleep disturbance due to railway-induced vibrations among the Dutch population (prevalence)?;
- Which vibration exposure indicator is the most suitable for predicting high annoyance and/or high sleep disturbance due to railway-induced vibrations?
- What DR relationships can be derived for (high) annoyance and (high) sleep disturbance due to railway-induced vibrations and exposure to vibrations from railway sources (passenger trains versus freight trains)? And:
- How do physical, contextual and personal factors influence high annoyance and high sleep disturbance due to railway-induced vibrations?

To answer these research questions, we have used the data collected as part of the Follow-Up Study. This concerns a survey conducted in 2021 among over 5,600 people aged 16 and over who live within 300 metres of a railway line. For all participants in this survey, we estimated exposure to railway-induced vibrations using version 2.1 of the OURS model and the latest input data. The risk of misclassification of exposure is expected to be lower, therefore, than during the 2013 measurement, meaning that the results are more useful.

Where possible, the results of this Follow-Up Study will be compared with the 2013 measurement [11]. Since the results of the Repeated Measurement study [19] cannot not serve as a basis for statements about the situation in the Netherlands, we have *not* included a comparison with the results from the 2019 Repeated Measurement study in this report.

The results of the Follow-Up Study serve as important input for laws and regulations on railway-induced vibrations as yet to be drafted.

1.4 Reading guide

Chapter 2 presents a concise overview of the latest knowledge in the field of railway vibrations and health. We will zoom in on DR

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[8] Van Kempen E, Hoekstra J, Simon S, Kok A, Van de Kassteele J, Van Wijnen H. Hinder en slaapverstoring door trillingen van treinen. Resultaten van de Vervolgmeting "Wonen langs het spoor". Bilthoven: RIVM, 2023.

relationships and the influence of other factors besides vibrations (co-determinants). After describing the study set-up and the methods used in Chapter 3, we provide insight into levels of response to both the survey and the associated non-response study in Chapter 4. In addition, we will describe the respondents based on general characteristics. In Chapter 5 we present the prevalences of high annoyance and high sleep disturbance compared with the survey conducted in 2013. Chapter 6 presents a picture of the levels of vibrations and noise from railway traffic to which participants are exposed, and identifies the exposure indicator that is the most suitable for predicting high annoyance and/or high sleep disturbance due to vibrations from railway traffic. Chapter 7 describes the DR relationships between exposure to railway vibrations and high annoyance and high sleep disturbance. Apart from exposure to railway-induced vibrations, other factors may influence the levels of reported annoyance and sleep disturbance due to these vibrations. The influence of these ‘co-determinants’ on the two endpoints is described in Chapter 8. After discussing the results in Chapter 9, we set out the main conclusions in Chapter 10 and conclude with a number of recommendations.

2 The latest knowledge

2.1 How are vibrations from railway traffic generated?

Railway traffic can generate vibrations in buildings. The vibration levels that ultimately occur in a building depend on a range of factors. The first of these is the source of the vibrations: the passing train. Vibrations are caused by movements in the soil generated by the passing train. Where the wheels of the train make contact with the track, a force is exerted on the track. Since the train itself is moving, these forces also move along the track, resulting in vibrations. The strength of those forces and the vibration level depend, for example, on the weight and speed of the train, and on any in the tracks, the wheels and the soil structure. Next, the vibrations propagate from the track to a building, via the soil. Important factors in this regard are soil condition, soil structure and the characteristics of the vibrations. When the vibrations reach a building, they can set the building in motion. Important factors in this regard are the foundation of the building and the magnitude of the vibration waves relative to the size of the building. When the foundations start vibrating, the vibrations will propagate to the various floors via the frame of the building. Depending on the construction and design of the building, the vibrations are either reinforced or weakened as they move up from the foundations [4].

2.2 Perception of vibrations

When the body comes into contact with a vibrating surface, humans are able to perceive vibrations in a frequency range of 1 to approximately 80 Hertz (Hz) [10]. Whether a person actually perceives vibrations depends on several features of the vibrations concerned (strength, frequency and direction), the part of the body impacted by the vibrations, and body posture (e.g. whether a person is lying or standing). We can also hear vibrations: i) primarily because a vibrating surface can emit low-frequency sound (construction sound); ii) the sound may also be an indirect consequence of vibrations through the rattling of cups, windows or doors; iii) finally, vibrations may also be perceived visually when people see objects shaking or through the movement of shadows in mirrors and/or windows [4].

As with noise, people may perceive vibrations as unpleasant and/or annoying. Yet vibrations are also different from noise: noise is a sensation outside the human body that you can escape from, for example by going to a quiet room or by closing the windows. Vibrations are different: they are felt inside the body and are difficult to escape inside a house. Or in Meloni's words:[20] “Vibration ‘shakes’ people in the truest sense of the word; it gets under one’s skin and causes the entire body to vibrate”. This explains why people often feel they cannot escape from vibrations.

2.3 Vibration exposure indicators

Multiple indicators are used to express exposure to vibrations from railway traffic. Many of those indicators express the strength of vibrations (vibration levels) in terms of acceleration (mm/s^2) or speed (mm/s); however, vibration strength can also be expressed in terms of movement (mm). In addition, a distinction can be made between measures that concern a) the average acceleration or speed during a particular period of time, and b) the maximum acceleration or speed. There are also cumulative measures (such as the Vibration Dose Value, or VDV[9]).

In the recent past there have been several attempts to identify the indicator that is the most suitable for predicting vibration-induced annoyance and/or sleep disturbance. In preparation for a revision of the Bts, TNO (the Netherlands Organisation for Applied Scientific Research) [21] examined the values of several exposure indicators for railway-induced vibrations in predicting the percentages of people experiencing high annoyance from railway traffic. For this purpose, the researchers used the results of a previous meta-analysis of seven studies (4,129 respondents) within the framework of the European CargoVibes project[10] [22]. As the original vibration indicators differed from each other, a conversion method was used, in order to allow comparison. Eventually, the relationship with annoyance was determined for each study, with exposure to vibrations from railway traffic expressed using three indicators: i) $V_{dir,max}$, or maximum vibration level in terms of speed[11], ii) RMS (root-mean-square): time-weighted average vibration level, and iii) VDV. The analysis revealed small differences between the three indicators in their ability to predict annoyance, with RMS achieving slightly better scores than $V_{dir,\ max}$ and VDV. However, the explained variances were of the same magnitude. Since the three indicators were strongly related, it was impossible to conclude which of them was the most suitable. All exposure indicators, moreover, had been subjected to ISO 2631 weighting [23]. This is to account for the fact that the human body is not equally sensitive to vibrations of different frequencies and directions (also see section 2.4).

The 2013 study ‘Living along the railway line’ [11] also sought to find an answer to the same question: what is the most suitable exposure indicator? At the time, exposure was estimated using the SRM-t model [12], and was expressed in V_{max} and RMS. The distance from the dwelling to the railway line was also included (in m). The study did not yield a preference for any particular exposure indicator. The three indicators turned out i) to have comparable correlations with effects, and ii) to have strong mutual correlations. In addition, in theory they afforded similar levels of protection in a steady state situation[12]. Distance turned out to produce the highest percentage of explained variance[13], followed by RMS and finally V_{max}. As V_{max} and RMS had been

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[9] The Vibration Dose Value (VDV) is a cumulative exposure indicator for vibrations over a specific assessment period (in $m/s^{1,75}$). The VDV is mainly used when vibrations are intermittent.

[10] CargoVibes is a study into the effects of vibrations due to freight trains on the health of people living near a railway line. It was conducted as part of the Seventh Framework programme of the European Union covering the 2011-2014 period. CargoVibes stands for ‘Attenuation of ground-borne vibration affecting residents near freight railway lines’. Also see https://cordis.europa.eu/project/id/266248

[11] $V_{dir,max}$ is a vibration indicator that is used to express the maximum vibration level, subject to frequency weighting based on ISO 2631.

[12] A steady state situation is a situation in which vibration levels remain unchanged.

[13] The literature often specifies the percentage of variance in a model that can be explained by the exposure or other factors (such as personal and context-related factors). The significance of this percentage is mainly statistical and serves as an indication of the reliability of individual predictions. The higher the explained

subjected to the same weighting, it was impossible to make statements about the influence of the weighting on predicted levels of annoyance and/or sleep disturbance.

Despite the fact that the various studies do not yield a data-based preference for any particular exposure indicator, theoretical analysis does provide some ground for statements about the level of protection afforded by specific exposure indicators [21, 22]: Although exposure indicators that say something about numbers and duration of passages as well as about vibration levels do not seem to offer more protection than indicators that only give an indication of maximum vibration levels, the choice does potentially make a difference in situations where the number of trains and/or duration of passages increase sharply. In such situations, there will be significant influence on a measure such as RMS, and very little on V_{max}. V_{max} appears to be a good indicator of the extent to which vibrations are perceptible, while a measure such as RMS is probably a better indicator of vibration-induced annoyance and other health effects [22].

2.4 The influence of frequency weighting

The sensitivity of the human body to vibrations not only depends on the vibration levels, but also on their frequency (in Hz) and direction[14]. In other words, these and other factors may cause vibrations of the same level to be perceived more (or less) acutely. This is taken into account by differentiating the weighting of vibrations depending on their frequency range and direction. There are various weighting methods in use at the moment. One common method has been laid down in ISO 2631 [23] and involves the use of separate weighting functions for horizontal and vertical direction as perceived by people who are either standing or sitting. The Dutch SBR Guideline B and the Bts use an approximate, i.e. an average of the two directional functions of ISO [11]. However, it is not clear whether the use of weighting methods such as ISO 2631 [23] actually result in a more reliable prediction of annoyance and sleep disturbance due to vibrations form railway traffic.

The researchers at the University of Salford [25] studied the effect of the frequency weighting method. For example, they compared the predictability of the measures defined in ISO 2631 [23, 26] and BS-6472 [27]. ISO and BS differ in terms of frequency weighting. The various types of frequency weighting did not affect the correlations found between vibrations and annoyance: those correlations were similar in both cases. Zapfe et al. [28] likewise studied the influence of the frequency weighting method. To that end they compared several weighting methods, including ISO 2631 and BS-6841. In addition, Zapfe et al. [28] examined whether the particular type of indicator used to express exposure to vibrations makes any difference. They concluded that the various indicators could all in fact be regarded as variants of the same physical quantity and, for that reason, were all strongly correlated.

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variance, the better the ability of the model to predict actual values based on factors contained in the model. NB. The level of explained variance does not denote the magnitude of the effect nor the potential influence of a particular factor on, for instance, the percentage of high annoyance (source: Dusseldorp et al., Handreiking geluidhinder wegverkeer. Berekenen en meten. Bilthoven: RIVM, 2011).

[14] So whether the body moves back and forth or up and down does make a difference.

According to the researchers, this means that no single parameter qualifies as the preferred parameter.

2.5 The effects of vibrations on health

Over time, various outcomes have been measured in people that are associated with vibrations (from railway traffic). These effects are disturbance of activities (including sleep quality), annoyance, reduced quality of life, fatigue, reduced performance levels or work focus, motion sickness and other health issues [10, 11, 19, 24, 29]. This section briefly describes the current state of knowledge on the influence of prolonged exposure to railway-induced vibrations on health effects such as annoyance and sleep disturbance. There has been very little research on other long-term health effects [30].

2.5.1 Annoyance

Annoyance is the most frequently described and studied health effect of ambient noise. It has also often been studied and described in connection with vibrations. The Health Council of the Netherlands [31] has described annoyance as ‘a sense of aversion, anger, discomfort, dissatisfaction or indignation felt when an environmental factor exerts a negative influence on a person's thoughts, feelings or activities’. Whether a particular sensation is experienced as annoying depends on the person involved. Analogous to the definition used by the World Health Organization (WHO)[15], we regard annoyance as a health effect [32]. Noise studies have shown that chronic annoyance can also be regarded as a stress factor that is associated with other health effects (such as: [33-37]). Annoyance is measured using questionnaires [38].

Van Kempen et al. [10] already presented an overview of studies into the influence of railway-induced vibrations on levels of annoyance [25, 28, 39-51]. Since then, several new studies have been published [11, 19, 22, 30, 52-56], but the results of those studies have not changed the picture presented by Van Kempen et al.[10]. Most studies found an association between (an indicator of) exposure to railway traffic vibrations and annoyance due to such vibrations. It remains difficult, however, to compare the results of the various studies, for several reasons: i) The studies used various different indicators to express exposure to vibrations; ii) It is not clear which indicators is the most suitable; iii) The vibration sources studied also differed from each other: freight trains, passenger trains, underground trains and high-speed trains; iv) Moreover, annoyance was measured in several different ways: on the basis of one or more questions in a questionnaire and/or an interview. The questions concerned were different.

2.5.2 Effects on sleep

Acoustic studies have taught us that the effects of an environmental stressor, such as noise, on sleep can become manifest in various ways: a) in sleep behaviour (causing a person to wake up earlier, more frequently or later, for example), b) in sleep structure (causing changes in the duration of the various sleep stages, for example), c) in physical

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[15] Since 1948, the WHO has used the following definition of health: ‘Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity’ (WHO, 1948).

reactions (such as changes in heart rate), or d) as effects in the period after sleep [57-59].

The main research focus over the years has been on the influence of night-time environmental noise on sleep disturbance. Sleep disturbance is a term that is often used to denote the effect of exposure to noise during the night. The (annoyance caused by) sleep disturbance is often measured as part of a questionnaire, in which respondents are asked about the frequency and/or degree of recent sleep disturbance over a particular period [60]. However, during the night people are often unaware of themselves or their environment. This explains why the process of falling asleep and the wakeful periods during the night contribute disproportionately to their estimation of the frequency and/or degree of sleep disturbance [61].

Even so, self-reported sleep disturbance is regarded as a good indication of the influence of noise on sleep as experienced by an individual over a prolonged period. Like annoyance, sleep disturbance is measured using questionnaires, in which respondents are asked to indicate the extent to which they experience sleep disturbance caused by the sound from a specific source. And like annoyance, sleep disturbance is associated with other health effects as well [62].

Van Kempen et al. [10] also presented an overview of studies into the influence of railway-induced vibrations on sleep disturbance [25, 44-47, 49]. Several new studies have been published since [11, 19, 22, 63-65]. Some studies found indications that vibrations from railway traffic influence sleep [11, 22, 25, 49, 64, 65]: the chance of sleep disturbance increased with increasing exposure to vibrations from railway traffic. Note however, that with the exception of the CargoVibes study [64, 65], none of the studies expresses the exposure to vibrations with an indicator that specifically concerns exposure to vibrations during the night. As in the case of annoyance, the results of the various studies are difficult to compare. One of the reasons for this is that the studies use different vibration exposure indicators. It is not clear which of those is the most suitable one. Like annoyance, sleep disturbance is measured in a variety of ways [25, 44-47, 49].

The CargoVibes study [64, 65] examined the effects of vibrations from railway traffic on sleep through experimental research as well as observational research (surveys). The participants in the experimental research were exposed to vibrations and noise from railway traffic during a number of nights, under controlled conditions. CargoVibes also included several experimental studies [64, 66-69]. In those studies, both questionnaires and polysomnography (PSG) were used to measure the effects on sleep[16]. With increasing vibration levels, biological changes were measured, and changes in sleep structure, wake-up responses and self-reported quality of sleep. In 2019, Persson Waye et al. [64] compared the results of the experimental studies and the outcomes of surveys. Those surveys had been conducted in the

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[16] Polysomnography is sleep research in which several physiological parameters are recorded during a person's sleep. The result is known as a polysomnogram.

Netherlands and Poland; the experimental studies in Sweden. Most importantly, the comparative study found a significant association between exposure to vibrations and self-reported sleep disturbance, and no significant difference between the results of the experimental and the observational studies. The researchers also studied the differences between countries, and found that with equal levels of vibrations from railway traffic, the chance of sleep disturbance in the Netherlands (observational research) was higher than in Sweden (laboratory setting). In Poland (observational research), the association between exposure to vibrations from railway traffic was not significant.

2.6 Other health effects

Unlike annoyance and effects on sleep, other health effects of exposure to vibrations from railway traffic have rarely been studied to date. One of the most recent studies into the health effects of prolonged exposure to train-related vibrations is the Swedish EpiVib study [30], which examined the health effects of prolonged exposure to railway-induced vibrations. The study, which began in 2016, consisted of several components. During the first phase, 57 in-depth interviews were held, as an explorative study into people's perceptions of railway-induced vibrations and their attitudes to such vibrations. The results [53] served as key input for a survey that was used to collect information about perception of vibrations from railway traffic and the effects of such vibrations (annoyance, sleep disturbance and other self-reported health effects), and about their possible determinants. In the survey, 35,011 people between 18 and 80 years of age who, in 2017, lived within one kilometre of a railway in the Swedish regions of Halland, Västra Götaland, Värmland and Örebro were asked to complete a questionnaire. People living in areas near a railway a) used by fewer than ten freight trains per 24 hours, and/or b) with other major motorways and/or an airport in the vicinity, were excluded from the study. People living in areas near a railway for which no multiple train-related vibration measurements were available were also excluded. In the end, 7,707 people (~22%) completed the questionnaire. Of this group, 89.8% (n=6,922) consented to their data being linked to health registers. For the addresses of all respondents, exposure to vibrations was estimated using a model that was developed on the basis of 643 vibration measurements previously carried out in the study area (also see [70]). Exposure to vibrations was expressed as the 'maximum vibration velocity on the building foundation' (V_{max}). The initial results have recently been published [30, 52, 71-73].

As part of the EpiVib study, researchers also examined the influence of exposure to vibrations from railway traffic on the cardiovascular and metabolic systems. Another research focus was the effect of vibrations on mental health. The most important effects that were studied were hypertension (increased blood pressure), stroke, ischemic heart disease, diabetes and overweight indicators (Body Mass Index ≥ 30 kg/m^2 and high waist circumference), depression, anxiety and the use of psychopharmaca[17]. The analyses showed that the risk of hypertension, stroke, ischemic heart disease, diabetes and overweight increased with

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[17] Psychopharmaca are medicines used in the treatment of psychiatric conditions and psychological problems.

increasing levels of exposure to vibrations from railway traffic. The increase was only statistically significant however for ischemic heart disease and diabetes. After adjustment for potentially confounding variables, an Odds Ratio (OR) of 1.06 per 0.1 increase in vibration level (V_{max}) was found for both ischemic heart disease and diabetes. No association was found between exposure to vibrations from railway traffic and mental health. One important qualification to bear in mind when interpreting the study results, is that the numbers of participants exposed to higher vibration levels were relatively small. Moreover, the higher risks of ischemic heart disease and diabetes observed among participants exposed to higher vibration levels were based on minor cases of ischemic heart disease and diabetes. In addition, the increases in the risks of ischemic heart disease and diabetes were not always statistically significant, which means that the increases might also have been coincidental [30, 71, 72].

The European CargoVibes project also studied other health effects besides annoyance and sleep disturbance. Since most of those effects occurred after *short-term* exposure [64], they are not discussed in further detail here.

2.7 Dose-response relationships

Dose-response (DR) relationships indicate the chance of a particular effect or response for a particular level of exposure (dose). There are various ways to derive these relationships: a) by using the results of individual studies, b) by using a quantitative summary of the results of individual studies (also known as a meta-analysis), or c) by re-analysing individual data from a number of individual studies or a part of a study [74, 75].

2.7.1 Annoyance

Over the years, several researchers have tried to derive a DR relationship for the association between exposure to vibrations from railway traffic and annoyance [11, 22, 25, 30, 49, 52, 76, 77]. We can distinguish two groups of DR relationships:

a) relationships which, like the 'Living alongside the railway line' study from 2013 [11], are based on the results of a single study [25, 30, 49, 52, 76]), and
b) relationships based on the results of multiple studies (meta-analyses) [22, 77].

Re a) The most recent DR relationship derived from a single study was part of the Swedish EpiVib study. As part of this project, researchers studied the relationship between exposure to vibrations (expressed in terms of distance to the railway and V_{max}) [30, 52]. As in the first study, 'Living along the railway line'[11], they found that people experienced more annoyance due to vibrations from railway traffic as they lived closer to a railway line. And the more they were exposed to higher vibration levels, the more annoyance they experienced from those vibrations. The strongest relationships were found for freight trains. The British Salford study also yielded DR relationships between exposure to vibrations from railway traffic and high annoyance caused by such vibrations. As in the EpiVib study, exposure was expressed in terms of several different indicators: distance from the railway line, VDV and RMS. The DR relationships from the Salford study are based on data from 752 individuals [25].

Re b) This concerns two DR relationships: i) a relationship between distance from the railway line and annoyance due to vibrations from railway traffic, derived by Janssen et al. [77], and ii) an DR relationship derived for the association between vibrations from railway traffic and annoyance caused by such vibrations, as part of the CargoVibes project [22, 78]. Janssen et al. [77] derived an DR relationship for the association between distance from the railway line and annoyance due to vibrations from railway traffic based on a meta-analysis combining the results of nine international surveys. The CargoVibes study also derived DR relationships based on a meta-analysis, by combining the results of seven surveys. Five of those had already been conducted in the past [28, 43-47, 49, 51, 76, 79-81]; two (in Poland and the Netherlands) as part of CargoVibes. These seven studies examined the effects of various sources of railway-induced vibrations on annoyance. Three DR relationships were derived, expressing exposure to vibrations in terms of three different exposure indicators, namely $V_{dir,max}$, RMS and VDV. This also involved the use of ISO weighting. The researchers did not draw any conclusions as to which of the exposure indicators studied was the most suitable.

2.7.2 *Sleep disturbance*

For sleep disturbance caused by vibrations from railway traffic, two studies are available [11, 25] in which researchers derived an DR relationship for the association between exposure to vibrations and the percentage of respondents experiencing high sleep disturbance. Both DR relationships are based on the results of a survey. To express exposure to vibrations at night, Woodcock et al. [25] used $VDV_{b23:00\text{-}7:00}$. Van Kamp et al. [11] used distance from the railway line, V_{max} and RMS to express exposure.

2.8 The role of co-determinants

Apart from exposure to vibrations, several other factors influence the level of annoyance and/or sleep disturbance that a person experiences. Analogous to the literature on environmental noise (such as [38, 82]), we use the term ‘co-determinant’ to denote such other factors.
We can distinguish the following groups of potential co-determinants:

- Situational or contextual factors: these include factors such as day/night ratio, passenger trains/freight trains ratio, number of train passages, appeal of local neighbourhood, noise levels, structure of the house, rattling;
- Demographic and socioeconomic factors: these include age, gender, socioeconomic status (SES) and level of education;
- Personal factors: such as concerns about damage to the home or hazardous substances, health damage caused by vibrations, acceptance and sensitivity (to noise);
- Social factors: such as the attitude towards the vibration source or the people responsible, attitude towards the increase in railway traffic, attitude towards current and future railway policy, attitude towards passenger trains and freight trains in terms of

their need and eco-friendliness and/or expectations about the future of rail transport.

Research into the influence of co-determinants on annoyance and/or sleep disturbance caused by vibrations from railway traffic has so far been limited. The review of Van Kempen et al. [10] and Chapter 2 of Van Kamp et al. [11] present an overview of the findings from previous studies. These overviews yielded a number of demographic, situational/contextual and personal factors that could co-determine the relationship between vibrations from railway traffic and effects. This concerns aspects such as duration of residence, type of dwelling, structure of the dwelling, day/night ratio in burden from railway traffic, passenger trains/freight trains ratio, people's attitude towards railway traffic, expectations, acceptance and concerns, for example about property damage. Many of these factors also emerged from the first measurement in the 2013 ‘Living along the railway line’ study [11]. That study showed that factors such as attitude towards railway traffic, concerns about property damage and visual or aural perception of rattling objects, expectations regarding future levels and acceptance of vibrations influence the degree to which people experience annoyance from the vibrations caused by railway traffic.

3 Research methods

3.1 Design

The Follow-Up Study ‘Living along the railroad track’ is a cross-sectional study using an online questionnaire with questions about health effects and possible determinants thereof. The fieldwork was carried out from September to November 2021.

3.2 Sampling

The study had two groups of participants: i) participants recruited via a new sample (group I), and ii) participants who had already taken part in previous surveys within the context of 'Living along the railway line’ [11, 19] (group II). The sampling procedure for each of these groups is described below.

3.2.1 Participants recruited via the new sample (group I)

Based on the Key Register of Addresses and Buildings (BAG (January 2018) and the ‘Spoorbanen’ file from 2019, we used the geographic information system (GIS) software ArcMap to make a selection of all addresses i) located within 300 metres of a railway line in use and ii) registered in the BAG as a building with a residential purpose and/or ‘in use’ status. In total, this selection included more than 848,000 addresses. The following addresses were then eliminated:

- All addresses where we suspected the possibility of reliably estimating exposure to railway vibrations using the OURS model might be compromised. The areas in which those addresses are situated are referred to as exclusion zones. These are addresses in the vicinity of the following railway features: railway bridges (n=268,697), sunken tracks (n=34,536) and large stations with many parallel tracks (n=2,524). Addresses in the exclusion zones may be outside the coverage of the OURS model. A total of 305,757 addresses were affected. The exclusion zones were defined generically and with considerable margins. Many addresses within the exclusion zones could produce reliable results if assessed individually. However, this is a very laborious and time-consuming process for which there was a lack of time and budget;
- All addresses whose residents were previously invited to participate in the 2013 survey. This is an estimated 16,000 addresses. More than 6,000 addresses were also found to be located in an exclusion zone.

From the remaining 532,730 addresses, we selected a random sample of 16,000 addresses, as we did in 2013. To obtain the best possible distribution of addresses across levels of vibration exposure , we stratified by distance from a railway line and year of construction of the residence. This approach is comparable to the one used in 2013 (also see [11]). Table 3.1 provides a description of the strata used.

The exposure to railway-induced vibrations is modelled (also see section 3.6) based on a number of input data. Key input data are the sounding data contained in the Key Register of Subsoils (*Basisregistratie Ondergrond*, BRO) and the geomorphological subsoil map.

When there are no sounding data within 600 metres of the address or within a geomorphological subsoil type in the vicinity of the address, the exposure level for that address cannot be calculated. This is because the available information on the composition of the subsoil is insufficient to be used within the model. This is estimated to affect between 15% and 20% of addresses. Identifying these affected addresses in advance is very difficult and requires a lot of computing time. However, we know that the availability of sounding data, and therefore the coverage provided by the model, will increase in the future. Nevertheless, as we still wanted to be able to estimate the exposure to train-related vibrations for as many participants as possible, we took a random sample of addresses from the sampling frame (which contains 532,730 addresses) and checked whether they were within 300 metres of a sounding location. If they were not, we randomly selected a new address. We continued this process until we had a set of 16,000 addresses. In the end, an additional 4,495 addresses were selected.

Table 3.1 Total addresses invited per stratum, selected using a new stratified sample.

Stratum	**Distance from railway line (m)**	**Year of construction of the dwelling**	**No. of addresses invited**
1	up to 50 m	before 1950	4,000
2	up to 50 m	from 1950	4,000
3	50–100 m	before 1950	2,400
4	50–100 m	from 1950	2,400
5	100–300 m	before 1950	1,600
6	100–300 m	from 1950	1,600
Total			16,000

In the 2013 survey, power calculations showed that an estimated 13,000 to 16,000 participants were needed to reach a sufficient number of people to make reliable statements. This was based on 95% reliability and a power of 60-90% to observe an effect on annoyance and achieve an expected response rate of 30% [11].

3.2.2 Participants in a previous survey (group II)

In addition to the 16,000 addresses, we invited 1,189 people who had already participated in the 2013 'Living along the railway line' [11, 19] study and who had agreed to be contacted again. See Box 2 for a brief description of how we obtained this group of 1,189 people. Table 2 shows how these 1,189 invited participants were distributed in terms of distance from railway line and the year of construction of their residence.

Box 2 Recruitment of participants in the 2013 and 2019 surveys

In 2013, residents aged 16 and over of 16,000 addresses located within 300 metres of a railway line received an invitation to participate in a survey called 'Living along the railway line'. Those 16,000 addresses had been obtained by means of a random sample, stratified for distance of the dwelling from the railway line, year of construction of the dwelling and type of soil on which it was built. In October 2013, the 16,000 candidate participants were invited to complete a questionnaire (online or on paper). In the end, 4,927 completed the questionnaire (32% response rate). Of these 4,927 respondents, 3,421 agreed that they could be approached again for any future follow-up study. This group of 3,421 people was invited for the Repeated Measurement study in 2019. They received a letter in which they were invited to participate in a survey. They were asked to ensure that the person taking part this time was the same as the one who had participated in 2013. Of the 3,421 people invited, 1,349 completed the questionnaire. At several addresses the letter proved to be undeliverable or the individuals concerned had moved or died in the meantime. Eventually, the response rate was 40%. Of the 1,349 respondents who had participated in the Repeated Measurement study in 2019, 1,189 agreed that they could be approached again for a future follow-up study. In 2021, these 1,189 people were invited to participate in the Follow-Up Study.

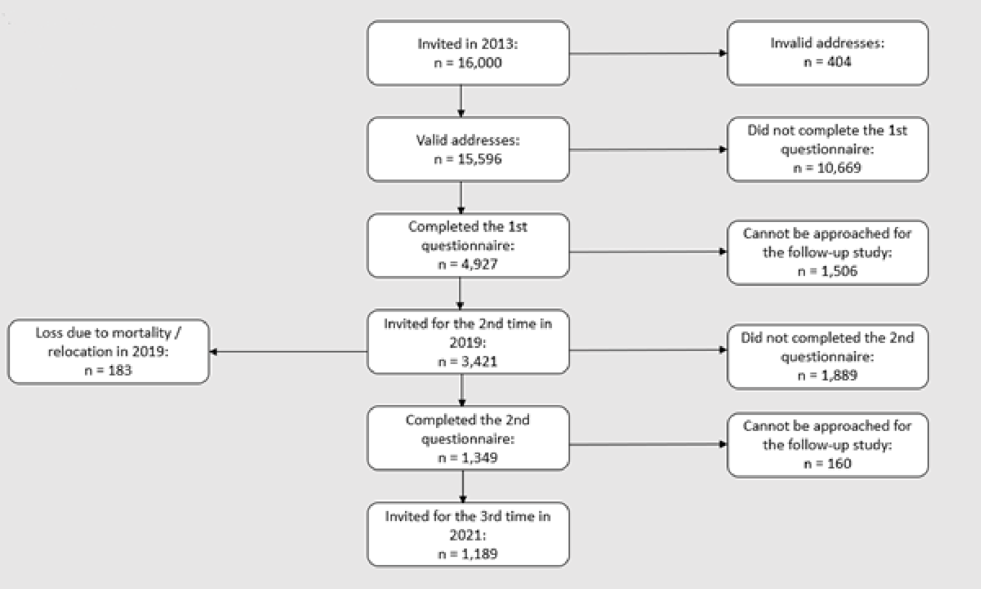

Figure B2 Flowchart for participation in the 'Living along the railway line' surveys in 2013 and 2019

Table 3.2 Distribution of invited participants from group II in the Repeated Measurement study across the six strata.

Stratum	Distance from railway line (m)	Year of construction of the dwelling	No. of people invited
1	up to 50 m	before 1950	378
2	up to 50 m	from 1950	342
3	50–100 m	before 1950	168
4	50–100 m	from 1950	156
5	100–300 m	before 1950	76
6	100–300 m	from 1950	69
Total			1,189

3.3 Fieldwork

The fieldwork was carried out by Kantar Public. The residents of the 16,000 selected addresses (Group I) received a written invitation to participate in the survey. At each address, the resident aged 16 or over with the earliest birthday was invited to complete an online questionnaire. The 1,189 former participants in the 2013 and 2019 surveys (Group II) also received a written invitation asking the person who had participated in these two previous surveys to complete the online questionnaire.

The invitation to *all* potential participants included the web address of a dedicated RIVM website. They were invited to visit this website and log in with a unique login code (provided by Kantar Public) to access the Kantar Public's questionnaire tool. Once the potential participant had given their consent to the processing of the data collected through the questionnaire, they could begin to complete the questionnaire.

About two weeks after sending out the questionnaire, we sent a reminder to the addresses that had not yet responded. Two weeks after sending the first invitations, we discovered that we had sent double invitations to 1,423 addresses in Group I, resulting in only 14,577 unique addresses rather than the planned 16,000 addresses
We then decided to select 1,423 new addresses from the full set of 532,730 addresses and invite them for the study, using the same distribution across the different strata as in the original sample.

Four weeks after the initial invitation and twee weeks after the additional invitation, a second reminder was send to all addresses that had still not responded. This second reminder came in the form of a postcard. To increase the response rate, thirty 50 Euro gift vouchers were raffled off among the participants.

3.4 The questionnaire

We used an online questionnaire to collect data about the perception of railway-induced vibrations, the effects of those vibrations and their possible determinants.

Table 3.3 Overview of the questionnaire used for the Follow-Up Study

Block	Title	Description
1	Your living environment	Information about the perception of the living environment: degree of satisfaction with the living environment, pleasant and unpleasant aspects, expectations regarding various aspects of the neighbourhood
2	Vibrations in and around your home	Information about people's perceptions of vibrations in and around their homes: annoyance caused by vibrations from various environmental sources (including railway traffic), frequency of experiencing vibrations produced by specific sources, experience of vibrations caused by railway traffic, annoyance due to vibrations from specific train-related sources, sleep disturbance due to vibrations from various environmental sources (including railway traffic and other train-related sources) and for specific train-related sources
3	Noise in and around your home	Information about people's perceptions of noise in and around their homes: their assessment of noise in and around the home, annoyance and sleep disturbance due to noise produced by various environmental sources and specific train-related sources
4	Questions about living near a railway line	How often do the participant/family travel by train, view of railway line from living room and bedroom, concerns, attitude with respect to railway traffic and rail transport policy, views on eco-friendliness and importance of rail travel, acceptance of train-related vibrations
5	Your home	Information about the dwelling: owner-occupied/rented, type of dwelling, number of floors and location of living room and bedroom, number of rooms, presence of a basement, floor construction in living room/bedroom, type of noise insulation, type of vibration insulation, windows open/closed
6	Health	Information about participants’ perception of their health. Respondents were asked specifically for information about: overall health, sleep quality, sensitivity to noise and changes in the situation concerning noise and vibrations from trains due to the COVID-19 pandemic
7	You and your household	Demographic data about the participant and their household: composition of household, gender, year of birth, highest level of education attained, employment situation
8	Other information	Consent to being approached again in future, first letter of first name, surname, home address, email address

The questionnaire is largely the same as the one used by Van Kamp et al. [11] in 2013. The questionnaire contains questions derived largely from the questionnaire used in the European CargoVibes project [65, 78], supplemented with questions from the study conducted by the University of Salford [83] and the Schiphol Medical Evaluation ('Gezondheidskundige Evaluatie Schiphol') [84]. We also used questions from national surveys, such as the Municipal Public Health Service's Health Monitor, the Survey of the Netherlands (WoON) from Statistics Netherlands (CBS) and others (such as [85]). The questionnaire consists of a number of blocks as shown in Table 3.3.

We submitted the draft questionnaire for comments to colleagues at the RIVM, the Ministry of Infrastructure and Water management and a stakeholder group including representatives of ProRail, Municipal Public Health Services (GGD), and provincial and municipal authorities. Finally, the questionnaire was also evaluated by a group of citizens living in the vicinity of a railway line. These citizens were recruited from a panel composed by Kantar Public. The aim of this evaluation was to find out whether people understood the questionnaire and whether there were any aspects that were missing or needed to be changed. The questionnaire was adapted on this basis on the comments received.

Since the measurement for participants from Group II was a repeated measurement, we did not again ask for a number of specific background details that we had already collected back in 2013 and which were likely to have remained unchanged. These were year of birth, sex, length of residence, type of dwelling, number of floors, position of living room/bedroom, number of rooms and presence of a basement.

3.5 Non-response study

We carried out a non-response study, as we did for the 2013 survey [11]. This is because participation in the survey may be influenced by factors directly related to the subject of the survey. For example, people who experience considerable annoyance due to railway-induced vibrations may be more likely to respond than people who do not. The resulting selective response would mean that the participants would not be fully representative for the sample as a whole, causing bias in the final results. To find out whether this was the case, we conducted a survey among a group of non-respondents. It was important to ensure the highest possible response rate for this survey, as a low response rate would affect the usability of the non-response survey data.

3.5.1 Procedure for Group I

The procedure for the non-response survey in Group I was as follows: Kantar Public took a random sample of 972 addresses among the addresses of the 16,000 candidate participants who had been invited for the first time to participate in the survey (Group I), but had not responded after two reminders. Candidate participants whose address details in the Key Register of Addresses and Buildings (BAG) were found to be an incorrect address were not invited to participate in the non-response survey. Candidate participants who had indicated that they did not wish to be invited again or who had already participated in 2013 and 2019 (Group II), were also not invited either.

The only detail known about the non-responders at the start of the non-response survey was their home address (from the BAG). In order to maximise the response rate among non-respondents, Kantar Public tried to enrich their address details with telephone numbers where possible. This step was performed by the company EDM, who enriched the data with telephone numbers by using licences to both private and public sources to build its databases (also see https://consubase.nl/wat-is-consubase). As we only had access to address details and not to names, prior to the non-response study we expected to be able to find telephone numbers for 30-35% of all addresses.

All candidate participants in the non-response survey received an invitation to complete a short online questionnaire. Non-respondents whose telephone numbers were available were contacted by telephone and asked to answer the eight questions. We also announced this in the letter of invitation, in which we also enabled candidate participants to opt out immediately if they did not want to be called.

Eight questions from the main survey were selected for inclusion in the non-response survey: i) two endpoints: annoyance due to railway-induced vibration and satisfaction with living environment; ii) four determinants: age, length of residence, gender, highest level of education; iii) two mediators: attitude towards rail policy and growth of railway traffic, and iv) reason for non-response.

3.5.2 *Procedure for group II*

As a lot of data on the 1,189 participants in 2013 and 2019 (Group II) was already available from the earlier measurements, we decided to compare respondents and non-respondents in group II. The following aspects were compared: age, gender, highest level of education, annoyance due to railway-induced vibrations measured in 2019, satisfaction with living environment measured in 2019 and attitude towards rail policy and growth of railway traffic measured in 2019.

3.6 Exposure to vibrations from railway traffic

The exposure to railway-induced vibrations of participants were modelled using the OURS calculation model [15, 16]. This model, commissioned by the Ministry of Infrastructure and Water Management and developed by a group of experts led by RIVM, calculates vibration levels based on the vibration source (trains and tracks) and the transmission of vibrations to the building foundations. The model then predicts the transmission of vibrations within the building. In order to accurately determine the transfer of vibrations in the soil, we use measured soil properties from the Key Register of Subsoils (BRO). The OURS model also calculates the degree of inaccuracy associated with each of these steps. This data was not used in further analysis due to its of minor relevance, as the group is large enough for any under- and overestimation to be balanced out.

The OURS model uses a variety of source data to calculate the exposure to vibrations from railway traffic. For train intensity and speed we used the data from 2019 (before train timetables were affected by COVID-19 measures), which is considered to be representative for the train intensity in 2021. In addition, we used railway location data from 2021. Intensity data (provided by ProRail) refers to train intensity levels in calculation units (railway carriages or cars as referred to in ISO-3095) as defined in the 2021 Calculation and Measurement Requirements for Noise. Railway-induced vibration exposure is based on the number of train movements, which is also the input required for the OURS model. Therefore, a general conversion factor was applied to estimate the number of train movements based on the number of railway cars ("carriages"), which was 0.2 for passenger trains and 0.05 for freight trains. This factor was based on the average number of railway cars ("carriages") of passenger (5 cars) and freight trains (20 cars) in The Netherlands.

Soil data was based on sounding data from the Key Register of Subsoils (BRO) of 4 February 2022.

Building data was derived from the BAG (reference date June 2022). This included a) year of construction, b) building dimensions, both at right angles to and parallel to the railway line, and c) building height (based on 3D BAG, June 2022). If the questionnaire indicated the presence of a wooden floor in the participant's home, this was also included as a characteristic in the calculation. The model was used to calculate the following exposure indicators for the participants' homes (see also Table 3.4):

Indicators for maximum exposure:
The $V_{dir,max}$ and V_{max} indicators represent the maximum vibration level of all train passages over a period of one week. The difference between V_{max} and $V_{dir,max}$ is that $V_{dir,max}$ is contains an directional ISO weighting [23], which takes into account the difference in sensitivity to vertical and horizontal vibrations in the perception of vibrations on a floor. Therefore, different frequency weights are applied depending on the direction of the vibration. The V_{max} indicator uses standard weighting from the SBR Guideline, part B [1]. The $V_{dir,\ max}$ and V_{max} indicators are dimensionless measures, as they are calculated by dividing vibration levels by a (weighted) reference vibration and are therefore given without a mm/s unit.

Indicators for average exposure:
The root mean square (RMS) of the effective vibration exposure by railway traffic was also used as a indicator of vibration exposure. Unlike the $V_{dir,max}$ and V_{max}, RMS takes the number of train passages into account. Analyses by TNO and the CargoVibes project [21, 22] suggest that RMS has added value in predicting annoyance. As with maximum vibration intensity, RMS is available in a version *with* directional ISO weighting [23] (referred to as RMS_{ISO+}) and a version *without* directional ISO weighting (RMS). In addition, both RMS_{ISO+} and RMS have been calculated separately for daytime, evening and nighttime hours. Daytime hours are from 7:00 to 19:00, evening hours are from 19:00 to 23:00 and nighttime hours are from 23:00 to 7:00.

The indicator V_{per} represents the root mean square average of the vibration level during the assessment period, weighted for exposure duration. Therefore, the V_{per} increases as the number of train passages increases. This also applies to V_{max} but to lesser extent. Similar to the other two indicators of vibration exposure, V_{per} is available in two versions, one *with* directional ISO weighting ($V_{per,ISO+}$) and one *without* [23] (V_{per}). The indicator V_{per} is used in both the Bts [2] and SBR [1]. In addition, both V_{per} and $V_{per, ISO+}$ have been calculated separately for daytime, evening and night-time hours. Daytime hours are from 7:00 to 19:00, evening hours are from 19:00 to 23:00 and nighttime hours are from 23:00 to 7:00. Similar to the V_{max} and $V_{dir,max}$ indicators, both the V_{per} and RMS are dimensionless indicators of vibration level.

All the indicators described above were calculated for total railway traffic and separately for freight trains and passenger trains. In addition, the distance (in metres) between the nearest railway line and the wall of the house facing the railway line was calculated for each participant.

Table 3.4 Overview of available exposure indicators for vibrations from different types of trains

Vibration source	**Maximum vibration level**		**Average vibration level**[a]	
ISO 2631 weighting	**Yes**	**No**	**Yes**	**No**
Total railway traffic	$V_{dir,max}$	V_{max}	RMS_{ISO+}, $RMS_{day,ISO+}$, $RMS_{evening,ISO+}$, $RMS_{night,ISO+}$, $V_{per,ISO+}$, $V_{per,day,ISO+}$, $V_{per,evening,ISO+}$, $V_{per,night,ISO+}$	RMS RMS_{day}, $RMS_{evening}$, RMS_{night}, V_{per}, $V_{per,day}$, $V_{per,evening}$, $V_{per,night}$,
Freight trains	$V_{dir,max}$	V_{max}	RMS_{ISO+}, $RMS_{day,ISO+}$, $RMS_{evening,ISO+}$, $RMS_{night,ISO+}$, $V_{per,ISO+}$, $V_{per,day,ISO+}$, $V_{per,evening,ISO+}$, $V_{per,night,ISO+}$	RMS, RMS_{day}, $RMS_{evening}$, RMS_{night}, V_{per}, $V_{per,day}$, $V_{per,evening}$, $V_{per,night}$,
Passenger trains	$V_{dir,max}$	V_{max}	RMS_{ISO+}, $RMS_{day,ISO+}$, $RMS_{evening,ISO+}$, $RMS_{night,ISO+}$, $V_{per,ISO+}$, $V_{per,day,ISO+}$, $V_{per,evening,ISO+}$, $V_{per,night,ISO+}$	RMS, RMS_{day}, $RMS_{evening}$, RMS_{night}, V_{per}, $V_{per,day}$, $V_{per,evening}$, $V_{per,night}$,

[a] Daytime hours are from 7:00 to 19:00, evening hours are from 19:00 to 23:00 and nighttime hours are from 23:00 to 7:00.

3.7 Exposure to noise from railway traffic

For each participant, RIVM calculated the exposure to railway noise using the Dutch National calculation methods (RMG-II). For this model we used speed and intensity data for 2019 as provided by ProRail to municipalities for noise mapping purposes within the context of the Environmental Noise Directive (END). The data was made available by

Infomil[18]. The environmental model from the 3D Key Register for Noise (reference date Autumn 2022) was used in the model.

The model calculates both annual average L_{den} and L_{night}. The L_{den} or Day-evening-night level is a sound exposure level descriptor based on energy equivalent noise level (L_{eq}) over a whole day with a penalty of 10 dB(A) for night time noise (23:00 – 7:00) and an additional penalty of 5 dB(A) for evening noise (i.e. 19:00 – 23:00). For each address we calculated the noise level on the highest exposed facade. For that purpose, noise exposure levels were calculated at five-metre intervals on the facades and on every floor. The highest calculated noise exposure level for a dwelling was assigned to the respondent residing in that dwelling. Figure 3.1 shows a 3D representation of part of the calculation model.

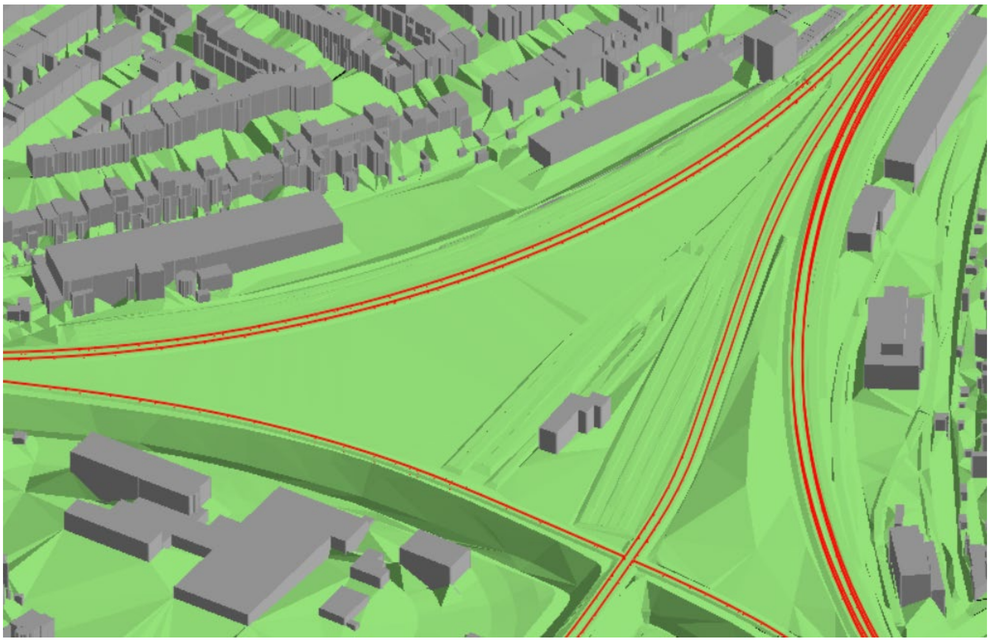

Figure 3.1 Detail of the 3D noise model featuring railway lines, embankments and buildings.

3.8 Physical and social characteristics of the local environment

Besides exposure to railway-induced vibrations and noise, we also included a number of physical and social characteristics of the local residential environment in the study. This concerns the following data:

- Distance (in m) from the participant's home address to the nearest road and/or thoroughfare (provincial road or motorway). This was obtained from the National Register of Roads (NWB), 2019. Just like railway traffic, road traffic is a source of vibrations;

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[18] https://www.infomil.nl/onderwerpen/geluid/uitvoering-kartering/index/uitwisseling/brongegevens-hoofdspoorwegen/. After the introduction of the Omgevingswet (January 2024) all information has moved to: https://iplo.nl/thema/geluid

- Noise generated by road traffic in L_{den} (in dB) and L_{night} (in dB) on the most exposed facade of the participant's home address (based on Stamina maps, RIVM 2017);
- Distance to the nearest train station (in m). This is the average distance by road of all residents in a particular neighbourhood to the nearest train station [86, 87]. To determine this distance, we identified the neighbourhood where the participant's home address was located and used that to link the data.
- Identifier if the nearest railway line to the participant's home address is part of the Basic Transport Network. The Basic Transport Network is a railway section that is used for the transport of hazardous materials[88];
- Percentage of green space within a radius of 500 metres of the participant's residential address [89]. This indicator is based on the total amount of green space (trees, shrubs and other plants) which is estimated with a resolution of 10 x 10 m within the radius;
- Percentage of tree-covered surface within a radius of 500 metres from the participant's residential address [90]. This indicator is specifically based on the surface area covered by trees that are at least 2.5 m tall;
- The annual average concentration of $PM_{2.5}$ ($\mu g/m^3$) [91]. This is address level information for participants' residential address with a resolution of 25 x 25 m: the $PM_{2.5}$ concentration is calculated using the National Air Quality Cooperation Programme (NLS) monitoring tool;
- The annual average concentration of NO_2 ($\mu g/m^3$) [92]. This is address level information for participants with a resolution of 25 x 25 m: the NO_2 concentration is calculated using the NSL monitoring tool;
- The degree of urbanisation in the neighbourhood of the participant's residential address [86, 87]: Each neighbourhood, district or municipality in The Netherlands has been assigned an urbanisation class based on address density levels by Statistics Netherlands (CBS) into five different classes: 1) extremely urbanised (≥2,500 addresses per km^2), 2) strongly urbanised (1,500 – 2,500 addresses per km^2), 3) moderately urbanised (1,000 – 1,500 addresses per km^2), 4) hardly urbanised (500 – 1,000 addresses km^2) and 5) not urbanised (<500 addresses per km^2);
- Liveability score from the Leefbaarometer (based on LBM3, neighbourhood-level information, 2021) [93]. See also Table 4.8: The liveability score gives an indication of how liveable a neighbourhood is in a particular year. The score is based on nine different categories and the total score can range from extremely poor to excellent. The liveability score of the participants' neighbourhood was obtained using the Leefbaarometer webtool (also see [93] and the website www.leefbaarometer.nl).
- Average Value of Immovable Property Act (Dutch acronym: WOZ) value in 2020 (in €) in the participant's neighbourhood [86, 87]. The average WOZ value is defined by the CBS as follows: 'The average WOZ value of all premises with a residential purpose. Dwellings with a value less than 10.000

euros or more than 5 million euros have been excluded from the calculation of the average WOZ value.'

3.9 Statistics

3.9.1 *Weighting to account for sampling method*

To obtain valid estimates of the prevalence of high annoyance and high sleep disturbance, we re-weighted the sample to the target population: all persons aged 16 and over living within 300 metres of a railway line (excluding those living in areas in the vicinity of railway bridges, sunken track sections and railway stations with many parallel tracks). For this purpose, each participant in the study was assigned a weighting factor, which indicates the number of individuals in the target population that each participant represents. The weighting factor used in the analyses takes the following aspects into account:

- *The sampling fraction*: this is the probability of a person aged 16 or over in the study area is included in the sample, stratified by distances and years of construction (dichotomised: before and after 1950) that occur in the study area.
- *Unit non-response*: this is the complete absence of questionnaire data for a person. Some of the people selected in the sample are likely not to respond for various reasons (refusal, moving house, etc.).

In contrast to the 2013 survey [11], participants in the Follow-Up Study could only complete the questionnaire online. In addition, once they had given their consent, they could not complete the questionnaire without answering every question. Therefore, the probability of item non-response was deemed to be very low. A detailed description of the weighting factors can be found in Annex 1.

3.9.2 *Determining the most suitable exposure indicator*

In order to best predict high annoyance and high sleep disturbance due to railway-induced vibrations, we determined the most appropriate exposure indicator of railway-induced vibrations by comparing the performance of logistic regression models based on different indicators. Models were compared based on their model fit and prediction accuracy. In this study the model fit is expressed in terms of the *Akaike Information Criterion* (AIC) and the model accuracy in terms of the *area under the curve* (AUC) of the *receiver operating characteristic*-curve *(ROC)*. See section 3.9.3 for a detailed explanation of these measures. In addition to determining fit and accuracy, we also examined the correlations between the different indicators.

3.9.3 *DR relationships*

A DR relationship describes the relationship between exposure and the response to that exposure within a population. In this study, the response is the expected percentage of people who experience high annoyance or high sleep disturbance due to railway-induced vibrations from rail. The relationship between exposure and response is often linear: in those cases, the chance of a response increases gradually as the level of exposure increases. Sometimes the relationship is rather more complex and is can be considered as non-linear. For example, there may be an threshold value of exposure below which no detectable response occur. There are also cases in which the response actually *decreases* with increasing levels of exposure [94].

We established DR relationships through population-weighted logistic regression models[19] using two different methods:

- *Continuous exposure*: In this method the exposure to vibrations is included in the regression model as a continuous predictor. This results in a DR relationship (plus a 95% confidence interval) that can be used to estimate the percentage of people experiencing high annoyance or high sleep disturbance due to railway-induced vibrations for a specific value of exposure.
- *Categorical exposure*: In this method the continuous exposure has been transformed into a categorical variable based on exposure deciles[20]. For example, the first category includes all observations with an exposure value below the first decile. The next category consists of all observations with an exposure value between the first and the second decile and so on. Since the structure is based on deciles of the collected data from participants in the Follow-Up Study, each category consists of approximately the same number of observations. We then built a (weighted) logistic regression model on the basis of this categorical variable. The category with the lowest exposure is set as the reference category for the model. For each decile group, the model produces an estimate (plus 95% confidence interval) of the expected percentage of high annoyance or high sleep disturbance due to railway-induced vibrations. To better compare this model with the model based on a continuous exposure, the expected percentage of people reporting high annoyance or high sleep disturbance was plotted against the median[21] of exposure of each decile group. This yields ten data points and a trend-line of these data points is used as the DR relationship of the categorical model.

A key difference between these two methods is that in the case of the logistic regression model with categorical exposure, it is possible to demonstrate non-linear connections between exposure and outcome. This is not possible with a continuous exposure model as it assumes a linear relationship between exposure and outcome. As the two models are based on the same number of observations, they can be compared directly with each other using the *Akaike Information Criterion* (AIC) [95]. This is a measure of the model fit, adjusted for the number of

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[19] Logistic regression is an analysis technique that allows us to produce a model for predicting the probability of a positive outcome of a dichotomous outcome variable (e.g. high annoyance due to rail-induced vibrations or no high annoyance due to railway-induced vibrations, complaints or no complaints) with one or more independent variables. When drawing up DR relationships we also re-weighted the sample to the target population, using the weighting factors derived in section 3.9.1 and Annex 1.

[20] A decile is one of the nine values that divides a data set into ten equal parts. Every decile contains a tenth of the observations. Deciles can be used, for example, to examine the way participants are distributed across vibration exposure levels. To illustrate this, the participants are first divided into ten equal parts depending on their level of exposure. The first decile contains the bottom 10% of participants: in other words, the 10% of participants with the lowest level of exposure. The second decile represents the second tenth part (from 10% to 20%), etcetera. The tenth decile represents the 10% of participants with the highest level of exposure.

[21] The median is a middle parameter. It is the middle value of observations if all values are positioned in sequence. It can be said, therefore, that 50% of observations have a value below the median and 50% have a value above the median.

predictors in the model. The AIC allows models to be compared with each other on the basis of their model fit. The lower the AIC, the better the fit of the model. The AIC is a relative parameter and the absolute value of the AIC has little value. Therefore, a measurement that is often used for easy comparison between various models is the ΔAIC. This measurement represents the difference between the AIC value of a model and the lowest AIC value observed. The model with the lowest AIC value (i.e., the model with the best fit) will have a ΔAIC of 0. A rule of thumb for using ΔAIC is that models with a ΔAIC value lower than 2 do not differ significantly in terms of fit from the best model and should therefore be equally useful [95]. A model with a ΔAIC value between 2 and 10 is probably less useful in terms of fit than the model with a ΔAIC value of 0. For ΔAIC values higher than 10, the model is almost certainly less useful than the model with a ΔAIC value of 0 [95].

Table 3.5 The rules of thumb used in this report for applying ΔAIC[a] *(based on [95])*

ΔAIC[*]	**Rule of thumb**
< 2	No difference in fit between the two models
2–10	The model with the highest AIC value probably offers a worse fit than the model with the lowest AIC value
>10	The model with the highest AIC value almost certainly offers a worse fit than the model with the lowest AIC value

[a] Determined by the difference in AIC value between the model with the lowest AIC value and a model with a higher AIC value.

For comparisons between models we also used the area under the curve (AUC) of the receiver operating characteristic (ROC) curve*.* This is a measure of the performance of a model and represents how accurately the model can predict the outcome. An AUC value can range from 0.5 (fully random prediction of outcome) to 1.0 (perfect prediction of outcome based on the model). The closer the AUC is to 1, the better the model’s ability to predict the outcome.

All analyses required for establishing the DR relationships were performed using the R package ‘survey’ [96] and the results were visualised using the R package ‘ggplot2’ [97].

3.9.4 *Determining the influence of co-determinants: determinant analysis*

In order to explain the influence of railway-induced vibrations on perceived levels of annoyance and sleep disturbance in relation to other possible variables (known as co-determinates), we also performed a multivariate logistic regression analyses. The central question here was to determine how high annoyance and high sleep disturbance due to railway-induced vibrations are associated with specific co-factors, while also taking into account the interrelationships between these factors.

Within a logistic regression model, the association between an exposure or co-determinant and the end point can be expressed as an Odds Ratio (OR). The OR is an indicator of the association and it represents an approximate value for the extent to which a person with a certain level of exposure is more likely (or less likely) to develop an illness or condition compared to a person not subject to that exposure. For example, in a model where the endpoint is lung cancer (1 = yes, 0 =

no), the exposure variable is smoking behaviour (1 = smoker, 0 = none-smoker). If the exposure smoking behaviour has an OR=2, then the chance of developing lung cancer is twice as high for smokers than for non-smokers. Another example, in a model with the endpoint the presence of a heart disease (1=yes, 0=no) the exposure variable is regular physical exercise (1=yes, 0=no). An OR value of 0.5 represents that the chance of developing a heart disease is half as high for people who regularly engage in physical exercise compared to people who do not. When an exposure variable has an OR value 1, the chance of having a specific endpoint is identical for the exposed group and the non-exposed group.

To find out which co-determinants, in addition to vibration exposure, are associated with high annoyance and high sleep disturbance due to railway-induced vibrations, we built several different logistic regression models:

High annoyance due to railway-induced vibrations (per train type):
A model including both an indicator for exposure to railway-induced vibrations and the following groups of co-determinants

a) Exposure: distance from the nearest railway line or exposure to railway-induced vibrations (expressed in V_{max}, V_{per} or RMS, per train type);
b) Situational/contextual factors: amount of freight trains (%), amount of night trains (%), degree of urbanisation, exposure to railway noise (dB), hearing/seeing/feeling windows, doors and/or crockery (‘rattle’), and high annoyance due to railway noise (per train type);
c) Demographic factors: gender, age, level of education;
d) Personal factors: concerns, acceptance of vibrations; and
e) Social factors: attitude towards railway policy and growth of railway traffic, and expectations regarding railway-induced vibrations.

High sleep disturbance due to railway-induced vibration(per train type):
A model including both an indicator for exposure to railway-induced vibrations (during the night) and the following groups of co-determinants

a) Exposure: distance from the nearest railway line or exposure to railway-induced vibrations (expressed in V_{max} or $V_{per,\ night}$ or RMS_{night}, per train type);
b) Situational/contextual factors: amount of freight trains (%), amount of night trains (%), degree of urbanisation, exposure to nocturnal railway noise, hearing/seeing/feeling windows, doors and/or crockery (‘rattle’), location of bedroom, keeping rooms open or closed in summer and/or winter, use of HR glass for bedroom windows, and high sleep disturbance due to railway noise (per train type);
c) Demographic factors: gender, age, level of education;
d) Personal factors: concerns, acceptance of vibrations; and
e) Social factors: attitude towards railway policy and growth of railway traffic, and expectations regarding railway-induced vibrations.

The predictors or potentially confounding variables included in the above models were partly selected *a priori* on the basis of relevant literature (also see Chapter 2), supplemented with variables that were identified as being of high importance within untargeted analyses (UA). See Annex 2 for a detailed description of the UA and an overview of the main results. Furthermore, Annex 3 gives a description of the coding of both the outcome measures and the predictors included in the above models.

As with the prevalence estimates, the sample was reweighted to the target population using the weighting factors derived in section 3.9.1 and Annex 1.

4 Descriptive results

4.1 Response in main study

Table 4.1 provides an overview of the response figures for the two groups of participants. The response calculation are based on *usable addresses*. These are *all* addresses that were contacted with the exception of i) addresses that turned out not to exist or to be unoccupied (also see section 3.2) and ii) addresses of participants of the 2013 and 2019 surveys who had either passed away or relocated.

In total, 0.9% of contacted addresses were removed for the above reasons. The term “Non-responders” refers to individuals who i) did not consent to their data being processed at the start of the questionnaire, or ii) who did not complete in the questionnaire. There were no people who qualified as non-responders due to an incomplete questionnaire response. The questionnaire was administered online and had been designed in a way that required participants to fully answer each question before moving on to the next..

A total of 5,611 fully completed questionnaires were received, which represents a response rate of 33%. The difference in response rate between the Groups I and II was considerable: 30.2% in Group I and 69.1% in Group II. The Group I response was slightly below the 32% achieved in the comparable 2013 questionnaire [11].

Table 4.1 Total response

	Group I	Group II	Total
Invited	16,000	1,189	17,189
Invalid address	160	-	160
Passed away/ moved house	-	2	2
Usable address	15,840	1,187	17,027
No permission	112	10	122
Not filled in	10,937	357	11,294
Filled in	4,791	820[a]	5,611
Response %	30.2	69.1	33.0

[a] This also includes the 36 participants who did not yet live at the contacted addresses at the time of the 2013 and 2019 measurements, but were willing to fill in the questionnaire.

An overview of response rates per stratum for groups I and II separately and for the entire participant group is given in Tables 4.2, 4.3 and 4.4. These tables show the response rates relative to the total of usable addresses within each stratum. The tables show that response rates are higher among participants who live closer to the railway lines.

Table 4.2 Response rates for group I per stratum

Distance from railway (m)	Year of construction of the dwelling	Invited	Unusable address	No permission	Filled in	Response %
up to 50 m	before 1950	4,000	36	26	1,488	37.5
up to 50 m	from 1950	4,000	51	28	1,305	33.0
50–100 m	before 1950	2,400	15	14	695	29.1
50–100 m	from 1950	2,400	20	24	623	26.2
100–300 m	before 1950	1,600	15	10	346	21.8
100–300 m	from 1950	1,600	23	10	334	21.2
Total		**16,000**	**160**	**112**	**4,791**	**30.2**

Table 4.3 Response rates for group II per stratum

Distance from railway (m)	Year of construction of the dwelling	Invited	Passed away/moved house	No permission	Filled in	Response %
up to 50 m	before 1950	378	0	4	276	73.0
up to 50 m	from 1950	342	0	4	247	72.2
50–100 m	before 1950	168	0	0	104	61.9
50–100 m	from 1950	156	0	2	100	64.1
100–300 m	before 1950	76	1	0	49	65.3
100–300 m	from 1950	69	1	0	44	64.7
Total		**1,189**	**2**	**10**	**820**	**69.1**

Table 4.4 Response rates for total group per stratum

Distance from railway (m)	Year of construction of the dwelling	Invited	Unusable address	Passed away/ moved house	No permission	Filled in	Response %
up to 50 m	before 1950	4,378	36	0	30	1,764	40.6
up to 50 m	from 1950	4,342	51	0	32	1,552	36.2
50–100 m	before 1950	2,568	15	0	14	799	31.3
50–100 m	from 1950	2,556	20	0	26	723	28.5
100–300 m	before 1950	1,676	15	1	10	395	23.8
100–300 m	from 1950	1,669	23	1	10	378	23.0
Total		**17,189**	**160**	**2**	**122**	**5,611**	**33.0**

Figure 4.1 presents a spatial view of total response rates, showing an even spatial distribution of participants. Only one route that was included in the sample is not represented.

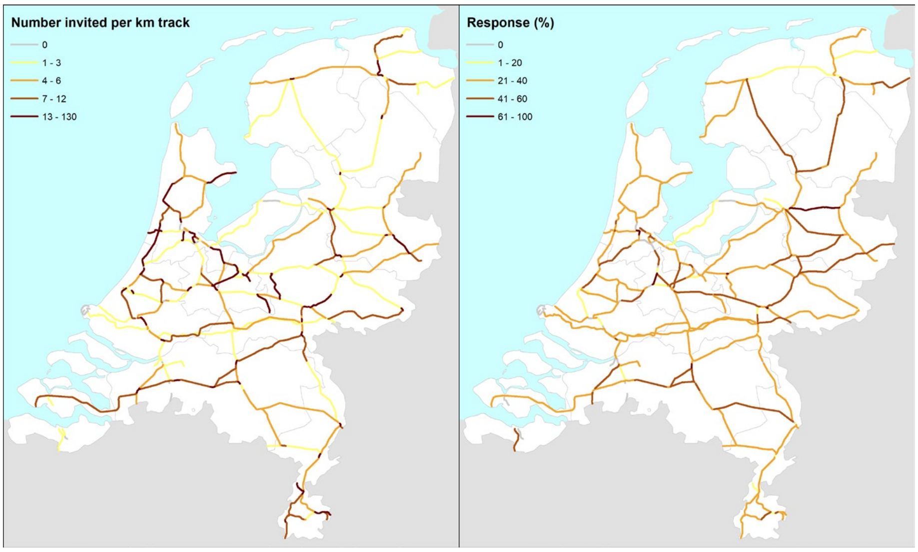

Figure 4.1 Spatial distribution of response rates.

Finally, data were collected on the types of devices used by participants to complete the questionnaire. The majority of participants (68.8%) used a personal computer. Over 19% of participants completed the questionnaire on a tablet, and over 11% did so on a smartphone.

4.2 Response rates in the non-response study

Of the 10,937 Group I addresses from which we did not receive a completed questionnaire, a random sample of 972 addresses was selected to include in the non-response study. We then tried to find a telephone number for as many of these addresses as possible in order to contact them directly for participation in the non-response study. We were able to identify a telephone number for 283 addresses (29.1%). For the remaining 689 addresses (70.9%) this was not possible and therefore these residences of these addresses were contacted in writing. Table 4.5 shows the response rates for the two groups.

Table 4.5 Response among the 972 participants in the non-response study

	By telephone	In writing	Total
Invited	283	689	972
No permission	67	5	72
Permission	216	684	900
Filled in	120	55	175
Response %	55.6	8.0	19.4

Overall, we achieved a response rate of over 19% among the 972 non-responders of the survey. This is lower than the response rate achieved in the 2013 non-response study (29%), which only included a written survey. Despite the fact that the response rate in the group for whom we were able to find telephone numbers was much higher (over 55%), this did not result in a higher *overall* response rate for the non-response study compared to the full survey.

As part of the non-response study we also asked participants why they did not want to take part in the main study. Over 29% said they did not have the time, over 15% were not interested and over 6% had another reason. In the majority of cases (over 49%), they were unable or unwilling to give a reason.

To check whether selective non-response might have played a role, in section 4.5 we will: a) compare the participants in the current non-response with group I participants in the main study; b) compare the characteristics of group II participants in the main study with those of participants in the Repeat Measurement [19]. After all, in 2013 and 2019 we already collected a great deal of information about group II participants in the main study.

4.3 General characteristics of participants in the main study

Table 4.6 presents a number of general characteristics of the different groups of participants. There were differences in the characteristics of Group I and Group II. For example, compared with Group II, Group I includes: a) more women, b) more participants aged 44 and under, c) fewer households with no children living at home, d) more persons in paid employment, e) fewer retired people, and f) fewer owner-occupiers. Compared with Group I, Group II participants have lived at their current address for a longer period of time. These differences are likely to be explained by the fact that Group II participants have been followed since 2013.

A comparison of the characteristics of the total group of participants from Table 4.6 with those of the general Dutch population shows that the proportion of women among participants in the survey is relatively low (around 46%). According to the CBS, in 2021 more than 50% of the Dutch population aged 16 and above are women. The proportion of participants aged 45 and over is also relatively high: 41.9% are in the 44-64 age group and 32.0% in the 65+ group. The corresponding percentages for the general Dutch population in 2021 were 33.1% and just under 24% [98].

Table 4.6 Characteristics of participants in the Follow-Up Study (N=5,611).

	Group I % (N)	**Group II % (N)**	**Total % (N)**
Number of participants	4,791	820	5,611
Gender[a]			
Men	52.7 (2,524)	60.8 (477)	53.8 (3,001)
Women	47.0 (2,251)	39.2 (307)	45.9 (2,558)
Other	0.3 (16)	0	0.3 (16)
Age class[a]			
16–44 years	29.4 (1,408)	6.2 (48)	26.1 (1,456)
45–64 years	41.0 (1,963)	47.2 (386)	41.9 (2,331)
65 and over	29.6 (1,419)	46.7 (364)	32.0 (1,783)
Highest level of education[b]			
No education, lower education, lower vocational, lower general secondary	20.0 (960)	15.0 (123)	19.3 (1,083)
Higher general secondary, pre-university, senior secondary vocational	31.8 (1,524)	31.6 (259)	31.8 (1,783)
Higher professional, university	48.2 (2,307)	53.4 (438)	48.9 (2,745)
Family situation[c]			
Single household	24.2 (1,136)	24.1 (193)	24.1 (1,329)
Couple living together with children aged 18 and over	13.1 (629)	13.5 (111)	13.2 (740)
Couple living together with children under 18	22.2 (1,062)	13.4 (110)	20.9 (1,172)
Household without children living at home	67.9 (3.255)	76.5 (627)	69.2 (3,882)
Single-parent household	6.3 (302)	5.2 (43)	6.2 (345)
Employment situation[c]			
Paid work	63.2 (3,028)	51.1 (419)	61.4 (3,447)
Unemployed	1.6 (76)	1.5 (12)	1.6 (88)
Retired	28.1 (1,344)	43.2 (354)	30.3 (1,698)
Fully incapacitated for work	3.8 (184)	4.1 (34)	3.9 (218)
Full-time housewife/househusband	4.2 (201)	2.7 (22)	4.0 (223)
Student	3.1 (150)	<1.2 (<10) [d]	x (x) [d]
Retired but still working	1.0 (50)	1.7 (14)	1.1 (64)
Partially unemployed	<0.2 (<10) [d]	<1.2 (<10) [d]	<0.2 (<10) [d]
Partially incapacitated for work	0.5 (22)	<1.2 (<10) [d]	x (x) [d]
Owner-occupied home	77.7 (3,722)	85.4 (700)	78.8 (4,422)
Years of residence[a]			
2 years or less	18.0 (864)	4.9 (40)	16.1 (904)
3-5 years	10.3 (492)	0	8.8 (492)
5-10 years	14.1 (674)	3.8 (31)	12.6 (705)
10-15 years	10.5 (501)	16.8 (138)	11.4 (639)
15-25 years	19.2 (922)	29.2 (239)	20.7 (1,161)
25 years and longer	27.9 (1,338)	45.4 (372)	30.5 (1,710)

Abbreviations: % = percentage, N = number of participants included in the analysis

[a] For participants in the 2013 and 2019 surveys, this characteristic was only measured in 2013. However, 36 participants live at an address of a person who had participated both in 2013 and in 2019 but had passed away or moved house by 2021. No gender, age or duration of residence were measured for these individuals;

[b] Given the small number of persons reporting to have had no education or only lower education, for the purpose of this table we decided to combine them with the group of participants with lower vocational or lower general secondary education;

[c] Questions about family and employment situation could have more than one answer, which explains why the percentages do not add up to 100;
[d] This characteristic was measured at least once, but fewer than 10 times. Where data could be reported for group I but not for group II, were reported ‘x’ for the total group (to allow re-calculation). For reasons of privacy, we did not report how often a characteristic was measured if it was measured fewer than 10 times in all. In this regard we followed the CBS guideline not to report frequencies lower than 10 so as to ensure privacy[99];

As in 2013 [11], the participants in the Follow-Up Study are comparatively highly educated: 48.9% of participants had a higher professional or university degree. This is higher than the general Dutch population, since the CBS estimates that in 2021 only 34.0% of persons between 15 and 90 years of age had a higher professional or university degree.

At over 24%, the share of single households among participants is relatively low compared to the general Dutch population [100]. Based on CBS figures on the composition and size of private households, it was estimated that 38.5% of households consisted out of single persons. The estimated proportion of households with children under the age of 18 in 2021 was just under 23% of the total number of households in the Netherlands [101]. The proportion of households with children under age 18 among participants in the Follow-Up Study was slightly lower, at 20.9%. The proportion of households with children aged 18 and over is more than 13% among participants in the Follow-Up Study. This is practically the same as the share of this group in the general Dutch population in 2021 (13.1%). The proportion of single-parent households among participants (6.2%) is slightly lower compared to the general Dutch population in 2021 (7.4%).

The proportion of unemployed persons among participants (1.6%) is lower than that of the general Dutch population. In the second quarter of 2021, 4.3% of the total Dutch labour force was unemployed. Similarly, the proportion of participants who are fully incapacitated (3.9%) is low compared to the general Dutch population, which was just over 5% in 2021.

Compared to the general Dutch population, homeownership among the study population is relatively high (78.8%). Homeownership among the general population was approximately 70% in 2019 [102].

Table 4.7 Dwellings' characteristics of the study population

	Group I % (N)	Group II % (N)	Total % (N)
Number of participants	(n = 4,791)	(n = 820)	(n = 5,611)
Type of dwelling[a]			
Terraced house, end-of-terrace house etc.	75.9 (3,635)	74.9 (614)	75.7 (4,249)
(Part of an) apartment etc.	20.0 (958)	20.7 (170)	20.1 (1,128)
Other types of dwellings	4.1 (198)	4.4 (36)	4.2 (234)
Building year			
before 1945	50.2 (2,404)	50.4 (411)	50.2 (2,815)
1945–1964	10.8 (515)	11.9 (97)	10.9 (612)
1965–1984	15.3 (733)	14.4 (117)	15.2 (850)
1985–2004	13.5 (648)	17.7 (144)	14.1 (792)
2005 and later	10.3 (491)	5.6 (46)	9.6 (537)
Floor material in living room			
Concrete	55.9 (2,677)	53.2 (436)	55.5 (3,113)
Wood	35.3 (1,688)	41.3 (338)	36.1 (2,026)
Wood and concrete	1.8 (86)	2.3 (19)	1.9 (105)
Other / Don't know	7.0 (336)	3.2 (26)	6.5 (362)
Vibration-reducing measures in place[b]			
Fortified floors	2.8 (134)	3.9 (32)	3.0 (166)
Vibration absorption device	0.7 (34)	<1.2 (<10)[c]	x (x)
Other measures in place	1.8 (86)	2.6 (21)	1.9 (107)
Noise-reducing measures in place[b]			
HE glazing or triple-glazed windows in living room	70.1 (3,360)	78.7 (645)	71.4 (4,005)
HE glazing or triple-glazed windows in bedroom	64.0 (3,067)	71.7 (588)	65.1 (3,655)
Cavity wall insulation	44.4 (2,125)	49.3 (404)	45.1 (2,529)
Ventilation grilles with mufflers	18.3 (876)	25.7 (211)	19.4 (1,087)
Other noise-reducing measures	29.0 (1,388)	37.8 (310)	30.3 (1,698)

Abbreviations: N=number of persons, %=percentage, HE glazing = high-efficiency glazing (an improved version of standard double glazing).

[a] As regards type of dwelling, the following groups are distinguished: i) terraced house, end-of-terrace house, detached house, semi-detached house, villa, bungalow or country house, ii) a flat, single-story home, apartment, maisonette, upstairs apartment, ground-floor flat, and iii) a farm, house with annexed market gardening firm/separate shop/office, practice or business space, residential unit with communal kitchen or toilet, other;

[b] For the questions about vibration-reducing or noise-reducing measures, multiple categories could be ticked. This explains why the answers do not add up to 100%;

[d] This characteristic was measured at least once, but fewer than 10 times. Where data could be reported for group I but not for group II, were reported 'x' for the total group (to allow re-calculation). For reasons of privacy, we did not report how often a feature was measured if it was measured fewer than 10 times in all. In this regard we followed the CBS guideline not to report frequencies lower than 10 so as to ensure privacy[99];

Table 4.7 shows that most participants (75.7%) lived in a terraced house, end-of-terrace house, detached house, semi-detached house, villa, bungalow or country house. This proportion is large compared to the general Dutch populations since according to the CBS, 64% of people in the Netherlands lived in a single-family house 2021 [103, 104].

Over half of all participants lived in a dwelling built before 1945. This is also a relatively high proportion compared to the general Dutch population: in 2021, 18.5% of all dwellings in the Netherlands were built before 1945.

More than 55% of participants' dwellings had a living room with a concrete floor. Furthermore, most participants' dwellings had HE glazing or triple glazing windows in the living room and bedroom. Only a small number of dwellings were fitted with vibration-reducing devices.

Table 4.8 Physical characteristics of the living environment of the study population

	Group I % (N)	**Group II % (N)**	**Total % (N)**
Number of participants	(n=4,791)	(n=820)	(n=5,611)
Degree of urbanisation of the postcode area[a]			
Not urbanised	12.6 (602)	14.5 (119)	12.9 (721)
Hardly urbanised	17.6 (844)	11.0 (90)	16.7 (934)
Moderately urbanised	16.0 (764)	21.3 (175)	16.7 (939)
Strongly urbanised	29.1 (1,393)	23.5 (193)	28.3 (1,586)
Extremely urbanised	24.8 (1,188)	29.6 (243)	25.5 (1,431)
WOZ value PC-6 area at least 290,000 euros[b]	35.2 (1,685)	41.6 (341)	36.1 (2,026)
Windows (in living room and/or bedroom) with a view of a [c]			
Railway line	78.7 (3,772)	100 (701)	81.5 (4,473)
Shunting yard	15.0 (719)	75.0 (81)	16.3 (800)
Train station	20.9 (999)	85.6 (155)	23.2 (1,154)
Liveability score[d]			
(Extremely/very) poor - weak	5.0 (241)	3.9 (32)	4.9 (273)
Sufficient	4.3 (208)	4.3 (35)	4.3 (243)
Quite sufficient	25.7 (1,229)	22.8 (187)	25.2 (1,416)
Good	25.8 (1,234)	23.2 (190)	25.4 (1,424)
Very good	21.5 (1,028)	22.0 (180)	21.5 (1,208)
Excellent	17.8 (851)	23.9 (196)	18.7 (1,047)
Distance to a train station[e]			
Less than 0.5 km	38.6 (1,849)	34.4 (282)	38.0 (2,131)
0.5–1 km	28.4 (1,359)	28.4 (233)	28.4 (1,592)
1–2 km	21.0 (1,008)	21.5 (176)	21.1 (1,184)
2–5 km	10.2 (487)	14.0 (115)	10.7 (602)
More than 5 km	1.8 (87)	1.7 (14)	1.8 (101)

Abbreviations: N=number of persons, %=percentage, km=kilometre.

[a] Degree of urbanisation is a measure for concentration of human activity based on average local address density (LAD), expressed in number of addresses per km^2. The following degrees of urbanisation are distinguished: not urbanised (average LAD <500), hardly urbanised (average LAD 500-1000), moderately urbanised (average LAD 1,000-1,500), strongly urbanised (average LAD 1,500-2,500) and extremely urbanised (average LAD >2,500) [86, 87];

[b] The WOZ value is the estimated market value on 1 January of the previous year. On 1 January 2020, the average WOZ value of a dwelling in the Netherlands was 290,000 euros[86, 87];

[c] These percentages are based on the answers to two separate questions. This means that they should not be added up;

[d] The liveability score gives an indication of the liveability of a particular residential area in a particular year. The score is based on nine categories, ranging from extremely poor to

excellent. The liveability score for an area in any particular year was estimated using data from the Leefbaarometer. This instrument can be used to make an estimate of local liveability (neighbourhood/district) based on a large number of attributes of the living environment (also see [93] and the website www.leefbaarometer.nl).

[e] This is the average distance by road of all residents in a particular neighbourhood to the nearest train station.

Table 4.8 presents a number of physical characteristics of the participants' immediate living environment. The table shows that most participants' dwellings (more than 53%) are located in highly or extremely urbanised areas. Over two thirds of participants live within 500 metres from a train station. For comparison: according to CBS, in 2021 the average distance to a train station was 5.1 kilometres [87]. Over 80% of participants live in a dwelling with one or more windows overlooking a railway line.

4.4 Comparison between group I participants and non-responders

As described in section 4.2, of the 10,937 group I addresses from which we did not receive a completed questionnaire, we took a random sample of 972 addresses to include in the non-response study. In the end, 175 persons participated in this non-response study.

A comparison between the 4,971 participants in Group I and the 175 participants in the non-response study shows that the former are slightly younger ($p=0.0016$) and higher educated ($p<0.0001$). Group I participants have a more negative attitude towards railway policy and the growth of railway traffic than participants in the non-response study. This difference was statistically significant. As regards to satisfaction with the living environment, the two groups are were similar ($p=0.0877$). Observed differences on distance ($p=0.3967$) and year of construction of the dwelling ($p=0.2502$) were also statistically significant. However, Group I participants did report more annoyance than participants in the non-response study ($p<0.0001$).

If we consider the annoyance score relative to distance, both the group of participants and the group of non-responders show increasing annoyance scores with decreasing distance from the railway line. We tested whether there were differences between responders and non-responders as regards the correlation between distance and annoyance score. This was not the case ($p=1.000$).

Table 4.9 Comparison between group I participants in the main study and participants in the non-response study

	Group I participants		**Participants in the non-response study**	
Number of participants	4,791		175	
	% (N)	Average (SD)	% (N)	Average (SD)
Age class		54.1 (16.4)		58.1 (15.9)
16–44 years	29.4 (1,408)		21.7 (38)	
45–64 years	41.0 (1,963)		41.1 (72)	
65 and over	29.6 (1,419)		37.1 (65)	
% women	47.0 (2,251)		46.9 (82)	
Highest level of education[a]				
No education, lower education, lower vocational, lower general secondary	20.0 (960)		32.3 (54)	
Higher general secondary, pre-university, senior secondary vocational	31.8 (1,524)		35.3 (59)	
Higher professional, university	48.2 (2,307)		32.3 (54)	
Annoyance score for railway-induced vibrations[b]		4.76 (3.36)		3.17 (2.93)
Attitude towards train policy[c]		4.92 (2.16)		5.83 (2.31)
Attitude towards growth in railway traffic[d]		4.02 (2.62)		4.52 (2.79)
Satisfaction with the living environment[e]		7.68 (1.45)		7.87 (1.58)
Distance from railway line (m)		69.3 (59.3)		73.2 (58.7)
Building year [f]		1942		1961

Abbreviations: N=number of persons, Av=average, %=percentage, SD=standard deviation

[a] Since the number of persons reporting to have had no education or only lower education was so small, for the purpose of this table we decided to combine them with the group of participants with lower vocational or lower general secondary education;

[B] The score can vary between 0 (no annoyance experienced) and 10 (extreme annoyance experienced). We assigned a score of 0 to participants who reported that the vibrations were imperceptible;

[c] Attitude towards current train policy for railway zones. This score can vary between 0 (very negative) and 10 (very positive);

[d] Attitude towards plans for a possible increase in railway transport in the Netherlands. This score can vary between 0 (very negative) and 10 (very positive); [e] This score can vary between 1 (highly unsatisfied) and 10 (highly satisfied)

[f] This concerns the median value.

ǂ This feature was measured at least once, but fewer than 10 times.

4.5 Comparison between group II participants and non-responders

Table 4.10 presents the differences between group II participants and 369 non-responders. These non-responders are persons who participated both in 2013 and in 2019 and had consented to being contacted again, but who eventually did not take part in the Follow-Up Study. Table 4.10 shows that the group II participants included a higher share of men, were older and slightly more highly educated compared with the 369 non-responders. In 2019, the group II participants reported more annoyance due to railway-induced vibrations than the 369 non-responders. However, none of the observed differences proved to be statistically significant.

In 2019, the attitude of group II participants towards railway policy and growth of railway traffic in the Netherlands was more negative (p=0.0024 and p<0.0001) compared with group II non-responders; the difference was statistically significant.

Table 4.10 Comparison between group II participants and persons who had participated both in 2013 and in 2019 and consented to being contacted again, but who eventually did not take part in the Follow-Up Study.

	Group II participants		**Group II non-responders**	
Number of participants	784[*]		369	
	% (N)	Av (SD)	% (N)	Av (SD)
Age class		62.7 (11.2)		61.5 (13.3)
16–44 years	6.2 (48)		11.2 (41)	
45–64 years	47.2 (368)		48.2 (177)	
65 and over	46.7 (364)		40.6 (149)	
Women	39.2 (307)		45.2 (166)	
Highest level of education[#]				
No education, lower education, lower vocational, lower general secondary	18.7 (144)		21.1 (76)	
Higher general secondary, pre-university, senior secondary vocational	30.2 (233)		28.3 (102)	
Higher professional, university	51.1 (394)		50.6 (182)	
Annoyance score for railway-induced vibrations in 2019[##]		6.14 (3.56)		5.78 (3.49)
Attitude towards rail policy[+]		3.89 (2.52)		4.39 (2.52)
Attitude towards growth in railway traffic[+]		3.94 (2.64)		4.76 (2.70)
Satisfaction with the living environment in 2019[++]		7.64 (1.43)		7.61 (1.50)
Distance from railway (m)		59.9 (46.0)		63.0 (48.9)
Building year [**]		1939		1938

[*] At 36 of the total of 820 addresses, we found that the persons who had participated in 2013 and 2019 no longer lived there. So these were new participants who lived at an address already known to us. The data for these 36 participants are excluded from this table;

[#] Given the small number of persons reporting to have had no education or only lower education, for the purpose of this table we decided to combine them with the group of participants with lower vocational or lower general secondary education;

[##] The score can vary between 0 (no annoyance experienced) and 10 (extreme annoyance experienced). We assigned a score of 0 to participants who reported that the vibrations were imperceptible;

[+] Attitude towards plans for a possible increase in railway transport in the Netherlands. This score can vary between 0 (very negative) and 10 (very positive);

[ǂ] Attitude towards current train policy for railway zones. This score can vary between 0 (very negative) and 10 (very positive);

[**] This concerns the median value;

[$] This feature was measured at least once, but fewer than 10 times;

[++] This score can vary between 1 (highly satisfied) and 10 (highly dissatisfied);

Abbreviations: N=number of persons, %=percentage, SD=standard deviation

5 The prevalence of self-reported annoyance and sleep disturbance due to railway-induced vibrations

5.1 Self-reported annoyance due to vibrations

Participants were asked to report the level of annoyance they experienced from several sources of vibration. Based on data from the Follow-Up Study, we estimated the percentage of people aged 16 and over who lived within 300 metres of a railway line (excluding areas in the vicinity of railway bridges, sunken track sections and major stations with many parallel tracks) and who experienced high annoyance[22] due to railway-induced vibrations and other environmental factors. In total, this concerns an area with an estimated population of over 1.1 million people, who live in approximately 533,000 houses (also see Annex 1). The result is presented in Figure 5.1, which also shows the estimated prevalences based on the 2013 survey. Despite the fact that the study set-up and statistical processing of the 2021 data are highly comparable with the data collected in 2013, the results of the Follow-Up Study are not fully comparable with the 2013 measurement. This is because for the Follow-Up Study we excluded all addresses in the vicinity of railway bridges, sunken track sections and stations with many parallel tracks (also see Chapter 3). On top of that, 2021 was in the middle of the COVID-19 pandemic.

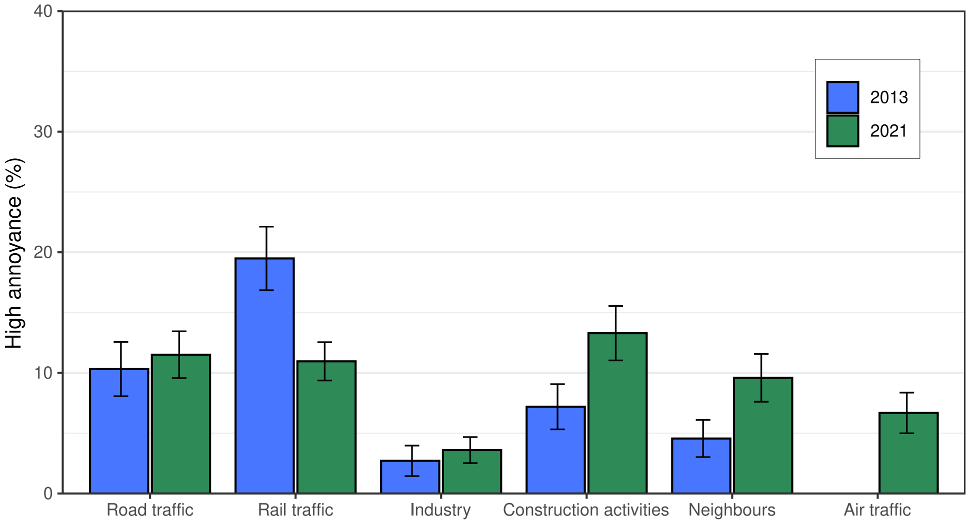

Figure 5.1 Prevalence (in %; including 95% confidence interval) of high annoyance due to vibrations in the study area from various vibration sources (persons aged 16 and over).

Based on the results of the Follow-Up Study, our estimate is that in 2021 11.0% (95% confidence interval: 9.6 - 13.5%) of persons aged 16 and over who live in the study area experienced high annoyance due to

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[22] Also see Annex 3 for the definition and coding of high annoyance. More information about the weighting factors applied can be found in Annex 1.

vibrations from railway traffic[23]. This amounts to an estimated 126,500 persons. In 2013, the prevalence of high annoyance due to vibrations from railway traffic was estimated at approximately 20%.

Railway traffic is no longer the main source of annoyance within 300 metres of a railway line: In 2021, vibrations caused by road traffic and construction activities were the main source of annoyance among the Dutch population aged 16 who lived in the study area. In 2013, vibrations caused by railway traffic were still the main source of annoyance. Annoyance due to vibrations from aircraft was not measured in 2013.

5.1.1 *Annoyance due to vibrations from various railway sources*

In the study area we studied annoyance due to vibrations from various railway sources: freight trains, passenger trains, railway maintenance or any other activity on the tracks. Figure 5.2 presents the results for 2021 and 2013. Again, the situation in 2021 cannot be fully compared with that in 2013, because in 2021 addresses near railway bridges, sunken tack sections and major stations with many parallel tracks were excluded from participation.

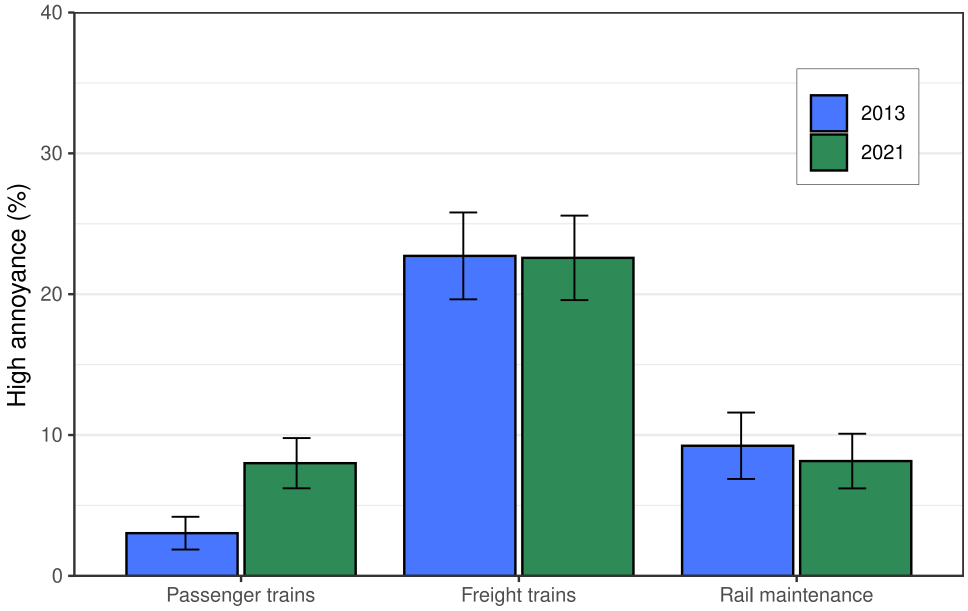

Figure 5.2 Prevalence (in %; including 95% confidence interval) of high annoyance due to railway-induced vibrations in the study area (persons aged 16 and over).

Figure 5.2 shows that the vibrations from freight trains are by far the main cause of annoyance: The prevalence of high annoyance due to vibrations from freight trains among persons aged 16 and over who live within 300 metres of a railway line in the Netherlands (excluding areas

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[23] Any reference in the report to high annoyance or high sleep disturbance due to railway traffic concerns the answer to the questions asking participants to report the degree to which they experience annoyance or sleep disturbance due to railway-induced vibrations.

near railway bridges, sunken track sections and major stations with many parallel tracks) is estimated to be 22.6% in 2021 (95% confidence interval: 19.6 – 25.6%). The prevalence of high annoyance due to vibrations from passenger trains is estimated at 8.0% (95% confidence interval: 6.2 – 9.8%).

The results of the Follow-up Study confirm the results of the 2013 survey: in that year, freight trains also were by far the most important source of annoyance. The prevalence of high annoyance due to vibrations from freight trains in 2013 was estimated at 22.7% (95% confidence interval: 19.6 – 25.8%). Just as in the Follow-up Study, the prevalence of high annoyance due to vibrations from passenger trains in the 2013 survey was low compared with the prevalence of high annoyance due to freight trains. The percentage high annoyance due to vibrations from passenger trains was an estimated 3.0% at the time (95% confidence interval: 1.9 – 4.2%).

NB Both in 2013 and in 2021, the percentage of high annoyance due to freight trains was higher than the percentage of high annoyance due to vibrations from total railway traffic. This is because this concerned the answers to two separate questions, both in 2013 and in 2021. Every participant was asked to answer the question about annoyance due to vibrations from railway traffic and annoyance due to vibrations from other sources; however, the question about annoyance due to vibrations from specific railway-related sources was only submitted to those who had reported to have perceived the vibrations from at least one of the three railway-related sources (passenger trains, freight trains or rail maintenance). When asked about total railway traffic, participants tend to average out the annoyance they experience from separate sources. This is different from what they report when asked specifically about annoyance due to vibrations from a specific type of train (e.g. passenger trains or freight trains). This results in higher scores for the separate questions per railway source. This phenomenon is known as the combined noise paradox or cumulation paradox: in most cases, total annoyance is equal to or even lower than the annoyance caused by the three separate sources ([105] in [11]).

5.2 Self-reported sleep disturbance due to vibrations

Figure 5.3 presents the prevalence of high sleep disturbance[24] due to various vibration sources, estimated on the basis of the Follow-Up Study. Sleep disturbance due to various vibration sources was not measured in 2013, so the figure only presents results for 2021.

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[24] See Annex 3 for the definition and coding of high sleep disturbance. More information about the weighting factors applied can be found in Annex 1.

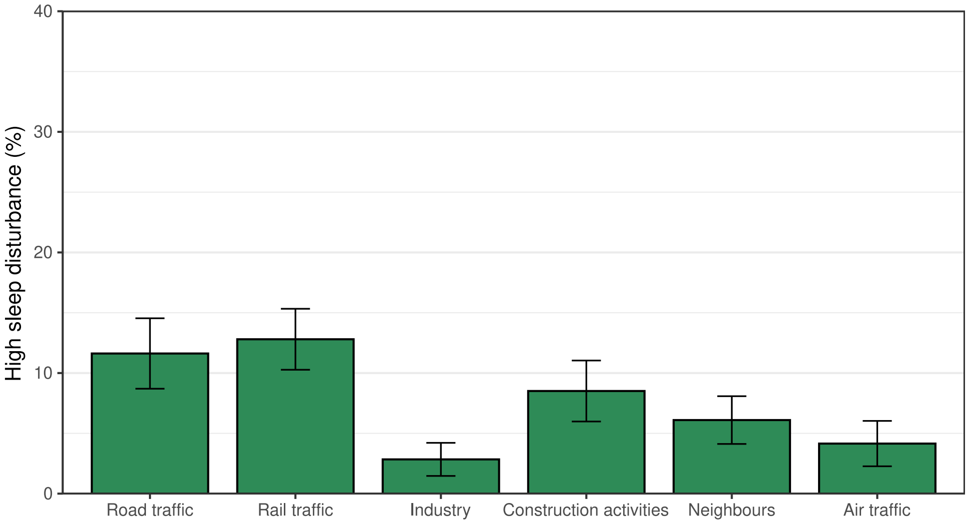

Figure 5.3 Prevalence (in %; including 95% confidence interval) of high sleep disturbance due to vibrations in the study area from various vibration sources (persons aged 16 and over) in 2021.

Figure 5.3 shows that most sleep disturbance in the study area is attributable to vibrations due to railway traffic and road traffic. Based on the results of the Follow-Up Study, our estimate is that in 2021 some 12.8% (95% confidence interval: 10.3–15.3%) of persons aged 16 and over in the Netherlands who live within 300 metres of a railway line (excluding areas near railway bridges, sunken track sections and major stations with many parallel tracks) experience high sleep disturbance due to vibrations from railway traffic; an estimated 11.6% (95% confidence interval: 8.7-14.5%) of persons aged 16 and over who live in the study area experience high sleep disturbance due to vibrations due to road traffic.

5.2.1 *Sleep disturbance due to vibrations from various railway sources*

As in the case of annoyance, we also studied sleep disturbance due to vibrations from various railway sources: freight trains, passenger trains, railway maintenance or any other activity on the tracks. Figure 5.4 presents the results of the Follow-Up Study (2021) and the 2013 measurement. As in the case of annoyance, the situation in 2021 cannot be fully compared with that in 2013, because in 2021 addresses near railway bridges, sunken tack sections and major stations with many parallel tracks were excluded from participation.

Figure 5.4 shows that vibrations from freight trains were by far the main cause of sleep disturbance in 2021: The prevalence of high sleep disturbance due to vibrations from freight trains among persons aged 16 and over who live within 300 metres of a railway line in the Netherlands (excluding areas near railway bridges, sunken track sections and major stations with many parallel tracks) is estimated to be 18.1% in 2021 (95% confidence interval: 15.2 – 21.0%). On the basis of the Follow-Up Study, the prevalence of high sleep disturbance due to vibrations from passenger trains is estimated at 6.0% (95% confidence interval: 6.4 – 10.6%).

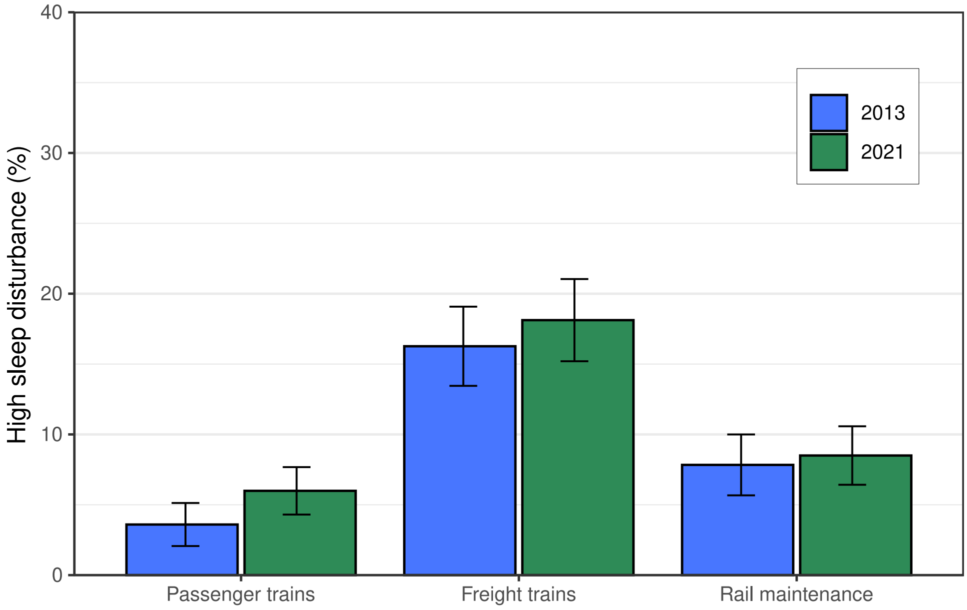

Figure 5.4 Prevalence (in %; including 95% confidence interval) of high sleep disturbance due to railway-induced vibrations in the study area (persons aged 16 and over).

As in the case of annoyance, the results of the Follow-Up Study confirm the results of the 2013 survey. Also in 2013 freight trains were by far the most important cause of sleep disturbance. At the time, the prevalence of sleep disturbance due to vibrations from passing freight trains was estimated at 16.3% (95% confidence interval: 13.5 – 19.1%). Furthermore, the prevalence of high sleep disturbance due to vibrations from passing passenger trains was low compared with the prevalence of high sleep disturbance due to vibrations from passing freight trains in 2013. At the time, the percentage high sleep disturbance due to vibrations from passenger trains was an estimated 3.6% (95% confidence interval: 2.1 – 5.1%).

NB In 2021, the percentage of high sleep disturbance due to passing freight trains was higher than the percentage of high sleep disturbance due to by vibrations from total railway traffic. As in the case of annoyance (section 5.1), this can be explained by the so-called combined noise paradox or cumulation paradox.

6 Exposure to noise and vibrations from railway traffic

6.1 Exposure of participants to railway-induced vibrations

We used the OURS model to calculate exposure to railway-induced vibrations for all participants in the Follow-Up Study (N=5,611). Table 6.1 shows the distribution of participants for several exposure indicators (distance, RMS, V_{per} and V_{max}) across the various vibration levels. In addition to providing an overview of estimated minimum and maximum vibration levels, the table presents average vibration levels produced by trains using the railway line in the vicinity of the participants' dwellings. The distribution is also shown in the form of percentiles (p_x). Percentiles (p_x) are used to identify the share of participants exposed to vibration levels equal to or lower than the value associated with the percentile concerned. Table 6.1 only presents vibration levels *without* ISO weighting as common measurement and assessment practices [1, 3] do not implement frequency-dependent weighting according to ISO 2631 [23]. Instead, the Bts and SBR use a weighting function for all three vibration directions as laid down in DIN-4150 [106] and SBR B [1]. This is a weighting approach under ISO 2631.

Table 6.1 shows that on average, the participants live at just over 62 metres of a railway line. The table also shows that over a 24-hour period, 50% of participants are exposed to railway-induced vibration levels of 0.061 (V_{per}) or less. In addition, 90% of participants are exposed to maximum railway-induced vibration levels (V_{max}) of 1.85 or less. For comparison: a V_{max} of 0.1 corresponds to the perceptibility limit [1]. Nearly 90% of participants are exposed to maximum vibration levels (V_{max}) in excess of 0.1. A V_{max} of 3.2 is included in the Bts as the maximum level for track sections subject to Route Decisions [3]. This vibration level is clearly perceptible and considered unacceptable; for values in excess of this, the effectiveness of anti-vibration measures is no longer relevant. Table 6.1 shows that nearly 2% of participants in the Follow-Up Study are exposed to maximum vibration levels (V_{max}) of 3.2 or higher.

One remarkable finding is that the average calculated vibration levels are slightly lower for freight trains than for passenger trains. Note however that the populations are not exactly the same, as there are quite a few railway lines *without* freight traffic. For that reason, the figures are not fully comparable. For both passenger trains and freight trains, the duration of the vibrations does not have any influence on any of the calculated units (while the number of train passages does). Table 6.2 compares vibration levels with and without ISO weighting. The table shows that vibration levels *without* ISO weighting (V_{max} and V_{per}) are lower, on average, than those *with* ISO weighting ($V_{dir,max}$ and $V_{per,ISO+}$). Table 6.3 shows the presence of a number of characteristics of the railway line along which the participants live. Those characteristics can also provide an indication of exposure to vibrations.

Table 6.1 Exposure of the dwellings of participants in the Follow-Up Study to vibrations from railway traffic (without ISO weighting)

Characteristic	**N**	**Av**	**Std**	**Min**	**Percentiles**					**Max.**
					P_{10}	**P_{25}**	**P_{50}**	**P_{75}**	**P_{90}**	
Distance (m)	5,519[a]	62.2	57.2	4.3	22.1	29.4	40.5	71.3	137.2	297.7
Total railway traffic										
V_{per}	5,519[a]	0.090	0.120	0	0.002	0.023	0.061	0.122	0.212	3.957
$V_{per, night}$	5,519[a]	0.055	0.072	0	0.001	0.014	0.037	0.074	0.130	2.227
V_{max}	5,519[a]	0.86	0.77	0	0.10	0.30	0.64	1.15	1.85	10.94
RMS	5,519[a]	0.00072	0.00089	0	0.00002	0.0002	0.00051	0.00098	0.00164	0.02588
RMS_{night}	5,519[a]	0.00046	0.00056	0	0.00001	0.00012	0.00031	0.00062	0.00107	0.01504
Freight trains										
V_{per}	4,289[b]	0.018	0.027	0	0	0.002	0.009	0.023	0.047	0.262
$V_{per, night}$	4,289[b]	0.017	0.025	0	0	0.002	0.008	0.020	0.042	0.254
V_{max}	4,289[b]	0.53	0.55	0	0.02	0.13	0.37	0.75	1.26	3.98
RMS	4,289[b]	0.00021	0.00031	0	0	0.00003	0.0001	0.00027	0.00055	0.00302
RMS_{night}	4,289[b]	0.0002	0.00029	0	0	0.00003	0.0001	0.00024	0.00048	0.00307
Passenger trains										
V_{per}	5,403[c]	0.092	0.119	0	0.003	0.026	0.063	0.124	0.215	3.957
$V_{per, night}$	5,403[c]	0.053	0.069	0	0.001	0.014	0.036	0.070	0.122	2.227
V_{max}	5.403[c]	0.85	0.77	0	0.11	0.31	0.65	1.15	1.86	10.94
RMS	5,403[c]	0.00069	0.00085	0	0.00002	0.0002	0.00049	0.00093	0.00156	0.02588
RMS_{night}	5,403[c]	0.00042	0.00051	0	0.00001	0.00012	0.00029	0.00057	0.00095	0.01503

Abbreviations: N=number of participants, Av=average, Std=Standard deviation, Min=minimum value, P_{10}=10^{e} percentile, P_{25}=25^{e} percentile, P_{50}=50^{e} percentile (median value), P_{75}=75^{e} percentile, P_{90}=90^{e} percentile, Max=maximum value

[a] This concerns participants who live within 300 metres of a railway line that is used by freight trains and/or passenger trains;

[b] This concerns participants who live within 300 metres of a railway line that is used by freight trains. Participants living within 300 metres of a railway line that is only used by passenger trains have been excluded;

[c] This concerns participants who live within 300 metres of a railway line that is used by passenger trains. Participants living within 300 metres of a railway line that is only used by freight trains have been excluded;

Table 6.2 Exposure of the dwellings of participants in the Follow-Up Study to vibrations from railway traffic (with and without ISO weighting)[a]

Characteristic	**N**	**Av**	**Std**	**Min**	**Percentiles**					**Max.**
					P_{10}	**P_{25}**	**P_{50}**	**P_{75}**	**P_{90}**	
Distance	5,519	62.2	57.2	4.3	22.1	29.4	40.5	71.3	137.2	297.7
Without ISO weighting										
V_{per}	5,519	0.090	0.120	0	0.002	0.023	0.061	0.122	0.212	3.957
$V_{per, night}$	5,519	0.055	0.072	0	0.001	0.014	0.037	0.074	0.130	2.227
V_{max}	5,519	0.84	0.77	0	0.10	0.30	0.64	1.15	1.85	10.94
RMS	5,519	0.00072	0.00089	0	0.00002	0.00020	0.00051	0.00098	0.00164	0.02588
RMS_{night}	5,519	0.00046	0.00056	0	0.00001	0.00012	0.00031	0.00062	0.00107	0.01504
With ISO weighting										
V_{per}	5,519	0.129	0.156	0	0.010	0.042	0.093	0.170	0.267	4.819
$V_{per, night}$	5,519	0.078	0.097	0	0.060	0.026	0.057	0.104	0.168	2.694
V_{max}	5,519	1.26	1.13	0	0.19	0.50	1.00	1.66	2.64	10.70
RMS	5,519	0.00102	0.00114	0	0.00009	0.00036	0.00077	0.00135	0.00216	0.03448
RMS_{night}	5,519	0.00065	0.00075	0	0.00005	0.00023	0.00048	0.00087	0.00142	0.01864

Abbreviations: N=number of participants, Av=average, Std=Standard deviation, Min=minimum value, P_{10}=10th percentile, P_{25}=25th percentile, P_{50}=50th percentile (median value), P_{75}=75th percentile, P_{90}=90th percentile, Max=maximum value

[a] This concerns participants who live within 300 metres of a railway line that is used by freight trains and/or passenger trains;

Table 6.3 Physical characteristics of the railway line that can provide an indication of vibration exposure

Characteristic	**N***	**Av**	**Std**	**Min**	**Percentiles**					**Max.**
					P_{10}	**P_{25}**	**P_{50}**	**P_{75}**	**P_{90}**	
Total number of trains / 24h	5,519	221.6	198.9	0	42.3	83.4	174.2	280.3	471	1,671.3
Freight trains										
Trains per hour (daytime hours)[a]	4,289	0.6	0.8	0	0	0	0.2	0.6	2.4	6.4
Trains per hour (evening hours)[a]	4,289	0.6	0.9	0	0	0	0.3	0.7	2.7	6.9
Trains per hour (night-time hours)[a]	4,289	0.5	0.8	0	0	0.1	0.2	0.4	2.2	6.5
Total number of trains / 24h[a]	4,289	13.4	20.4	0	0.2	1.4	6.7	13.9	59.8	158.6
Av speed (km/h)[a]	4,185	69.1	32.7	0	0	53.6	88.9	90	90	90
Passenger trains										
Trains per hour (daytime hours)[b]	5,403	11.1	10.1	0.2	2.5	4.2	8.5	14	23.9	84.6
Trains per hour (evening hours)[b]	5,403	8.9	7.9	0	2	3.4	7	11.4	19.7	68.1
Trains per hour (night-time hours)[b]	5,403	2.8	2.6	0	0.6	1.2	1.9	3.6	5.7	22.8
Total number of trains / 24h[b]	5,403	215.7	193.7	2.9	50.1	81.7	155.1	271.2	465.1	1,651.9
Av speed (km/h)[b]	5,402	80.8	25.3	29.2	40	61.5	84.9	100.5	111.2	130
Fraction trains during the night in total railway traffic (%)[c]	5,519	5.6	2.4	0	4	4.6	5.4	6.2	7.5	100
Fraction freight trains[c] **in total railway traffic (24h)**	5,519	6.5	15.7	0	0	0.1	1.3	5.8	18.2	100
Fraction freight trains in total railway traffic (night)	5,435[d]	10.1	16.0	0	0	0.7	3.7	12.7	34.6	100

Abbreviations: N=number of participants, Av=average, Std=Standard deviation, Min=minimum value, P_{10}=10th percentile, P_{25}=25th percentile, P_{50}=50th percentile (median value), P_{75}=75th percentile, P_{90}=90th percentile, Max=maximum value, km=kilometre

[a] This concerns participants who live within 300 metres of a railway line that is used by freight trains. Participants living within 300 metres of a railway line that is only used by passenger trains have been excluded;

[b] This concerns participants who live within 300 metres of a railway line that is used by passenger trains. Participants living within 300 metres of a railway line that is only used by freight trains have been excluded;

[c] This concerns participants who live within 300 metres of a railway line that is used by freight trains and/or passenger trains;

[d] The total number of observations is less than 5,519 because sometimes there are no trains during the night. This concerns both freight trains and passenger trains;

Table 6.3 shows that the sections of railway lines studied are used mainly for passenger trains. Every 24 hours, the railway lines along which the participants in the Follow-Up Study live, see an average of over 215 passenger trains and an average of over 13 freight trains.

During the night, the number of passenger trains is considerably lower: during the day (between 7:00 and 19:00) there are, on average, over 11 passenger trains per hour; during the night (between 23:00 and 7:00) on average just under 3 per hour. The numbers of freight trains during the different parts of the day are much more similar. The average fraction of freight trains is small (6.5% of total railway traffic). The average fraction of night-time trains is 5.6%. However, the fraction of freight trains relative to total night-time railway traffic is twice as large, at an average 10.1%. Passenger trains pass at higher speeds than freight trains.

6.2 Exposure of participants to noise from railway traffic

In addition to emitting vibrations, trains also produce noise (also see Table 6.4). On average, the participants were exposed to noise levels produced by railway traffic of 54.5 dB L_{den}. For comparison: in 2018, the Guideline Development Group (GDG) of the World Health Organization (WHO) "strongly recommended reducing noise levels produced by railway traffic below 54 dB (L_{den}), as railway noise above this level is associated with adverse health effects." And: "The GDG also strongly recommends reducing noise levels produced by railway traffic during the night below 44 dB (L_{night}), as night-time railway noise above this level is associated with adverse effects on sleep" [107, 108]. On average the participants in the Follow-Up Study were exposed to night-time noise levels produced by railway traffic of 46.6 dB (L_{night}).

Table 6.4 Exposure to noise[a].

Characteristic	N	Av	SD	Min	Percentiles					Max.
					P_{10}	P_{25}	P_{50}	P_{75}	P_{90}	
Noise from railway traffic										
L_{den} (in dB)	5,540	54.5	11.2	25.0	36.7	48.3	57.1	62.7	66.7	78.0
L_{night} (in dB)	5,540	46.6	11.1	20.0	28.7	40.4	49.0	54.6	58.9	71.0
Noise from road traffic										
L_{den} (in dB)	5,611	50.4	6.5	30.0	42.9	45.5	49.3	59.8	59.8	75.8
L_{night} (in dB)	5,611	41.0	6.2	20.0	34.2	36.3	39.7	50.1	50.1	67.1

Abbreviations: N=number of participants, Av=average, SD=Standard deviation, Min=minimum value, P_{10}=10th percentile, P_{25}=25th percentile, P_{50}=50th percentile (median value), P_{75}=75th percentile, P_{90}=90th percentile, Max=maximum value, L_{den}=day-evening-night level, L_{night}=night level, dB=decibel

[*] This concerns participants who live within 300 metres of a railway line that is used by freight trains and/or passenger trains;

6.3 Correlations between the various exposure indicators

Table 6.5 shows there is a moderate correlation between distance from the railway line (r ~0.6) and exposure to vibrations; the correlation between distance from the railway line and exposure to noise from railway traffic is also moderate (r ~ 0.5). The indicators for exposure to vibrations from railway traffic (RMS, V_{per} and V_{max}) are strongly (r ~ 0.9) correlated with each other. The correlation between exposure to vibrations from railway traffic and exposure to noise from railway traffic is moderate (r ~ 0.6).

Table 6.5 Spearman correlation coefficients between the various exposure indicators (N=5,519)[a,b]*.*

	Distance	**RMS**	**RMS night**	**V_{per}**	**$V_{per, night}$**	**V_{max}**	**L_{den}**	**L_{den}**	**TN trains**	**S freight**	**S night**	**S freight (night)**
Distance	1	-0.66	-0.65	-0.64	-0.63	-0.69	-0.54	-0.54	0.06	-0.02	-0.04	-0.01
RMS	-0.66	1	0.99	0.99	0.98	0.91	0.65	0.64	0.35	0.17	0.02	0.14
RMS_{night}	-0.65	0.99	1	0.98	0.99	0.91	0.64	0.65	0.34	0.19	0.10	0.16
V_{per}	-0.64	0.99	0.98	1	0.99	0.91	0.67	0.66	0.38	0.18	-0.02	0.16
$V_{per, night}$	-0.63	0.98	0.99	0.99	1	0.91	0.66	0.66	0.36	0.19	0.06	0.16
V_{max}	-0.69	0.91	0.91	0.91	0.91	1	0.58	0.58	0.14	0.11	0.02	0.10
L_{den}	-0.54	0.65	0.64	0.67	0.66	0.58	1	0.99	0.38	0.27	-0.02	0.24
L_{night}	-0.54	0.64	0.65	0.66	0.66	0.58	0.99	1	0.38	0.30	0.02	0.28
Total number of trains	0.06	0.35	0.34	0.38	0.36	0.14	0.38	0.38	1	0.34	-0.08	0.28
Share of freight trains[c]	-0.02	0.17	0.19	0.18	0.19	0.11	0.27	0.30	0.34	1	0.15	0.96
Share of night trains[d]	-0.04	0.02	0.10	-0.02	0.06	0.02	-0.02	0.02	-0.08	0.15	1	0.10
Share of freight trains (night)[e]	-0.01	0.14	0.16	0.16	0.16	0.10	0.24	0.26	0.28	0.96	0.10	1

Abbreviations: TN trains=total number of trains, S freight= share of freight trains, S night =share of night trains, S freight (night)=share of freight trains in total railway traffic at night

[a] RMS, V_{per} and V_{max} have been calculated using the OURS model, without ISO weighting;

[b] This concerns participants who live within 300 metres of a railway line that is used by freight trains and/or passenger trains;

[c] The percentage of freight trains in total number of trains per 24 hours;

[d] he percentage of night trains in total number of trains per 24 hours;

[e] The percentage of freight trains in total number of night trains.

For the sake of clarity, in Table 6.5 we only included exposure indicators that have *not* been subjected to ISO weighting. Table 6.6 shows the correlations between the various measures for exposure to vibrations with and without ISO weighting. As shown in this table, the correlation between an exposure indicator without ISO weighting and the corresponding equivalent with ISO weighting remains strong or very strong.

Table 6.6 Correlation coefficients for various exposure indicators with and without ISO weighting (N=5,519).

Exposure indicator	***Spearman correlation coefficient****	***Pearson correlation coefficient***
V_{max}	*0.90*	*0.94*
RMS	*0.91*	*0.93*
RMS_{night}	*0.92*	*0.93*
V_{per}	*0.92*	*0.93*
$V_{per,\ night}$	*0.92*	*0.93*

*This is the correlation coefficient for the relationship between the exposure indicator with and without ISO weighting.

6.4 What is the most suitable exposure indicator for railway-induced vibrations?

In this section we aim to find out which exposure indicator for railway-induced vibrations is the best predictor of annoyance and sleep disturbance due to vibrations from railway traffic. We considered both the fit of the model with the underlying data and its accuracy as a predictor of annoyance. The results are presented in Table 6.7.

6.4.1 Annoyance

Table 6.7 shows that that in predictive models for high annoyance due to vibrations from railway traffic, the RMS *without* ISO weighting ($RMS_{24hr,}$) provides the best fit with the underlying data (ΔAIC=0), followed by V_{max} (ΔAIC=1) and V_{per} *without* ISO weighting (ΔAIC=2). The difference in fit between the models based on these three exposure indicators is so small that it is not possible to say with certainty which is the most suitable for predicting high annoyance. What is clear though is that these three exposure indicators score significantly better than distance from the railway line, $V_{max,dir}$, and V_{per} and RMS *with* ISO weighting ($V_{per,ISO+}$ and RMS_{ISO+}).

There was also little difference between the models in terms of accuracy (measured via the AUC value). This means that a prediction of the percentage of people experiencing high annoyance based on any of the tested exposure indicators (such as V_{max}) is more or less equally accurate as a prediction based on any of the other exposure indicators (such as distance from the railway line). So the differences between the various exposure indicators are small and mainly concern the model fit. The outcome of the comparison therefore suggests that RMS, V_{per} and V_{max} (without ISO weighting) are the best predictors of high annoyance due to vibrations from railway traffic.

Within the comparison of the various predictors of high annoyance due to vibrations from passenger trains, the exposure indicators with the best model fit are distance from the railway line (ΔAIC=0) and V_{max} (ΔAIC=2). Again, it is not possible to distinguish between these two models in terms of fit. We also found that the fit of models with RMS

(ΔAIC=6) and V_{per} (ΔAIC=9) was comparable with the fit of the two best models. As with annoyance due to vibrations from railway traffic, the fit of models with exposures *without* ISO weighting (V_{max}, RMS, V_{per}) was better than for models that did use ISO weighted exposures ($V_{dir,max}$, RMS_{ISO+}, $V_{per\ ISO+}$). In terms of model accuracy, no real differences have emerged. Given that the accuracy of the model based on V_{max} is slightly higher (AUC=0.61) that that of the model based on distance from the railway line (AUC=0.58), V_{max} appears to be the best predictor of high annoyance due to by vibrations from passenger trains.

Table 6.7 Fit and accuracy of models based on various exposure indicators in predicting high annoyance due to vibrations from total railway traffic, passenger trains and freight trains.

Outcome measure	Exposure indicator	ΔAIC	AUC (CI 95%)
High annoyance due to vibrations from total railway traffic	RMS	0	0.66 (0.61 -0.70)
	V_{max}	1^a	0.65 (0.60 -0.70)
	V_{per}	2^a	0.66 (0.61 -0.70)
	Distance from railway line	11	0.65 (0.62 -0.67)
	$V_{dir,max}$	22	0.64 (0.58 -0.69)
	RMS_{ISO+}	30	0.64 (0.59 -0.69)
	$V_{per,ISO+}$	32	0.65 (0.60 -0.69)
High annoyance due to vibrations from passenger trains	Distance from railway line	0	0.58 (0.52 -0.63)
	V_{max}	2^a	0.61 (0.56 -0.65)
	RMS	6^b	0.60 (0.57 -0.63)
	V_{per}	9^b	0.60 (0.57 -0.64)
	$V_{dir,max}$	15	0.61 (0.57 -0.65)
	RMS_{iso+}	30	0.60 (0.58 -0.62)
	$V_{per,ISO+}$	31	0.60 (0.58 -0.63)
High annoyance due to vibrations from freight trains	Distance from railway line	0	0.61 (0.56 -0.63)
	V_{per}	29	0.66 (0.61 -0.71)
	RMS	33	0.66 (0.61 -0.71)
	V_{max}	66	0.65 (0.6 -0.69)
	$V_{per\ iso+}$	78	0.67 (0.64 -0.71)
	$V_{dir,max}$	79	0.66 (0.63 -0.69)
	RMS_{iso+}	84	0.66 (0.63 -0.70)

Abbreviations: ΔAIC=delta Aikake's Information Criterion, a measure for model fit, AUC=Area Under the Curve, a measure for model accuracy, CI95%= 95% confidence interval;

[a]=no difference in terms of fit with the best model;

[b]=similar but slightly lower fit than the best model (ΔAIC=0).

Within the comparison of the various predictors of high annoyance due to vibrations from freight trains, distance from the railway line emerges as the exposure indicator with the best fit. The ΔAIC values we found for the other exposure indicators studied are far above 10, meaning that those indicators certainly offer a worse fit than distance. As with annoyance due to vibrations from total railway traffic and passenger trains, the fit of models with exposures without ISO weighting (V_{max}, RMS, V_{per}) was better than for models that did use ISO weighted exposures ($V_{dir,max}$, RMS_{ISO+}, $V_{per\ ISO+}$).

One notable outcome is that distance from the railway line as a vibration indicator has the best fit but not the highest accuracy (AUC=0.61). The models based on V_{per} (ΔAIC=29, AUC=0.66) and RMS (ΔAIC=33, AUC=0.66) achieve lower scores for fit but higher scores for accuracy. This makes it difficult to identify the best vibration indicator for predicting high annoyance due to vibrations from freight trains.

The AUC values of models for passenger trains (AUC range=0.58-0.61) are lower than those for freight trains (AUC range=0.61-0.67) and total railway traffic (AUC range=0.64-0.66). This means that annoyance due to vibrations from passenger trains is more difficult to predict than annoyance due to total railway traffic and freight trains. We see a similar picture for sleep disturbance due to passenger trains (AUC range=0.57-0.58) relative to sleep disturbance due to freight trains (AUC range=0.62-0.65) and total railway traffic (AUC range=0.59–0.62) (also see Table 6.8).

6.4.2 *Sleep disturbance*

Likewise, we also tried to identify the vibration indicator for sleep disturbance that offers the best fit and accuracy scores. In this context, we used the night-time values for the indicators V_{per} and RMS. We used 24-hour values for V_{max} and $V_{dir,max}$ because no night-time values were available for these vibration indicators. The results of the comparison are presented in Table 6.8.

The best fit for sleep disturbance due to vibrations from total railway traffic was found for V_{max}, followed by distance from the railway line, the vibration indicators *without* ISO weighting and, finally, the exposure indicators *with* ISO weighting. Note however that the various indicators were very similar in terms of fit, and the models also showed little difference in their prediction accuracy. Therefore, it was difficult to identify a single vibration indicator that qualified as the best.

The outcomes for sleep disturbance due to vibrations from passenger trains and freight trains are very similar to the outcomes for sleep disturbance due to vibrations from total railway traffic.

Table 6.8 Fit and accuracy of models based on various exposure indicators in predicting high sleep disturbance due to vibrations from total railway traffic, passenger trains and freight trains.

Outcome measure	Exposure indicator	ΔAIC	AUC (CI 95%)
High sleep disturbance due to vibrations from total railway traffic	V_{max}	0	0.61 (0.58-0.63)
	Distance from railway line	3^b	0.59 (0.57-0.61)
	RMS_{night}	4^b	0.62 (0.59-0.65)
	$V_{per\ night}$	5^b	0.62 (0.59-0.65)
	$RMS_{night,\ ISO+}$	8^b	0.61 (0.59-0.64)
	$V_{dir,max}$	10	0.60 (0.58-0.63)
	$V_{per\ night,\ ISO+}$	11	0.61 (0.58-0.64)
High sleep disturbance due to vibrations from passenger trains	V_{max}	0	0.58 (0.54-0.62)
	RMS_{night}	3^b	0.58 (0.55-0.61)
	$V_{per\ night}$	5^b	0.58 (0.54-0.61)
	$V_{dir,max}$	19	0.58 (0.53-0.62)
	Distance from railway line	21	0.58 (0.51-0.65)
	$RMS_{night,\ ISO+}$	28	0.57 (0.54-0.60)
	$V_{per\ night,\ ISO+}$	29	0.57 (0.53-0.60)

Outcome measure	Exposure indicator	ΔAIC	AUC (CI 95%)
High sleep disturbance due to vibrations from freight trains	Distance from railway line	0	0.62 (0.60-0.63)
	$V_{per\ night}$	3[b]	0.64 (0.62-0.67)
	RMS_{night}	5[b]	0.64 (0.62-0.67)
	$V_{per\ night,\ ISO+}$	25	0.64 (0.60-0.67)
	V_{max}	28	0.64 (0.62-0.67)
	$V_{dir,max}$	31	0.64 (0.62-0.67)
	$RMS_{night,\ ISO+}$	32	0.65 (0.61-0.68)

Abbreviations: ΔAIC=delta Aikake's Information Criterion, a measure for model fit, AUC=Area Under the Curve, a measure for model accuracy, CI95%= 95% confidence interval;

[a]=no difference in terms of fit with the best model;

[b]=similar but slightly lower fit than the best model (ΔAIC=0).

7 The relationship between exposure to railway-induced vibrations and annoyance and sleep disturbance

In this chapter we present the DR relationships between exposure to railway-induced vibrations and high annoyance and high sleep disturbance. Because the indicators for exposure to vibrations *without* ISO weighting (see section 6.4) offered a better fit than those *with* ISO weighting, and to ensure maximum alignment with current regulations (Bts and SBR), this chapter only presents the results for the indicators *without* ISO weighting. See Annex 5 for the formulas used for a selection of the DR relationships derived in this chapter.

7.1 Self-reported annoyance

Figure 7.1 presents the relationship between distance from the railway line (in m) and the percentage of participants reporting high annoyance due to vibrations from total railway traffic, freight trains and passenger trains. For all three types of trains, the figure shows an association between the percentage of participants who experience high annoyance due to vibrations and distance from the railway line: the closer a participant lives to the railway line the greater the probability of annoyance due to vibrations. At similar distance from the railway line, vibrations from freight trains cause the most annoyance compared to passenger trains and total railway traffic. Freight trains also show the strongest relationship between distance from the railway line and high annoyance due to vibrations from trains: when the distance from the railway line decreases, for example from 200 to 100 metres, the percentage of high annoyance shows the steepest increase for freight trains.

We used various models to derive the DR relationships (also see section 3.9.3). In the figure, these are represented by a coloured line (continuous exposure) and a black dotted line (categorical exposure). The main differences between the models are found at short distances from railway line. The (non-linear) categorical models for annoyance due to vibrations from total railway traffic and freight trains predict more high annoyance in close proximity (<50 metres) of a railway line than the continuous models.

Table 7.1 Model with the best fit for the association between exposure to railway-induced vibrations (without directional frequency weighting) and high annoyance due to vibrations from railway traffic.

	Outcome: High annoyance due to vibrations from		
Exposure indicator	**Total railway traffic**	**freight trains**	**passenger trains**
Distance from railway line	Categorical	Continuous	Continuous
RMS	Categorical	Categorical	Continuous
V_{per}	Categorical	Categorical	Continuous
V_{max}	Categorical	Categorical	No difference

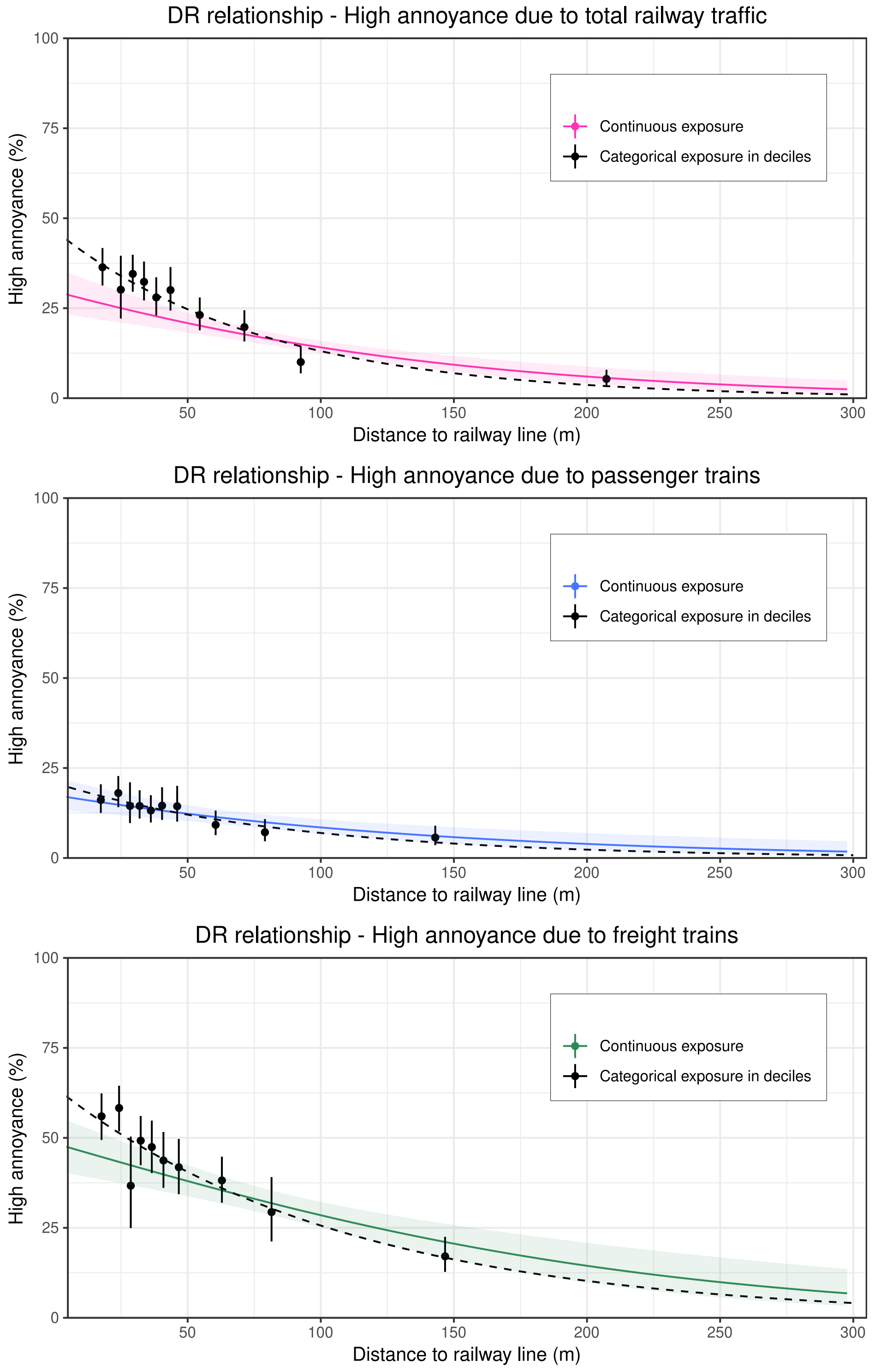

Figure 7.1 DR relationships for distance from the railway line and high annoyance due to vibrations from total railway traffic (top), passenger trains (centre) and freight trains (bottom). The relationships were drawn up for continuous exposure (coloured line) and for categorical exposure based on exposure deciles (black lines). The dotted line represents the trend line of the estimate of the categorical model. The figure also shows an estimate, per train type, of the prevalence of high annoyance with a 95% confidence interval. The coloured sections around the coloured lines represent the 95% confidence interval for the DR relationship based on continuous exposure.

The continuous and categorical models were compared based on their model fit and the results are presented in Table 7.1. See Annex 5 for the formulas of the DR relationships between exposure to railway-induced vibrations and high annoyance due to vibrations from railway traffic. Based on model fit, the *categorical* model is a better representation of the DR relationships between distance from the railway line and high annoyance due to vibrations from railway traffic than the continuous model. However, the continuous models provide a better fit for DR relationships between distance from the railway line and annoyance due to vibrations from freight trains and passenger trains. Note that the difference with the categorical model in terms of fit, is small. This is reflected in the major overlap for these DR relationships in Figure 7.1.

Figure 7.2 shows the relationship between maximum vibration levels (V_{max}) from the total railway traffic, passenger trains and freight trains and the percentage of participants reporting high annoyance due to vibrations from those trains. For all three types of trains, the figure shows a positive relationship between the percentage of participants reporting high annoyance due to vibrations from total railway traffic and the maximum vibration level: the higher the maximum vibration level, the higher the probability of high annoyance. At equal V_{max} levels, vibrations caused by freight trains cause the most annoyance. Vibrations from freight trains also show the strongest relationship between exposure and outcome: when the vibration level increases, for example from 0.1 to 1, the percentage of high annoyance shows the steepest increase for freight trains.

Again, we used various models to estimate the DR relationships. The difference between the continuous and categorical models is particularly large for high annoyance due to vibrations from freight trains. The use of a categorical exposure model produces a stronger DR relationship, especially for annoyance due to freight trains. The DR-relationships based on the two different methods are fairly similar for lower exposure levels, but tend to diverge for the higher levels. At high values for V_{max} (V_{max} higher than ~ 0.7), the categorical models predict a higher percentage of participants reporting high annoyance than the continuous models (when exposure levels remain unchanged). The models using categorical exposure have the better model fit (also see Table 7.1). Therefore, these DR relationships are better aligned with the underlying data than the DR-relationship based on the continuous model. There was no difference in model fit between the categorical and continuous model for the relationship between maximum vibration level and high annoyance due to vibrations from passenger trains.

Annex 4 shows how the DR relationship between maximum vibration level *without* ISO weighting (V_{max}) and high annoyance due to vibrations from railway traffic relates to the DR relationship between maximum vibration level *with* ISO weighting ($V_{dir,max}$) and high annoyance caused by vibrations from railway traffic. This serves to illustrate the influence of ISO weighting on derived DR relationships.

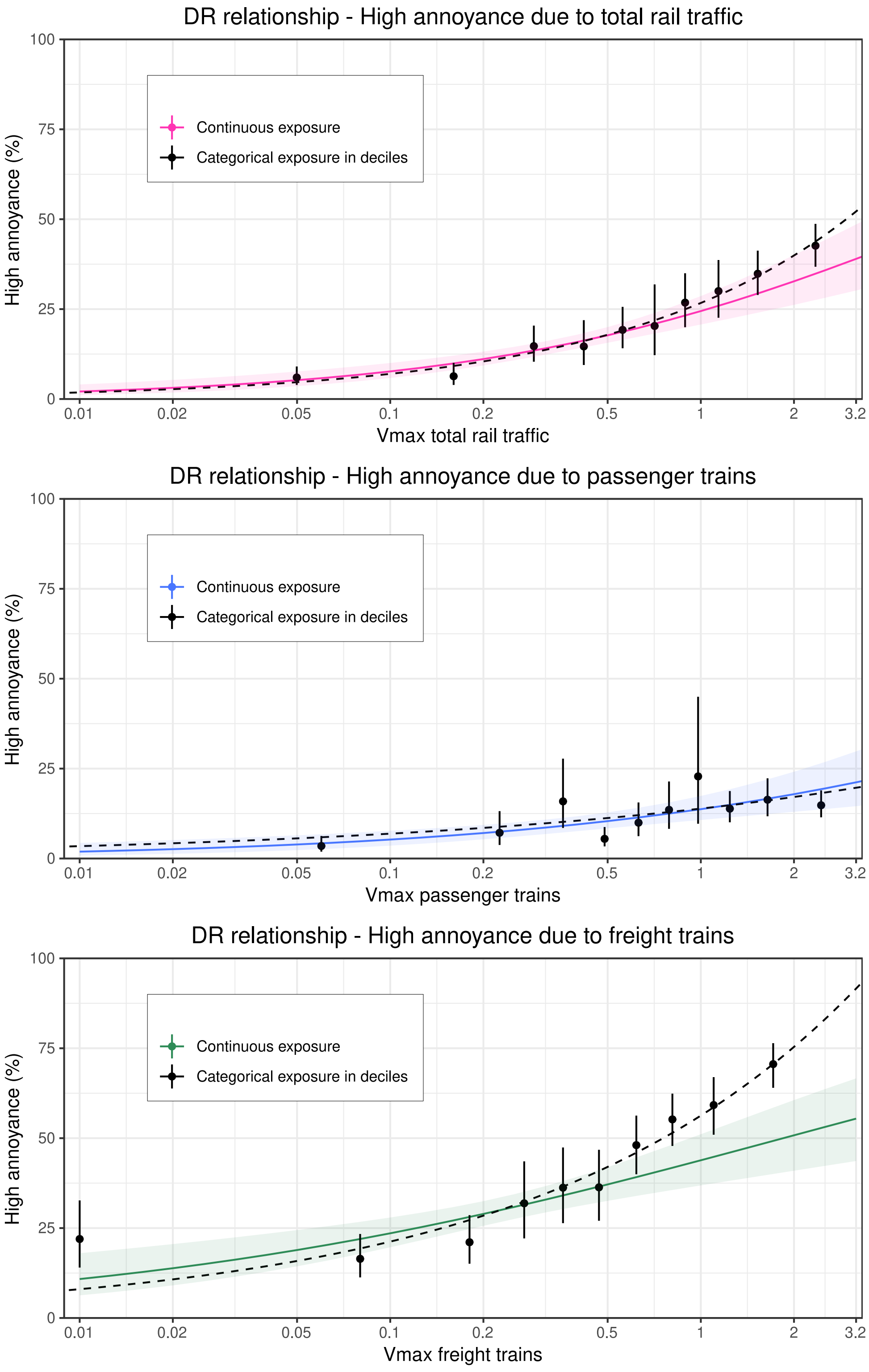

Figure 7.2 The DR relationships between maximum exposure to vibrations (V_{max}) and high annoyance due to vibrations from total railway traffic (top), passenger trains (centre) and freight trains (bottom). The relationships were drawn up for continuous exposure (coloured line) and categorical exposure based on exposure deciles (black lines). The dotted line represents the trend line of the estimate of the categorical model. The figure also shows an estimate, per train type, of the prevalence of high annoyance with a 95% confidence interval. The coloured sections around the coloured lines represent the 95% confidence interval for the DR relationship based on continuous exposure. The V_{max} values are presented on a logarithmic scale. NB No ISO weighting was applied for estimating vibration exposure.

Figure 7.3 shows the relationship between average vibration level (expressed as V_{per}) and the percentage of participants reporting high annoyance due to vibrations from the various train types. For all three sources of vibration, we found an association between the percentage of participants reporting high annoyance due to railway-induced vibrations and average vibration level: the higher the vibration level, the higher the probability of high annoyance. At equal vibration levels, vibrations produced by freight trains cause the most annoyance. Vibrations from freight trains also show the strongest relationship between average vibration level and high annoyance: when average vibration levels increase, expressed for example as V_{per} from 0.01 to 0.1, the percentage of high annoyance shows the largest increase for freight trains compared to the other two sources of vibration.

For high annoyance due to vibrations from total railway traffic *and* freight trains, there is a substantial difference between the two models we used for deriving a DR relationship. In both cases, the use of a categorical exposure model yields stronger DR relationships, particularly for higher levels of vibration exposure. The DR relationships between annoyance due to freight trains and average vibration level based on continuous and categorical exposure are practically identical to the DR relationships derived for high annoyance due to railway traffic total. The categorical model offers the best model fit for both total railway traffic and freight trains, but the continuous model offers the best fit for passenger trains (also see Table 7.1).

The results based on exposure to railway-induced vibrations expressed in RMS have are not shown here. They do however present a picture that is similar to that provided by the results based on exposure to railway-induced vibrations expressed in V_{per}.

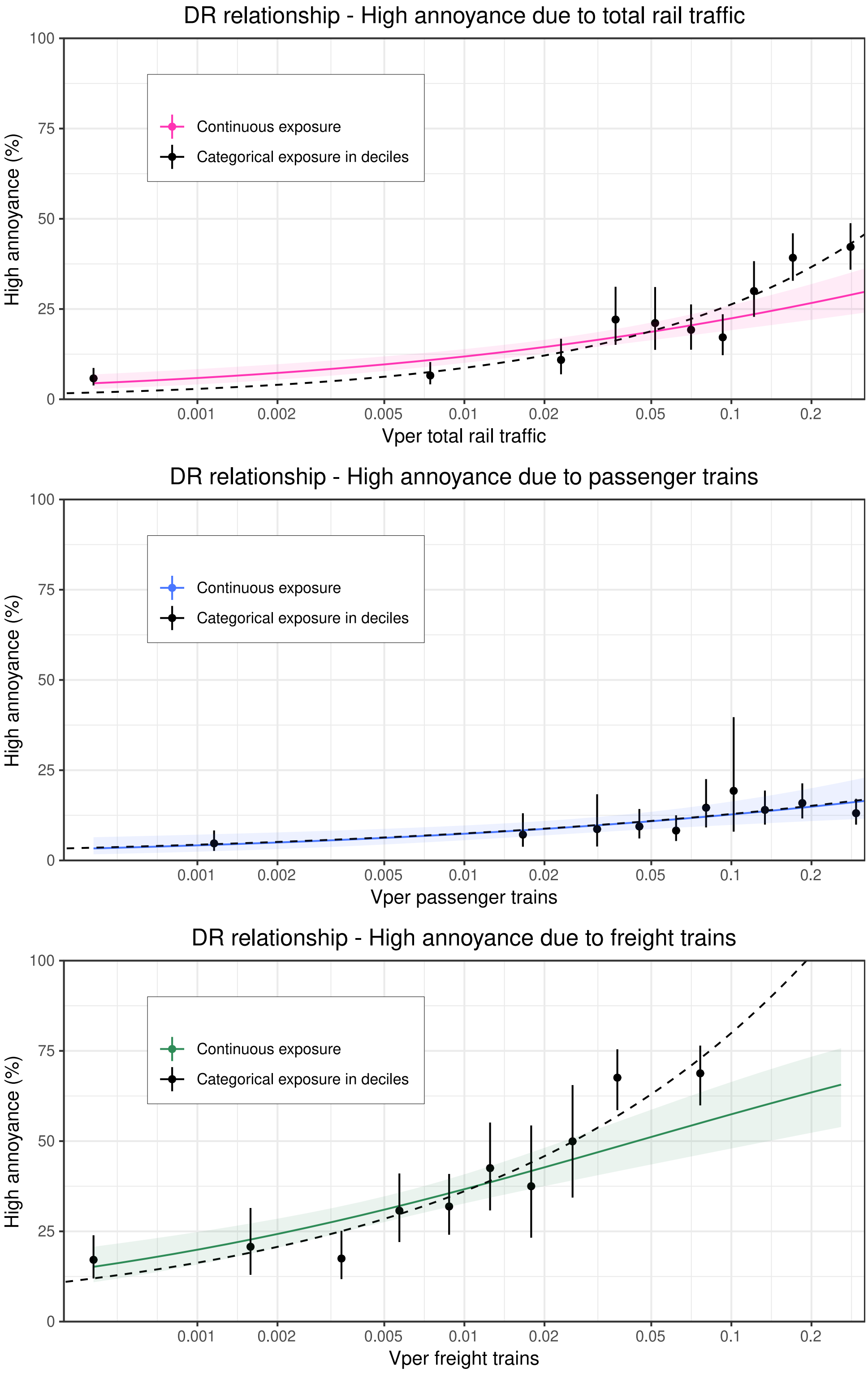

Figure 7.3 DR relationships for V_{per} and high annoyance due to vibrations from total railway traffic (top), passenger trains (centre) and freight trains (bottom). The relationships were drawn up for both continuous exposure (coloured line) and categorical exposure based on exposure deciles (black lines). The dotted line represents the trend line of the estimate of the categorical model. The figure also shows an estimate, per train type, of the prevalence of high annoyance with a 95% confidence interval. The coloured sections around the coloured lines represent the 95% confidence interval for the DR relationship based on continuous exposure. The V_{per} values are presented on a logarithmic scale. NB No ISO weighting was applied for estimating vibration exposure.

7.2 Self-reported sleep disturbance

Figure 7.4 presents the DR relationships between distance from the railway line and the percentage of participants reporting high sleep disturbance due to vibrations from total railway traffic, freight trains and passenger trains. For all three types, the figure shows an association between the percentage of participants who experience high sleep disturbance and distance from the railway line: the closer a participant lives to the railway line, the higher the probability of high sleep disturbance. At equal distance from the railway line, vibrations from freight trains cause the most sleep disturbance. Vibrations from freight trains also show the strongest DR relationship between distance from the railway line and high sleep disturbance : when the distance from the railway line decreases, for example from 200 to 100 metres, the percentage of high sleep disturbance shows the largest increase for freight trains. However, the difference with the DR relationship for total railway traffic is small.

As in the case of annoyance, we used various types of models to establish the DR relationships. Most differences between the models are found at short distances from the railway line. We have run tests to determine which model offers the best fit. The results of these tests are described in Table 7.2. Annex 5 presents the formulas of the DR relationships between exposure to railway-induced vibrations and high sleep disturbance due to railway-induced vibrations.

Table 7.2 shows that the categorical model has a better model fit than the continuous model. However, the continuous models provide a better fit for DR relationships between distance from the railway line and sleep disturbance due to freight trains and passenger trains. The difference with the categorical model in terms of fit is small, which is reflected in the largely overlapping curves of the two DR relationships in Figure 7.4.

Table 7.2 Model with the best fit for the association between exposure to railway-induced vibrations (without directional frequency weighting) and high sleep disturbance due to vibrations from railway traffic.

	Outcome: high sleep disturbance due to vibrations from		
Exposure indicator	**Total railway traffic**	**freight trains**	**passenger trains**
Distance from railway line	Continuous	Continuous	Continuous
RMS_{night}	Categorical	Categorical	Categorical
$V_{per\ night}$	Categorical	Categorical	Categorical
V_{max}	Categorical	Categorical	Categorical

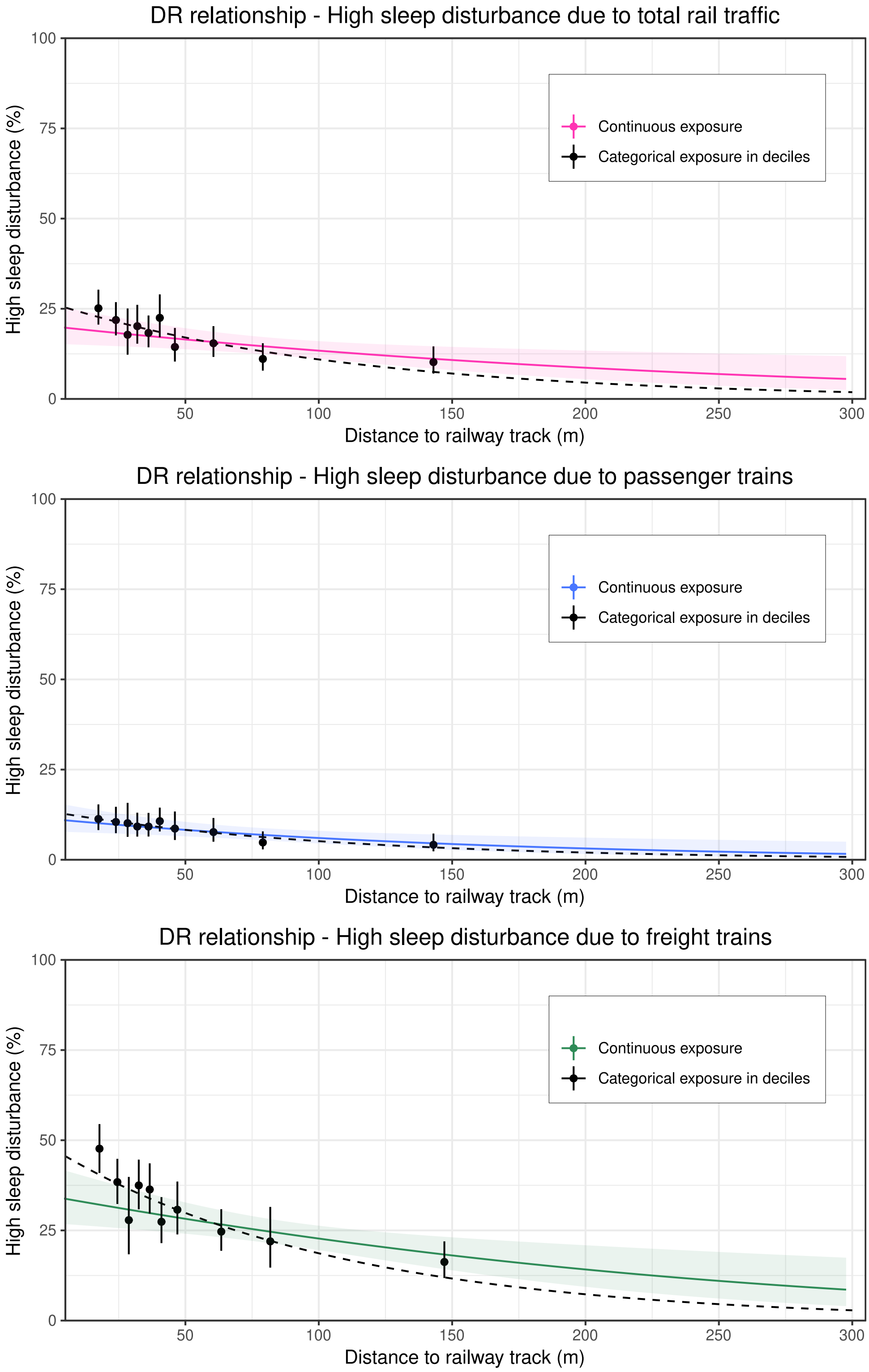

Figure 7.4 DR relationships for distance from the railway line and high sleep disturbance due to vibrations from total railway traffic (top), passenger trains (centre) and freight trains (bottom). The relationships were drawn up for both continuous exposure (coloured line) and categorical exposure based on exposure deciles (black lines). The dotted line represents the trend line of the estimate of the categorical model. The figure also shows an estimate, per train type, of the

prevalence of high sleep disturbance with a 95% confidence interval. The coloured sections around the coloured lines represent the 95% confidence interval for the DR relationship based on continuous exposure.

Figure 7.5 shows the DR relationship between maximum vibration level (V_{max}) from total railway traffic, passenger trains and freight trains and the percentage of participants reporting high sleep disturbance due to vibrations from those trains. For all three types of exposure, we found an positive association between the percentage of participants reporting high sleep disturbance and the maximum vibration level: the higher the maximum vibration level, the higher the probability of high sleep disturbance. At equal vibration levels, vibrations from freight trains cause the most sleep disturbance. Vibrations from freight trains also show the strongest relationship between maximum vibration strength and high sleep disturbance: when the maximum vibration level increases from 0.1 to 1, the percentage of high sleep disturbance shows the strongest increase for freight trains.

Again, we used two methods to derive the DR relationships. The difference between the categorical and continuous DR relationships is particularly large for high sleep disturbance due to vibrations from freight trains. The use of the categorical exposure yields a stronger DR relationship.

For DR relationships between maximum vibration level and sleep disturbance due to vibrations from total railway traffic freight trains and passenger trains, the models with categorical exposure provide the best fit (also see Table 7.2).

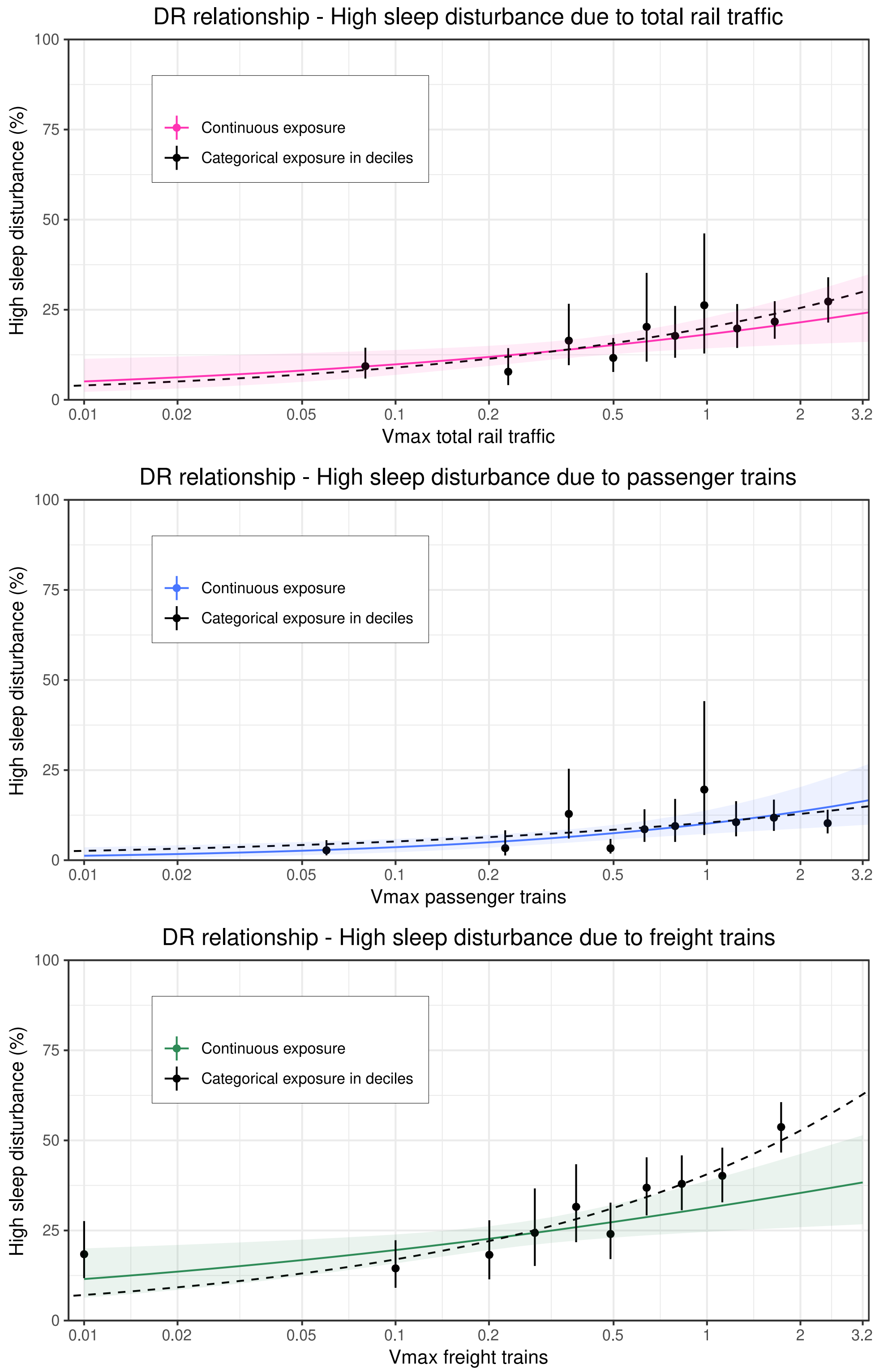

Figure 7.5 DR relationships for maximum exposure to vibrations (V_{max}) and high sleep disturbance due to vibrations from total railway traffic (top), passenger trains (centre) and freight trains (bottom). The relationships were drawn up based on both continuous exposure (coloured line) and categorical exposure based on exposure deciles (black lines). The dotted line represents the trend line of the estimate of the categorical model. The figure also shows an estimate, per train type, of the prevalence of high sleep disturbance with a 95% confidence interval. The coloured sections around the coloured lines represent the 95% confidence interval for the DR relationship based on continuous exposure. The V_{max} values are presented on a logarithmic scale. NB No ISO weighting was applied for estimating vibration exposure.

Figure 7.6 shows the relationship between average vibration level during the night without ISO weighting (expressed as $V_{per,\ night}$) and the percentage of participants reporting high sleep disturbance due to vibrations from different sources. For all three types, a positive association was found between the percentage of participants reporting high sleep disturbance and average vibration level during the night: the higher the vibration level during the night, the higher the probability of high sleep disturbance. At equal night-time vibration levels, vibrations from freight trains cause the most sleep disturbance. Vibrations from freight trains also show the strongest relationship between average vibration level during the night and high sleep disturbance: when average night-time vibration levels increase, expressed for example as $V_{per,\ night}$ from 0.01 to 0.1, the percentage of high sleep disturbance shows the steepest increase for freight trains.

We used continuous and categorical models to derive the DR relationships. For high sleep disturbance due to vibrations from total railway traffic and freight trains, the DR relationships based on continuous and categorical exposure differ. The use of the categorical model yields a stronger DR relationship in both cases. As shown in Table 7.2, the categorical model provides the best fit for all three vibration sources. For the models based on distance to the nearest railway line, the continuous models had the better model fit.

The results based on exposure to railway-induced vibrations expressed in RMS_{night} have not been included here. These results are however highly similar to the models based on exposure to railway-induced vibrations expressed in $V_{per,\ night}$.

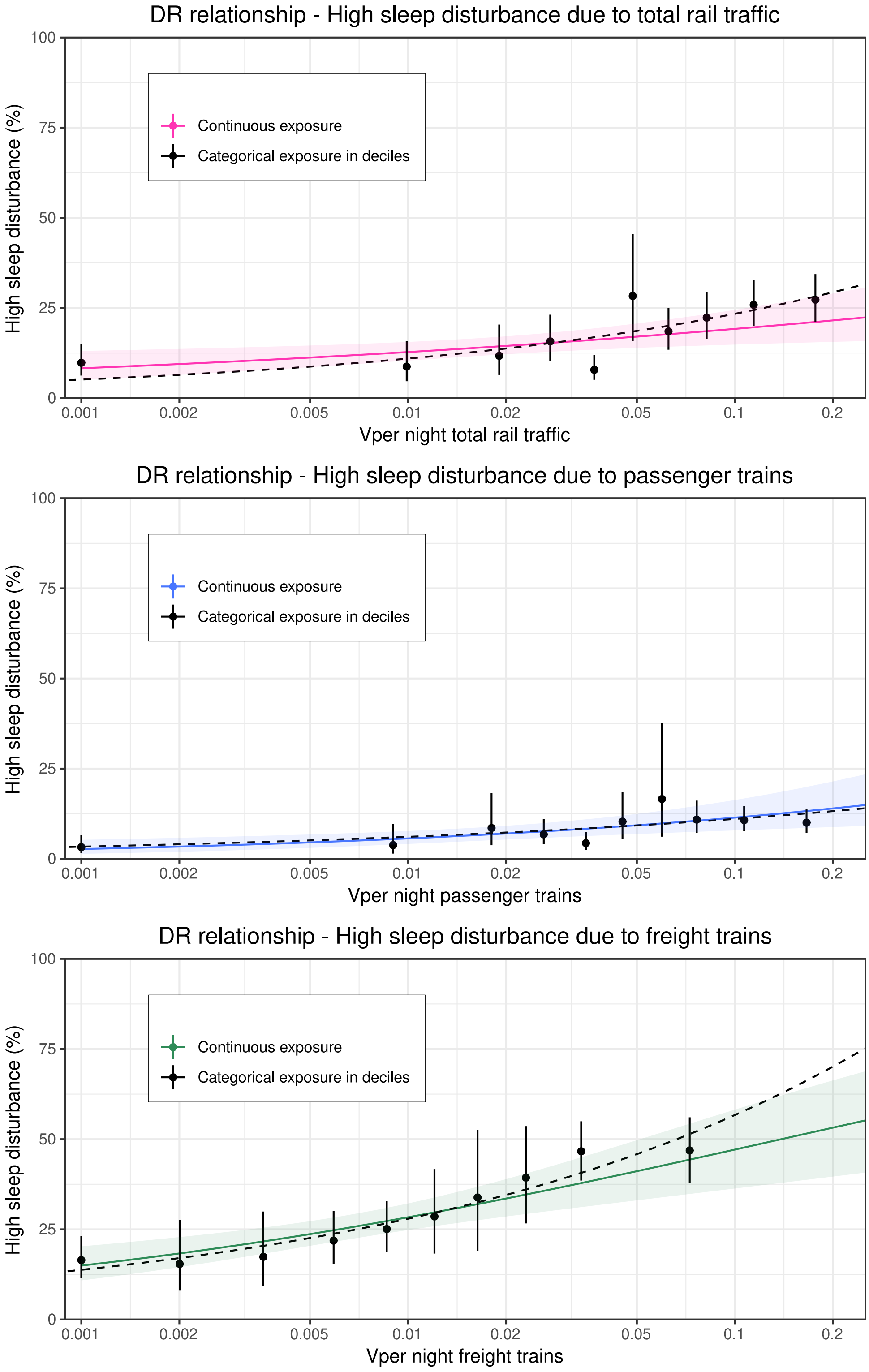

Figure 7.6 DR relationships for average exposure to vibrations during the night ($V_{per,\ night}$) and high sleep disturbance due to vibrations from total railway traffic (top), passenger trains (centre) and freight trains (bottom). The relationships were drawn up for both continuous exposure (coloured line) and categorical exposure based on exposure deciles (black lines). The dotted line represents the trend line of the estimate of the categorical model. The figure also shows an estimate, per train type, of the prevalence of high sleep disturbance with a 95% confidence interval. The coloured sections around the coloured lines represent the 95% confidence interval for the DR relationship based on continuous exposure. The $V_{per,\ night}$ values are presented on a logarithmic scale. NB No ISO weighting was applied for estimating vibration exposure.

7.3 How do the DR relationships compare with SBR and Bts?

Table 7.3 shows the percentages of high annoyance due to railway-induced vibrations corresponding with the various target and limiting values included in SBR and Bts (also see Box 1). For this purpose we used: a) the DR relationship between maximum exposure to vibrations from railway traffic (V_{max}) and the percentage of participants reporting high annoyance due to vibrations from railway traffic, as represented in Figure 7.2; and b) the DR relationship between average exposure to vibrations from railway traffic (V_{per}) and the percentage of participants reporting high annoyance due to vibrations from railway traffic, as represented in Figure 7.3. Based on model fit (Table 7.1), the predictions of the categorical model are the most reliable.

Table 7.3 Expected percentage of participants reporting high annoyance due to vibrations from railway traffic in relation to limit values and target values in Bts and SBR.

Regulation	**Indicator**	**V_{max}**	**Continuous model[b,c] (%)**	**Categorical model[c] (%)**
SBR	Perceptibility	0.1	8 (6-10)	7
	Lower target value	0.2[a]	11 (9-13)	10
Bts	Target value	0.2[a]	11 (9-13)	10
	Maximum Value	3.2	39 (30-48)	53
Regulation	**Indicator**	**V_{per}**	**Continuous model[b,d] (%)**	**Categorical model[d] (%)**
SBR	Target value	0.1[a]	22 (19-26)	26
Bts	Limit value	0.1[a]	22 (19-26)	26

[a] This target value is the same for daytime, evening and night-time hours;
[b] Within the continuous model, it is also possible to determine a 95% confidence interval;
[c] Estimated on the basis of the relationship derived in the Follow-Up Study between vibrations from railway traffic (expressed in V_{max}) and the percentage of participants reporting high annoyance due to vibrations from railway traffic in Figure 7.2;
[d] Estimated on the basis of the relationship derived in the Follow-Up Study between vibrations from railway traffic (expressed in V_{per}) and the percentage of participants reporting high annoyance due to vibrations from railway traffic in Figure 7.3.

SBR and Bts also include limit values and target values specifically for nighttime exposure (also see Box 1). Table 7.4 shows the percentages of high sleep disturbance due to vibrations from railway traffic corresponding with these target and limit values. For this purpose we used: a) the DR relationship between maximum exposure to vibrations from railway traffic (V_{max}) and the percentage of participants reporting high sleep disturbance due to vibrations from railway traffic, as represented in Figure 7.5; and b) the DR relationship between average exposure to vibrations from railway traffic ($V_{per,\ night}$) and the percentage of participants reporting high sleep disturbance due to by vibrations from railway traffic, as represented in Figure 7.6. Based on model fit (also see Table 7.2), the predictions of the categorical models are the most accurate.

Table 7.4 Expected percentage of participants reporting high sleep disturbance due to vibrations from railway traffic in relation to limit values and target values in Bts and Bts.

Regulation	**Indicator**	**V_{max}**	**Continuous model[b,c] (%)**	**Categorical model[c] (%)**
SBR	Perceptibility	0.1	10 (7 -14)	9
	Lower target value	0.2[a]	12 (9 -15)	11
Bts	Target value	0.2[a]	12 (9 -15)	11
	Maximum value	3.2	24 (16 -34)	30
Regulation	**Indicator**	**$V_{per,night}$**	**Continuous model[b,d] (%)**	**Categorical model[d] (%)**
SBR	Target value	0.1[a]	19 (15 -24)	23
Bts	Limit value	0.1[a]	19 (15 -24)	23

[a] This target value is the same for daytime, evening and night-time hours;
[b] Within the continuous model, it is also possible to determine a 95% confidence interval;
[c] Estimated on the basis of the relationship derived in the Follow-Up Study between vibrations from railway traffic (expressed in V_{max}) and the percentage of participants reporting high sleep disturbance due to vibrations from railway traffic in Figure 7.5;
[d] Estimated on the basis of the relationship derived in the Follow-Up Study between vibrations from railway traffic (expressed in $V_{per,\ night}$) and the percentage of participants reporting high sleep disturbance due to vibrations from railway traffic in Figure 7.6

7.4 Comparison with the results of the 2013 measurement

In this section we compare the results of the Follow-Up Study with the results of the first measurement of the 'Living along the railway line' study in 2013 [11]. In order to ensure maximum comparability of data, we also estimated the vibration exposure levels of participants in the 2013 measurement using the OURS model.

The DR relationships of the measurements from 2013 and 2021 are compared in the top figure of Figure 7.7. In Figure 7.7a the relationship between distance from the railway line and high annoyance due to vibrations from railway traffic, derived on the basis of data collected during the Follow-Up Study and the 2013 measurement is presented [11]. The bottom figure of Figure 7.7b shows the relationship between maximum vibration level (V_{max}) and high annoyance due to vibrations from railway traffic, derived on the basis of data collected during the Follow-Up Study and the 2013 measurement.

A comparison of the DR relationships between distance to the railway line and annoyance by the total railway traffic from the two studies shows that when distance from the railway line remaining equal, the probability of high annoyance was lower in 2021 than it was in 2013. This also applies to high annoyance due to vibrations from freight trains. In contrast, for high annoyance due to vibrations from passenger trains, the annoyance levels in 2021 were *higher* than in 2013 at equal distance from the railway line.

A comparison between the DR relationships of maximum exposure to vibrations from railway traffic and high annoyance due to vibrations from railway traffic shows that at equal maximum vibration levels, the probability of high annoyance due to vibrations from railway traffic was lower in 2021 than it was in 2013. When we express vibration exposure using RMS, a similar picture emerges.

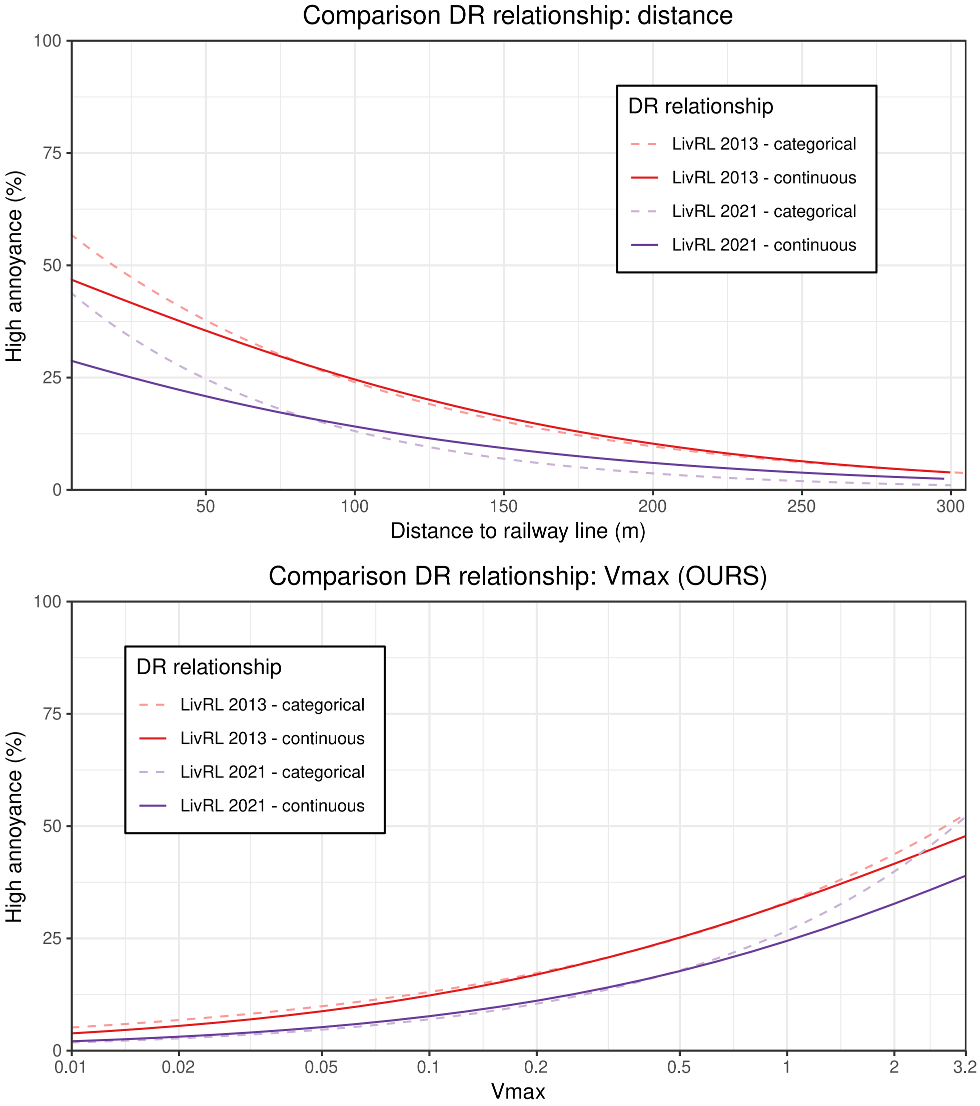

Figure 7.7 Comparison of the DR relationships between distance from the railway line and maximum vibration levels from railway traffic and the percentage of participants reporting high annoyance due to vibrations from railway traffic from the 'Living along the railway line' studies in 2013 and 2021. The relationships were drawn up for both continuous exposure (continuous line) and categorical exposure based on exposure deciles (dotted lines).

The situation for high sleep disturbance is different. A comparison between the DR relationships of between distance from the railway line and high sleep disturbance due to vibrations from railway traffic shows that, the probability of high sleep disturbance was actually *higher* in 2021 than it was in 2013, at equal distance from the railway line.

A comparison of the DR relationships between maximum exposure to vibrations from railway traffic and high sleep disturbance due to vibrations from railway traffic shows that at equal maximum vibration levels the probability of high sleep disturbance due to vibrations from railway traffic was *higher* in 2021 than it was in 2013. When we express exposure to vibrations using RMS, a similar picture emerges.

7.5 Comparison with the results of other studies

As described in Chapter 2, a number of studies have been previously published examining the relationship between exposure to railway-induced vibrations and high annoyance due to vibrations from railway traffic. Several of those studies also report DR relationships. In this section, we compare the results of the Follow-Up Study with a) the DR relationship between distance from the railway line (in m) and high annoyance due to vibrations from railway traffic derived using a meta-analysis carried out by TNO [77], b) the DR relationship between exposure to railway-induced vibrations (expressed in RMS and $V_{dir,max}$) and the percentage of participants reporting high annoyance due to vibrations from railway traffic derived in the CargoVibes project [22], and c) the DR relationship between distance from the railway line (in m) and high annoyance due to vibrations from railway traffic derived in the Salford study [25]. (see also Figure 7.8).

7.5.1 The DR relationship between distance from the railway line and high annoyance

The DR relationship between distance from the railway line and the percentage of participants reporting high annoyance due to vibrations from railway traffic based on the current Follow-Up Study differs from the DR relationship derived by Janssen et al (TNO) [77]: At equal distance from the railway line, the DR-relationship based on the TNO’s meta-analysis estimates a lower percentage of high annoyance than the DR-relationship of the Follow-Up Study. To illustrate, at a distance of 100 metres from the nearest railway line the TNO DR-relationship estimates approximately 7% of the population to experience high annoyance and the current DR-relationship based on the Follow-up study estimates approximately 13%. The BR-relationship derived from data collected in the Salford study [25] expects even less high annoyance, with an estimated 2% of the population experiencing high annoyance at 100 metres from the railway line.

7.5.2 The DR relationship between exposure to vibrations and high annoyance

Since the CargoVibes study uses $V_{dir,max}$ and the DR relationships within the Follow-Up Study are based on V_{max}, the DR relationships shown Figure 7.2 cannot be compared to the CargoVibes DR relationship. For that reason, additional DR relationships have been establish for the 2021 and 2013 measurements based on $V_{dir,max}$. A comparison of these DR relationships with the CargoVibes one shows that at lower exposure levels, the DR relationships based on the Follow-Up Study and CargoVibes tend to be quite consistent with each other. At higher exposure levels ($V_{dir,max}$>1) the categorical models of the Follow-Up Study consistently predict higher percentages of participants reporting high annoyance than the continuous models.

The DR relationship based on the 2013 measurement differs from the DR relationships from the Follow-Up Study and CargoVibes. For the same $V_{dir,max}$, the DR relationship from 2013 predicts substantially more annoyance than the other DR relationships.

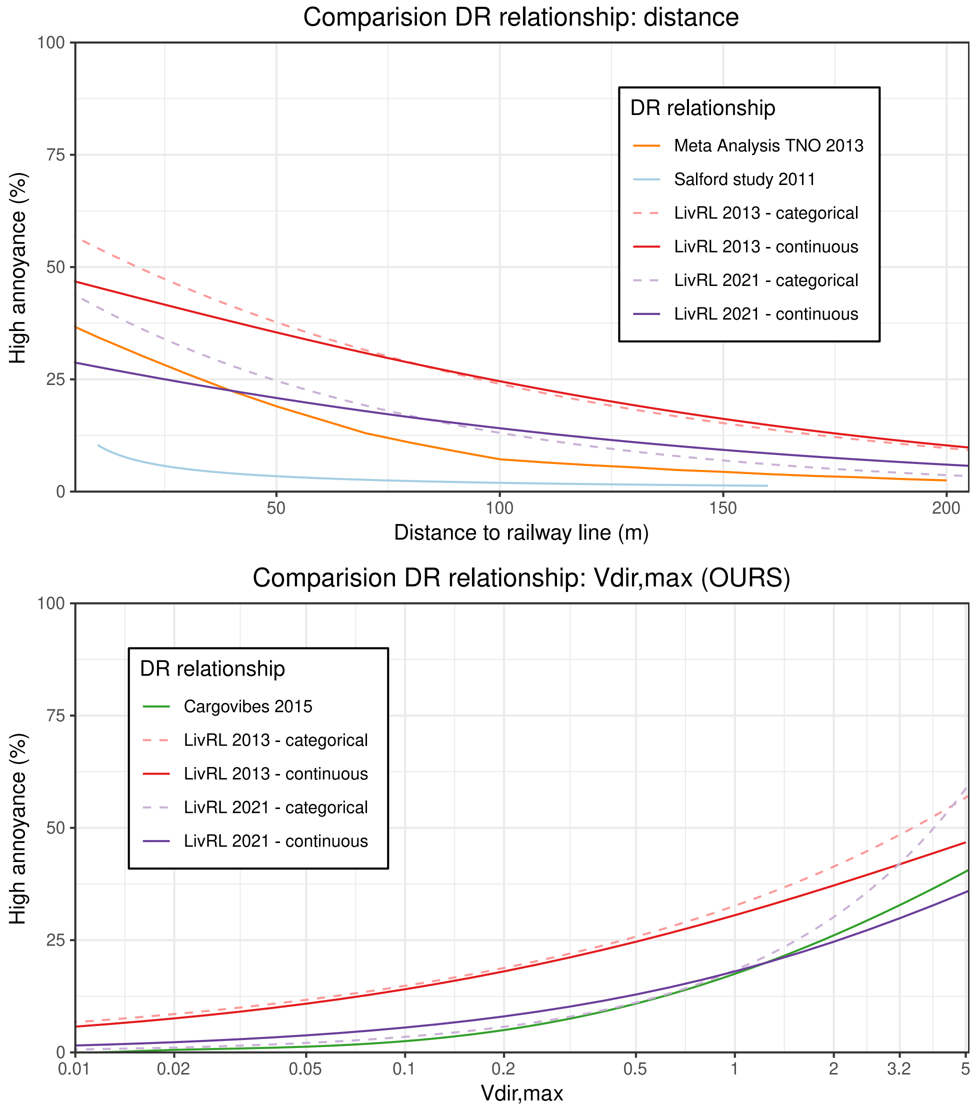

Figure 7.8 Comparison of the DR relationships between distance from the railway line (top) and maximum vibration strength (bottom) from railway traffic and the percentage of participants reporting high annoyance due to vibrations from railway traffic from the 'Living along the railway line' studies in 2013 and 2021 and other studies[22, 25, 77].

8 Determinants of annoyance and sleep disturbance due vibrations from railway traffic

We tried to find out which determinants, besides different indicators of exposure to vibration, influence self-reported high annoyance and high sleep disturbance due to railway-induced vibrations. As in the 2013 measurement, we analysed the relative importance of the determinants of high annoyance and high sleep disturbance using a logistic regression model. The variables eventually included in the model were selected largely on the basis of findings from earlier research (also see Chapter 2) and the results of a non-parametric exploration by means of a so-called untargeted analysis: (UA) (see Annex 2).

8.1 The determinants of high annoyance due to vibrations from railway traffic

Table 8.1 presents the outcomes of the logistic regression analysis that investigates the association between high annoyance due to vibrations (from total railway traffic, passenger trains and freight trains) and maximum vibration exposure (V_{max}), adjusted for other factors. In this analysis, the variable V_{max} is expressed as a categorical variable based on quartiles.

Maximum vibration level and characteristics of the railway line
Table 8.1 shows that even after adjustment for other factors, people who are exposed to higher maximum vibration levels are more likely to report high annoyance due to vibrations both from total railway traffic and freight trains. This is reflected in the table by the increasing ORs per quartile group. However, the only statistically significant difference was found between the reference group and the highest quartile group. Persons who fall in the highest quartile group in terms of V_{max} exposure of the total railway traffic are more than 2.6 times more likely to report high annoyance than persons in the lowest quartile group (p=0.0176). Furthermore, persons who fall in the highest quartile in terms of exposure to maximum vibration levels from freight trains are 3.1 times more likely, on average, to report high annoyance due to vibrations from freight trains than their counterparts in the reference group (p=0.0017). For high annoyance due to vibrations from passenger trains there is no clear pattern between maximum vibration levels and reported annoyance. This means that persons in the second, third and fourth quartile groups are as likely to experience high annoyance due to vibrations from passenger trains as persons in the first quartile group.

Table 8.1 The relationship between maximum exposure to vibrations from railway traffic and high annoyance due to railway-induced vibration

Variable	**High annoyance caused by vibrations from railway traffic**	**High annoyance due to vibrations from passenger trains**	**High annoyance due to vibrations from freight trains**
	OR (95% CI)	**OR (95% CI)**	**OR (95% CI)**
Vibration exposure (V_{max})			
Quartile 1	*Ref.:*	*Ref.:*	*Ref.:*
Quartile 2	1.32 (0.74-2.34)	0.76 (0.38-1.53)	1.10 (0.55-2.19)
Quartile 3	1.39 (0.56-3.45)	1.22 (0.63-2.38)	1.32 (0.70-2.48)
Quartile 4	2.63 (1.18-5.84)*	0.80 (0.40-1.60)	3.14 (1.54-6.42)*
Fraction of freight trains (%)[a]			
Quartile 1	*Ref.:*	*Ref.:*	*Ref.:*
Quartile 2	0.62 (0.26-1.5)	1.11 (0.55-2.25)	3.35 (0.68-16.65)
Quartile 3	1.41 (0.65-3.02)	0.51 (0.26-0.99)*	5.24 (1.04-26.52)*
Quartile 4	1.90 (0.87-4.12)	0.32 (0.16-0.66)*	3.36 (0.72-15.64)
Fraction of night trains (%)[b]			
Tertile 1	*Ref.:*	*Ref.:*	*Ref.:*
Tertile 2	0.80 (0.44-1.44)	0.77 (0.41-1.46)	1.20 (0.64-2.25)
Tertile 3	0.62 (0.32-1.21)	1.0 (0.55-1.80)	0.88 (0.43-1.77)
Gender			
Men	*Ref.:*	*Ref.:*	*Ref.:*
Women	1.96 (1.12-3.42)*	1.19 (0.72-1.97)	1.22 (0.69-2.18)
Age class			
16–44 years	*Ref.:*	*Ref.:*	*Ref.:*
45-64 years	0.78 (0.41-1.5)	1.17 (0.66-2.07)	0.70 (0.34-1.43)
65 and over	0.70 (0.32-1.53)	0.58 (0.26-1.29)	0.47 (0.22–1.0)
Education			
None/lower education	2.06 (0.21-20.03)	0.38 (0.06-2.45)	0.04 (0.01-0.51)*
Lower general secondary/lower vocational	0.51 (0.27-0.96)*	0.60 (0.27-1.33)	1.16 (0.46-2.9)
Higher general secondary/pre-university/ senior secondary	*Ref.:*	*Ref.:*	*Ref.:*

Variable	High annoyance caused by vibrations from railway traffic OR (95% CI)	High annoyance due to vibrations from passenger trains OR (95% CI)	High annoyance due to vibrations from freight trains OR (95% CI)
vocational			
Higher professional/university	1.09 (0.61-1.95)	0.47 (0.26-0.87)*	0.92 (0.48-1.76)
Degree of urbanisation[c]			
Extremely urbanised	0.73 (0.27-1.96)	0.86 (0.36-2.08)	0.95 (0.34-2.66)
Highly urbanised	0.62 (0.29-1.33)	1.55 (0.63-3.81)	1.04 (0.39-2.82)
Moderately urbanised	0.71 (0.33-1.52)	1.12 (0.41-3.06)	1.15 (0.36-3.69)
Hardly urbanised	0.95 (0.43-2.1)	0.66 (0.26-1.66)	0.99 (0.33-2.97)
Not urbanised	*Ref.:*	*Ref.:*	*Ref.:*
Railway traffic noise (L_{den}) in dB(A)	1.0 (0.96-1.03)	1.0 (0.98-1.03)	1.0 (0.97-1.03)
High annoyance due to the noise from:			
Total railway traffic	5.58 (3.07-10.12)*	-	-
Passenger trains	-	33.80 (18.45-61.93)*	-
Freight trains	-	-	18.21 (9.14-36.26)*
Hearing, feeling, seeing windows, doors and/or crockery ('rattle')	2.62 (1.55-34.41)*	3.91 (2.16-7.07)*	2.83 (1.64-4.68)*
Concerns about:			
Loss of property value	2.01 (1.05-3.85)*	1.39 (0.71-2.71)	1.10 (0.46-2.63)
Health effects of vibrations	0.99 (0.44-2.23)	1.22 (0.61-2.45)	1.22 (0.48-3.09)
Property damage	2.94 (1.70-5.09)*	2.31 (1.16-4.62)*	2.80 (1.00-7.79)*
Negative attitude towards:			
Current policy for railway zones	1.08 (0.37-3.12)	1.04 (0.32-3.35)	0.68 (0.24-1.91)
Plans to allow railway traffic to grow in some parts of the Netherlands	1.12 (0.32-3.89)	0.98 (0.35-2.74)	1.64 (0.61-4.44)
Vibrations from railway traffic are (highly) unacceptable	2.69 (1.65-4.4)*	5.64 (2.68-11.99)*	2.97 (1.59-5.53)*

Variable	High annoyance caused by vibrations from railway traffic OR (95% CI)	High annoyance due to vibrations from passenger trains OR (95% CI)	High annoyance due to vibrations from freight trains OR (95% CI)
Expect decline due to vibrations from railway traffic	3.81 (2.25-6.44)*	1.17 (0.63-2.18)	1.44 (0.80-2.61)

Abbreviations: Ref=reference group, OR=Odds Ratio, 95% CI=95% confidence interval, L_{den}=day-evening night level, *=statistically significant

[a] Categories based on quartiles;

[b] Categories based on tertiles;

[c] Degree of urbanisation is a measure for concentration of human activity based on average local address density (LAD), expressed in number of addresses per km^2. The following degrees of urbanisation are distinguished: not urbanised (average LAD <500), hardly urbanised (average LAD 500-1000), moderately urbanised (average LAD 1000-1,500), highly urbanised (average LAD 1500-2,500) and extremely urbanised (average LAD >2500);

[*] Statistically significant (p<0.05)

With regard to the fraction of freight trains, we mainly found effects in relation to high annoyance from passenger trains: persons who live in the vicinity of a railway line and are in the two highest quartiles for the fraction freight trains are significantly less likely to report high annoyance due to vibrations from passenger trains than their counterparts in the lowest quartiles. As regards to high annoyance caused by vibrations from freight trains, an opposite results was observed: persons who live in the vicinity of a railway line and who are in a higher quartile group are more likely to report high annoyance caused by vibrations from freight trains than their counterparts in the lowest quartile group. This difference was only statistically significant (p=0.0451) for the second-highest quartile group. After adjustment for the other factors in Table 8.1, no effect of the fraction of freight trains on high annoyance due to vibrations from railway traffic was found. For none of the train types did we find an effect of the fraction of night trains.

Socio-demographic factors and degree of urbanisation
The influence of various socio-demographic factors has also been investigated. The analysis shows that women are more likely to report high annoyance due to vibrations from the three types of exposure than men. This association was only statistically significant for high annoyance due to vibrations from total railway traffic (p=0.0178). Age did not have any influence on the likelihood of annoyance due to vibrations from any of the three train types and the influence of education on annoyance is ambiguous. In addition, we found that the degree of urbanisation has no influence on the likelihood of annoyance due to vibrations from any of the three different sources.

Social and personal factors
We also studied social and personal factors that may influence perceived levels of annoyance due to vibrations from the three different sources. In particular, acceptance of vibrations and being able to hear, feel and see windows, doors and/or crockery ('rattle') turned were significantly associated with reported annoyance: people who feel that vibrations from railway traffic are (highly) unacceptable are significantly more likely to experience annoyance due to vibrations from all of the three sources of railway-induced vibration. Persons who perceive vibrations by seeing, feeling or hearing windows, doors or crockery ('rattle') are also significantly more like likely to experience high annoyance due to vibrations from total railway traffic, freight trains and passenger trains.

Similar to the results of the 2013 study, we also found associations between people's expectations and high annoyance. Persons who expect that vibrations from railway traffic are going to increase in the coming year are more likely to report high annoyance due to vibrations from all three sources than persons who do not expect this. This difference was only statistically significant for high annoyance due to vibrations from the total railway traffic (p<0.001).
Likewise, concerns about property damage also were associated with annoyance: persons who felt concerned that railway-induced vibrations are causing damage to their property, are significantly more likely to report high annoyance due to vibrations from total railway traffic (OR=2.94; p<0.001), passenger trains (OR=2.31; p=0.0174) and

freight trains (OR=2.80; p=0.0492). Persons who felt concerned that vibrations from railway traffic were causing a decrease in the value of their property are also more likely to report high annoyance due to vibrations from all of the three types of vibration exposure. Only the association with high annoyance due to vibrations from total railway traffic was statistically significant (p=0.0349).

Note that the attitude towards the current railway policy and towards a potential increase in the number of trains was not associated with reported high annoyance due to vibrations from any of the three sources of vibration.

Noise from railway traffic and annoyance due to the noise from railway traffic

The results of the untargeted analyses demonstrated that both noise from railway traffic (L_{den}) and annoyance due to the noise from railway traffic are important predictors of high annoyance due to vibrations from all three sources. Therefore, we decided to include both high annoyance due to noise from railway traffic and exposure to noise from railway traffic (expressed in annual average L_{den}) in the logistic regression analysis. However, these two factors are strongly correlated. We have tried to reduce this correlation by not including the annoyance score itself in the model, but rather a binary variable that expresses whether a person does or does not experience high annoyance due to the noise produced by the three railway sources. For comparison, we also created several additional logistic regression models in which exposure to noise from railway traffic (L_{den}) and the reported level of annoyance due to the noise of the three sources were *not* included together. The analyses showed that within a model (adjusted for all other factors in Table 8.1) that includes the factor high annoyance due to noise, exposure to noise produced by railway traffic (expressed in L_{den}) is *not* associated with high annoyance due to vibrations from any of the three sources of vibration. However, eliminating the factor high annoyance due to noise from railway traffic effects this outcome. In a model without the factor high annoyance due to noise, the factor noise exposure does show a positive and significant association with reported levels of annoyance due to vibrations. In other words: the likelihood of high annoyance due to vibrations from any of the three sources of vibration increases with increasing levels of noise from railway traffic.

High annoyance due to noise produced by any of the three railway sources is consistently associated with high annoyance due to vibrations produced by the corresponding railway source. After adjustment for the other factors in Table 8.1 (including noise from railway traffic), people who report high annoyance due to noise from total railway traffic, passenger trains, or freight trains are significantly more likely to experience high annoyance due to vibrations from total railway traffic, passenger trains, or freight trains respectively. Excluding exposure to noise from railway traffic (L_{den}) from the model does not influence this association. Furthermore, the association between maximum exposure to railway-induced vibrations (V_{max}) and high annoyance due to vibrations produced by the various railway sources is not influenced by including the noise factor or annoyance by railway noise factor, both individually and together, within the model.

Other indicators of exposure to vibrations

We have also conducted logistic regression analyses that included other exposure indicators for vibrations than V_{max}. These are the average vibration exposure (expressed in RMS and V_{per}) and distance from the nearest railway line (in metres). As for V_{max}, the RMS and V_{per} exposure indicators are divided into quartile groups. For distance, exposure is divided into four separate distance groups (<25 m, 25-50 m, 50-100 m and 100-300 m), with the highest-distance group serving as the reference group. Figure 8.1 shows the adjusted ORs for these exposure indicators, together with the ORs for the V_{max} for high annoyance due to vibrations from total railway traffic and freight trains.

Figure 8.1 shows that the closer a person lives to a railway line, the more likely they are to report high annoyance due to vibrations from total railway traffic and freight trains. This is reflected in the figure in the increasing ORs per distance group. For persons living at living 25-50m or less than 25 m of the nearest railway there is a statistically significant difference with the reference group. After adjustment for other distorting factors, persons living at 25-50 m of a railway line are more likely to experience high annoyance due to vibrations from total railway traffic (OR=1.91; p=0.0485) and freight trains (OR=2.15; p=0.0208) compared to people living at 100-300 m of a railway line. In addition, persons living within 25 metres from the railway line are also more likely to experience high annoyance due to vibrations from total railway traffic (OR=2.67; p=0.0084) and freight trains (OR=2.96; p=0.0068) than the reference group.

After adjustment for potentially confounding factors, persons exposed to higher maximum vibration levels are more likely to report high annoyance due to vibrations both from total railway traffic and freight trains. This is reflected in Table 8.1 and Figure 8.1 in the increasing ORs per quartile group. When we express exposure to vibrations using the average vibration exposure (expressed in RMS), a similar pattern emerges. Persons in the fourth exposure quartile of RMS (e.g. the 25% of the population with the highest exposure) are significantly more likely to report high annoyance due to vibrations from both total railway traffic and freight trains compared with persons in the control group.

For V_{per} we see the same picture as for RMS. Persons in the fourth quartile group are significantly more likely to report high annoyance due to vibrations from both total railway traffic and freight trains compared with persons in the first quartile group.

Figure 8.1 does not include the results for high annoyance due to vibrations from passenger train because no significant associations were found between the different vibration indicators and annoyance. After adjustment for the various factors described in Table 8.1, persons living close to a railway line (<25 m, 25-50 m, and 50-100 m) are just as likely to report high annoyance as those living at a greater distance of a railway line (100-300 m). In addition, we also found that if a person is exposed to higher vibration levels, they do not report more high annoyance due to vibrations from passenger trains.

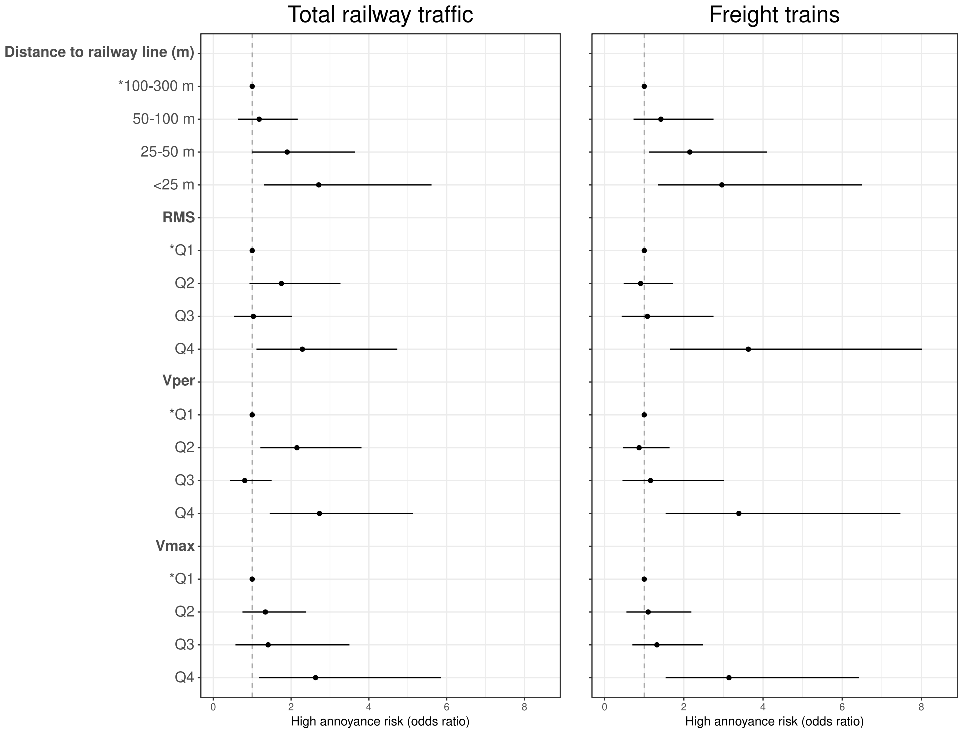

*Figure 8.1 The association between exposure to vibrations from railway traffic and high annoyance due to vibrations from total railway traffic and freight trains, adjusted for potentially confounding factors. The risk of high annoyance is expressed in an Odds Ratio (OR) plus a 95% confidence interval, with the lowest-exposure groups (marked with *) serving as the reference groups. With an OR value significantly higher than 1 (the vertical dotted line), a group has a higher chance of experiencing high annoyance relative to the reference group.*

8.2 The determinants of high sleep disturbance caused by vibrations from railway traffic

Table 8.2 presents the results of the logistic regression analysis which examined the association between maximum exposure to vibrations (V_{max}) and high sleep disturbance due to vibrations from total railway traffic, passenger trains, and freight trains.

Maximum vibration levels and railway characteristics
Table 8.2 shows that, after adjustment for potential confounders, persons in the second and third quartile group for maximum exposure to vibrations are more likely to experience high sleep disturbance due to vibrations from passenger trains than persons in the first-quartile group. Only the difference between the third quartile group and the first quartile is statistically significant (p=0.0102). As regards to high sleep disturbance due to vibrations from both total railway traffic and freight trains, no significant association was found between maximum vibration levels and reported sleep disturbance. This means that persons in the different quantile groups are all just as likely to experience high sleep disturbance due to vibrations as persons in the first quartile group.

As with high annoyance due to railway-induced vibrations, we also examined the effect of the fraction of freight trains in total night-time railway traffic and the fraction of night trains on high sleep disturbance from railway traffic. With regard to the fraction of freight trains, after adjustment for the other factors in Table 8.2, only in the case of freight trains does the probability of high sleep disturbance due to vibrations increases with the freight trains. However, this increase was not statistically significant for any quartile.

For the fraction of night trains, we find that the chance of high sleep disturbance due to vibrations from both total railway traffic and passenger trains increases as the fraction of night trains increases. In contrast, the likelihood of high sleep disturbance due to vibrations from freight trains *decreases* as the fraction of night trains increases. None of these observed increases and decreases were statistically significant.

Socio-demographic factors and degree of urbanisation
As with high annoyance due to railway-induced vibrations, we also examined the associations between various socio-demographic factors and high sleep disturbance. As shown in Table 8.2, women are more than twice as likely to report high sleep disturbance due to vibrations from total railway traffic (p=0.0162) and freight trains (p=0.0090) than men. For sleep disturbance due to vibrations from passenger trains, no statistically significant difference between men and women was found. Furthermore, there was no association between age and high sleep disturbance due to vibrations from the total railway traffic and freight trains. For sleep disturbance due to vibrations from passenger trains a statis statistically significant difference between the youngest and the oldest age groups was found: persons aged 65 and over were less likely to report high sleep disturbance due to vibrations from passenger trains than persons in the 16-44 age group (p=0.0187). Education level was not associated with high sleep disturbance due to vibrations from any of the three sources.

The degree of urbanisation is associated with high sleep disturbance due to vibrations from the total railway traffic: persons living in low to extremely urbanised neighbourhoods were more likely to report high sleep disturbance due to vibrations from railway traffic than persons not living in an urbanised neighbourhood. This difference was only statistically significant for persons living in moderately urbanised (p=0.0213) and highly urbanised (p=0.0148) neighbourhoods. We did not find any association with degree of urbanisation for sleep disturbance due to vibrations from freight trains or passenger trains.

Social and personal factors
We examined the influence of social and personal factors on the experienced level of sleep disturbance due to railway-induced vibrations. As with high annoyance due to vibrations from railway traffic, we found clear associations between sleep high disturbance and acceptance and expectations of railway traffic. Persons who feel that vibrations from railway traffic are (highly) unacceptable are more likely to report sleep disturbance due to vibrations from all three sources.
The strongest association was found for sleep disturbance due to vibrations from total railway traffic (OR=4.21; p=0.0016), followed by vibrations from passenger trains (OR=3.56; p=0.0021) and freight trains (OR=3.07; p=0.0003). Persons who expect that railway-induced vibrations are going to increase in the future are approximately twice as

likely to report high sleep disturbance due to vibrations from total railway traffic and freight trains than persons who expect that the level of vibrations will stabilise or decrease in future. In contrast, persons who expect that railway-induced vibrations are going to increase in the future are *less* likely to report high sleep disturbance due to vibrations from *passenger* trains. This was however not statistically significant.

Furthermore, concerns over loss of property value, health damage from vibrations and property damage were associated with high sleep disturbance due to vibrations from some of the different sources of vibrations. Health concerns due to vibrations and high sleep disturbance due to vibrations from railway traffic were significantly associated ($p=0.0305$). Also, there a significant association between loss of property value and high sleep disturbance due to vibrations from passenger trains ($p=0.0219$).
Persons who perceive vibrations by seeing, feeling or hearing windows, doors or crockery ('rattle') are not more likely to experience high sleep disturbance due to vibrations from the three sources of railway-induced vibrations. Remarkably, persons with a negative attitude towards current railway policy for railway zones are *less* likely to report high sleep disturbance due to vibrations from the total railway traffic ($p=0.0165$). Finally, no significant associations were found between a negative attitude towards plans to expand current railway traffic in some parts of the Netherlands and sleep disturbance due to vibrations from all three sources.

Night-time noise from railway traffic and sleep disturbance due to the noise from railway traffic
The results of the UA demonstrated that both night-time noise from railway traffic and sleep disturbance due to night-time noise from railway traffic are important predictors of high sleep disturbance due to vibrations from any of the three sources of vibrations. For that reason, we decided to include both high sleep disturbance due to night-time noise from the three train types and exposure to night-time noise from total railway traffic (expressed in annual average L_{den}) in the logistic regression analysis. However, these two factors are strongly correlated. We have tried to reduce this correlation within the model by not including the sleep disturbance score itself, but rather a binary variable that expresses whether a person does or does not experience high sleep disturbance from the night-time noise produced by a certain source of vibration. For comparison, we have also created additional logistic regression models in which exposure to night-time noise from railway traffic (L_{den}) and the reported level of sleep disturbance from the noise of a particular type of train were *not* included together in a single model.

The model results showed that exposure to night-time noise from railway traffic (L_{night}) is not associated with reported sleep disturbance due to vibrations from railway traffic *in the presence of* high sleep disturbance due to the noise from railway traffic and the other factors within the model (Table 8.2).

If we excluded the reported high sleep disturbance due to the noise form railway traffic, exposure to night-time noise from railway traffic (expressed in L_{night}) *was* in fact associated with reported high sleep

disturbance due to vibrations from railway traffic. In other words: without adjustment for high sleep disturbance due to the noise from railway traffic, the likelihood of high sleep disturbance due to vibrations from any of the three sources of vibration significantly increases with increasing levels of noise from railway traffic.
However, high sleep disturbance due to noise produced by the three different railway sources is consistently associated with high sleep disturbance due to by the same sources. Persons who report high sleep disturbance due to the night-time noise from total railway traffic, passenger trains and freight trains are significantly more likely to report high sleep disturbance due to vibrations from total railway traffic, passenger trains and passing freight trains. When exposure to noise from railway traffic (L_{night}) is excluded from the model, high sleep disturbance due to noise from the different railway sources types remains a strong predictor of high sleep disturbance due to railway-induced vibration.

Characteristics of the dwelling
Finally, we also examined the influence of the location of the bedroom, the presence of HE glazing in bedrooms and of the habit of residents to close windows or leave them open on high sleep disturbance due to railway-induced vibrations. As shown in Table 8.2, persons whose bedroom is located on the third floor or higher are more likely to report high sleep disturbance due to vibrations from passenger trains than persons whose bedroom is located on the second floor or lower (p=0.0067).
As regards to window opening and closure habits, effects were found for sleep disturbance due to vibrations from total railway traffic and passenger trains, but not vibrations from freight trains. Persons who close the windows in winter or summer are more likely to report high sleep disturbance due to vibrations from total railway traffic (OR=2.67; p=0.0127) and passenger trains (OR=4.3; p<0.0001) than persons who always keep their windows closed. No association was found between HE glazing in the bedroom and high sleep disturbance due to vibrations from any of the three railway sources.

Other vibration exposure indicators
We also conducted a logistic regression analysis for the average railway-induced night-time vibration level (expressed in RMS and $V_{per\ night}$) and distance from the railway line (in m). The analyses have shown that, after adjustment for the potential confounding variables from Table 8.2, persons living close to a railway line (<25 m, 25-50 m, and 50-100 m) are just as likely to report sleep disturbance due to vibrations from the different railway sources types as those living at a greater distance of a railway line (100-300 m). Furthermore, no significant associations were found between average night-time vibration levels and high annoyance.

Only the difference between persons in the third quartile for exposure to maximum vibration levels from passenger trains and those in the first quartile is statistically significant. As regards severe sleep disturbance due to vibrations from both total passing trains and passing freight trains, after adjustment for the other factors in Table 8.2 we found no clear pattern between maximum vibration levels and reported sleep disturbance. This means that persons in the second, third and fourth quartile groups are as likely to experience severe sleep disturbance due to vibrations as persons in the first quartile group.

Table 8.2 The relationship between maximum exposure to vibrations from railway traffic (expressed in V_{max}) and high sleep disturbance due to vibrations from railway traffic

Variable	**High sleep disturbance due to vibrations from total railway traffic OR (95% CI)**	**High sleep disturbance due to vibrations from passing passenger trains OR (95% CI)**	**High sleep disturbance due to vibrations from passing freight trains OR (95% CI)**
Maximum exposure (V_{max}) ‡			
Quartile 1	*Ref*	*Ref*	*Ref*
Quartile 2	0.62 (0.28-1.36)	1.42 (0.67-3.02)	0.64 (0.29-1.38)
Quartile 3	2.43 (0.93-6.34)	2.91 (1.29-6.55)*	0.93 (0.35-2.49)
Quartile 4	0.86 (0.38-1.95)	0.96 (0.39-2.36)	0.86 (0.37-1.99)
Fraction of freight trains %[a]			
Quartile 1	*Ref*	*Ref*	*Ref*
Quartile 2	0.81 (0.20-3.31)	0.70 (0.24-2.03)	1.45 (0.44-4.8)
Quartile 3	1.58 (0.28-8.88)	1.14 (0.26-4.96)	2.95 (0.75-11.55)
Quartile 4	0.30 (0.03-3.16)	0.37 (0.06-2.2)	2.39 (0.39-14.79)
Night train ratio (%)[b]			
Tertile 1	*Ref*	*Ref*	*Ref*
Tertile 2	1.18 (0.34-4.11)	1.25 (0.36-4.36)	0.46 (0.15-1.43)
Tertile 3	2.72 (0.31-23.66)	1.82 (0.38-8.77)	0.45 (0.09-2.376)
Gender			
Men	*Ref*	*Ref*	*Ref*
Women	2.33 (1.17-4.64)*	0.61 (0.34-1.1)	2.23 (1.22-4.06)*
Age class			
16-44 years	*Ref*	*Ref*	*Ref*
45-64 years	0.82 (0.34-1.95)	1.64 (0.93-2.88)	0.95 (0.42-2.13)
65 and over	0.46 (0.16-1.33)	0.40 (0.19-0.86)*	0.85 (0.33-2.15)
Education			
None/lower education	0.82 (0.19-3.59)	0.41 (0.05-3.02)	4.62 (0.89-24.08)
Lower general secondary/lower vocational	1.15 (0.52-2.56)	1.40 (0.67-2.94)	1.61 (0.51-5.13)
Higher general secondary/pre-university/ senior secondary	*Ref*	*Ref*	*Ref*

Variable	High sleep disturbance due to vibrations from total railway traffic OR (95% CI)	High sleep disturbance due to vibrations from passing passenger trains OR (95% CI)	High sleep disturbance due to vibrations from passing freight trains OR (95% CI)
vocational **Higher professional/university**	 0.93 (0.44-1.94)	 0.59 (0.32-1.09)	 1.20 (0.64-2.27)
Urbanisation[c] **Extremely urbanised** **Highly urbanised** **Moderately urbanised** **Hardly urbanised** **Not urbanised**	 1.78 (0.79-3.99) 2.86 (1.23-6.65)* 2.73 (1.16-6.43)* 3.16 (0.93-10.75) *Ref*	 0.80 (0.34-1.9) 1.09 (0.45-2.61) 1.14 (0.44-2.93) 0.50 (0.21-1.21) *Ref*	 0.55 (0.2-1.52) 1.10 (0.48-2.53) 0.96 (0.4-2.33) 0.68 (0.22-2.08) *Ref*
Noise level from railway traffic (L_{night}) in dB(A)	0.97 (0.93-1)	1.0 (0.97-1.04)	1.01 (0.98-1.04)
High sleep disturbance due to noise **Total railway traffic** **Passenger trains** **Freight trains**	 43.76 (19.29-99.27)* - -	 - 55.13 (26.27-115.687)* -	 - - 19.78 (7.45-52.55)*
Hearing, feeling, seeing windows, doors and/or crockery ('rattle')	1.30 (0.64-2.66)	1.51 (0.68-3.34)	1.81 (0.99-3.29)
Concerns about: **Loss of property value** **Health effects of vibrations** **Property damage**	 1.11 (0.49-2.53) 2.66 (1.10-6.45)* 2.02 (0.83-4.90)	 2.10 (1.11-3.96)* 1.41 (0.72-2.78) 1.22 (0.48-3.12)	 1.81 (0.82-3.97) 1.57 (0.64-3.85) 1.90 (0.95-3.83)
Negative attitude towards: **Current railway policy for railway zones**	 0.14 (0.03-0.70)*	 0.47 (0.09-2.46)	 0.9 (0.28-2.87)
Plans to increase railway traffic in some parts of the Netherlands	1.41 (0.50-3.97)	1.77 (0.54-5.82)	1.45 (0.55-3.78)
Vibrations from railway traffic	4.21 (1.73-10.28)*	3.56 (1.59-57.97)*	3.07 (1.68-5.6)*

Variable	High sleep disturbance due to vibrations from total railway traffic OR (95% CI)	High sleep disturbance due to vibrations from passing passenger trains OR (95% CI)	High sleep disturbance due to vibrations from passing freight trains OR (95% CI)
are (highly) unacceptable			
Expect decline due to vibrations from railway traffic	2.02 (1.06-3.82)*	0.62 (0.30-1.28)	1.87 (1.01-3.48)*
Location of bedroom:			
Ground floor up to 2nd floor	*Ref*	*Ref*	*Ref*
3rd floor or higher	1.04 (0.39-2.77)	3.14 (1.37-7.17)*	0.39 (0.08-1.91)
Windows open/closed			
Closed (always)	*Ref*	*Ref*	*Ref*
Closed (in summer or winter)	2.67 (1.23-5.79)*	4.3 (2.18-8.49)*	1.22 (0.53-2.78)
Open (in summer and winter)	1.03 (0.54-1.97)	1.22 (0.64-2.36)	0.76 (0.37-1.55)
HE glazing in bedroom			
No	*Ref*	*Ref*	*Ref*
Yes	1.71 (0.92-3.19)	0.86 (0.47-1.6)	1.56 (0.84-2.88)
Don't know	2.24 (0.78-6.46)	2.49 (0.95-6.56)	1.88 (0.73-4.85)

Abbreviations: Ref=reference group, OR=Odds Ratio, 95% CI=95% confidence interval, L_{night}=night level, *=statistically significant. HE=high-efficiency glazing

a) Categories based on quartiles;

b) Categories based on tertiles;

c) Degree of urbanisation is a measure for concentration of human activity based on average local address density (LAD), expressed in number of addresses per km^2. The following degrees of urbanisation are distinguished: not urbanised (average LAD <500), hardly urbanised (average LAD 500-1000), moderately urbanised (average LAD 1000-1,500), highly urbanised (average LAD 1500-2,500) and extremely urbanised (average LAD >2500);

* Statistically significant (p<0.05)

9 Discussion

In this study we focused on the influence of exposure to railway-induced vibrations on people in the Netherlands aged 16 and over living within 300 metres of a railway line. This chapter discusses the most important results of the study based on the research questions. We will also zoom in on a number of aspects that are relevant to the interpretation of our findings, such as the strengths and weaknesses of the study, any findings from other studies and the significance of the results for policy. We will then use that as a basis for formulating several recommendations.

9.1 Answering the research questions

In this section we will answer the four research questions.

9.1.1 What is the extent of high annoyance and high sleep disturbance due to vibrations from railway traffic among the Dutch population?

The survey area of the Follow-up Study has an estimated population of over 1.1 million, who live in approximately 533,000 dwellings. Zones in the vicinity of railway bridges, tunnels and major stations with many parallel tracks have been excluded.

High annoyance
Based on the Follow-up Study, it is estimated that around 11% of the population of the Netherlands aged 16 and over who live within 300 metres of a railway line (excluding zones in the vicinity of railway bridges, tunnels and major stations with many parallel tracks) experience high annoyance due to vibrations from railway traffic. This amounts to an estimated 126,500 persons.

If we consider different sources of railway-induced vibration, vibrations from freight trains appear to be the largest source of annoyance. Based on the survey of the Follow-Up Study, it is estimated that in 2021 approximately 22.6% of the Dutch population living within 300 metres of a railway line (excluding areas in the vicinity of railway bridges, tunnels and major stations with many parallel tracks) experienced high annoyance due to vibrations from freight trains. The percentage of people reporting high annoyance due to vibrations from passenger trains, estimated at 8%, is low compared with the percentage for freight trains.

High sleep disturbance
Based on the results of the Follow-up Study, it is estimated that in 2021 around 13% of Dutch population aged 16 and over who live within 300 metres of a railway line (excluding zones in the vicinity of railway bridges, tunnels and major stations with many parallel tracks) experience high sleep disturbance due to vibrations from railway traffic.

The amount of sleep disturbance caused by vibrations from sources other than railway traffic was also measured as part of the Follow-Up Study. Railway traffic was the main source of vibration-induced sleep disturbance among people in the Netherlands aged 16 and over who live within 300 metres of a railway line (excluding zones in the vicinity of railway bridges, tunnels and major stations with many parallel tracks).

As regards the different sources of railway-induced vibration involved, we found that vibrations caused by freight trains are responsible for the most sleep disturbance. Based on the survey of the Follow-up Study, it is estimated that in 2021 around 18% of the Dutch population aged 16 and over who live within 300 metres of a railway line (excluding zones near railway bridges, tunnels and major stations with many parallel tracks) experience high sleep disturbance due to vibrations from freight trains. Based on the Follow-Up Study, the prevalence of high sleep disturbance due to vibrations from passenger trains is estimated at 6%.

Comparison with the 2013 study
The results of the Follow-up Study are in agreement with the results of the 2013 survey. Same as in 2013, freight trains were by far the most important source of annoyance. Furthermore, the prevalence of high annoyance due to vibrations from passenger trains was low compared with the prevalence of high annoyance due to freight trains both in the current study and the 2013 study. The picture for high sleep disturbance is similar.

As pointed out in Chapter 5, the results of the Follow-Up Study cannot be fully compared with those of the 2013 study because addresses in the vicinity of railway bridges, sunken tracks and stations with many parallel tracks were excluded from the Follow-Up Study. These addresses were included in 2013 [11]. We have tried to determine the extent to which the prevalence of high annoyance due to vibrations from railway traffic reported in 2013 was influenced by the inclusion or elimination of those exclusion zones. The result is presented in Table 9.1, which shows that in 2013 the prevalence of high annoyance among persons living inside an exclusion zone was lower than the prevalence among persons living outside any exclusion zones. The prevalence of high annoyance due to vibrations from railway traffic among persons aged 16 and over who live within 300 metres of a railway line (excluding the exclusion zones) is estimated to be 11.0% in 2021 (95% confidence interval: 9.6 – 13.5%). If areas in the vicinity of railway bridges, sunken tracks and stations with many parallel tracks had also been excluded in 2013, the overall prevalence of high annoyance due to vibrations from railway traffic would have been an estimated 20.3% instead of the 19.5% now reported. These sampling difference between 2013 and 2021 resulted in a slightly different study area. However, this cannot fully explain the observed differences between 2013 and 2021 in the prevalence of high annoyance and sleep disturbance due to railway-induced vibrations. Indeed, the actual differences in prevalence between 2013 and 2021 even appear to be slightly greater.

Table 9.1 The percentage of high annoyance due to vibrations from railway traffic (including the 95% confidence interval) among persons aged 16 and over in the 2013 study area

	% high annoyance due to vibrations from railway traffic in 2013	**95% CI**	
Only exclusion zones[a]	16.1	10.7	21.4
Total study area[a] ***without* exclusion zones**	20.3	17.3	23.3
Total study area (*with* exclusion zones)[b]	19.5	16.9	22.1

Abbreviations: 95% CI=95% confidence interval

[a] These are zones up to 300 metres of a railway line in the vicinity of railway bridges, sunken tracks and stations with many parallel tracks.

[b] As reported in Van Kamp et al.[11].

Besides the similarities described above, we also observed a major difference between the results of the Follow-Up Study and the 2013 study. In both studies, the amount of annoyance due to vibrations from sources other than railway traffic was also measured and unlike the situation in 2013, the Follow-Up Study found that railway traffic was no longer the main source of vibration-induced annoyance among the Dutch population aged 16 and over who live within 300 metres of a railway line (excluding zones near railway bridges, tunnels and major stations with many parallel tracks). In 2021, vibrations due to road traffic and construction work were the main source of annoyance. However, railway traffic did emerge as the main source of *sleep disturbance* due to vibrations in the study area compared with a number of other sources.

The finding that in 2021 railway traffic was no longer the main source of vibration-induced annoyance among the Dutch population of 16 and over living within 300 metres of a railway line could be explained by the fact that the Follow-Up Study was conducted during the COVID-19 pandemic (also see section 9.2.2).

9.1.2 *Which vibration exposure indicator is the most suitable for predicting annoyance and/or sleep disturbance due to vibrations from railway traffic?*

To determine which exposure indicator is the most suitable for predicting high annoyance and high sleep disturbance from railway traffic, we examined various indicators for exposure to vibrations from railway traffic. For this purpose, we created several predictive models based on various types of exposure. We then compared those models with each other based on their model fit (how well the model matches the underlying data) and model accuracy (how accurate the model can predict annoyance or sleep disturbance). Finally, we looked at the correlations between the various measures.

We found strong correlations between indicators of maximum (V_{max}) and average vibration levels (RMS, V_{per}). The differences between the predictive models based on these indicators were small as regards the accuracy of the models. This means that a prediction of the number of persons experiencing annoyance or sleep disturbance based on any of the tested exposure indicators (such as V_{max}) is about as accurate as a prediction based on any of the other exposure indicators (such as V_{per} or RMS). However, differences do emerge when we look at fit of the different models. Although the differences between exposure indicators with and without ISO weighting were small, those *without* ISO weighting have a better fit with the data on which the model is based. This means that the hypothesis underlying such weighting (i.e., an exposure indicator subjected to directional frequency weighting according to ISO 2631 corresponds more closely with people's perception of vibrations) must be rejected. Indeed, it also appears that ISO weighting actually reduces the predictive strength of the models.

The differences in fit between models based on V_{max}, V_{per} and RMS (all without ISO weighting) are small for both annoyance and sleep disturbance. Only for high annoyance due to vibrations from freight trains does distance from the railway line give a substantially better fit than the other indicators studied. Strikingly though, the accuracy in that case is lower.

The findings of the Follow-Up Study are in line with the conclusions of other studies [21, 28, 81] that attempted to identify the most suitable indicator and establish whether the choice of frequency weighting method makes any difference. In those studies, as in the Follow-Up Study, the exposure indicators subjected to ISO weighting were not found to be better predictors of annoyance than the exposure indicators subjected to other frequency weighting methods. In addition, the various exposure indicators were consistently strongly correlated to each other. Statistical analysis did not yield any particular indicator that was clearly preferable to the others. The 2013 study also examined several different vibration exposure indicators. As in 2021, the strong mutual correlation in the 2013 study made it difficult to identify potential differences between the effects of those indicators on reported levels of annoyance or sleep disturbance [11].

9.1.3 *What dose-response relationships can be derived for (high) annoyance and (high) sleep disturbance due to vibrations from railway traffic and exposure to vibrations from railway traffic (passenger trains versus freight trains)?*

High annoyance

For both total railway traffic and freight trains, we found a clear DR relationship between calculated exposure to vibrations and the percentage of people experiencing high annoyance due to vibrations from different sources of railway-induced vibrations. The percentage of persons reporting high annoyance due to railway-induced vibrations increases as the level of exposure to these vibrations increases. These DR relationships were less pronounced for passenger trains.

High sleep disturbance

We also established DR relationships between calculated exposure to vibrations and the percentage of people experiencing high sleep disturbance due to these vibrations. The percentage of persons reporting high sleep disturbance due to railway-induced vibrations increases as the level of exposure to these vibrations increases. As with annoyance, the DR-relationships were strongest for freight trains. The DR relationships between exposure to vibrations from passenger trains and high sleep disturbance were less pronounced.

Type of DR relationship

The relationship between exposure and response is not always linear. If the method used for establishing DR relationships always assumes a linear relationship between dose and response, this may result in unreliable DR relationship. In the analyses we used two different methods to establish DR relationships: logistic regression with a continuous exposure and with a categorical exposure. Whereas logistic regression models with a continuous exposure can describe a linear relationship, a logistic regression with a categorical exposure can describe both linear and non-linear relationships. The analyses in this rapport showed that in most cases, the categorical model had a better model fit than the continuous model. Furthermore, the DR-relationship curves of the continuous and categorical models differed, particularly in the higher exposure range. This outcome suggests that the relationship between exposure to vibrations and high annoyance and/or sleep disturbance is not linear.

Comparison with 2013

We also compared the results of the Follow-up Study with the results of the 2013 study [11]. A comparison of the DR relationships between exposure to railway-induced vibration and high annoyance due to vibrations shows that at equal vibration levels, the probability of high annoyance was generally lower in 2021 than it was in 2013.

However, the situation is different for high sleep disturbance. Comparing the 2013 and 2021 DR relationships between railway-induced vibrations and high sleep disturbance due to vibrations from railway shows that for equal vibration levels, the probability of high sleep disturbance due to vibrations was generally *higher* in 2021 than in 2013.

As possible explanation for the observed difference between the Follow-Up Study and the 2013 study is the effect of eliminating addresses located in the exclusion zones. Section 9.1.1 discusses the potential effect of this elimination on estimated prevalence. We did not study the effect of eliminating participants living in the exclusion zones on the DR relationships of 2013.

However, the addresses of participants in the 2013 survey outside the exclusion zones were on average closer to a railway line than addresses of participants within the exclusion zones. This is a result of the way the exclusion zones are determined, as illustrated in Figure 9.1 on the basis of an exclusion zone (yellow) around a bridge (pink). All dwellings within the yellow line are located in an exclusion zone and were therefore left out of the Follow-Up Study. The vibrations caused by trains crossing the bridge have an effect on the dwellings within the exclusion zone.
The shape and size of the exclusion zone is explained by the fact that the effect of the bridge on the vibration exposure of further away dwellings is minimal. Outside the exclusion zone this relationship is different. So away from the bridge there is less exclusion near the railway line.

Figure 9.1 Example of determining an exclusion zone (yellow area) near a bridge (pink). The two red parallel lines indicate the tracks. The two distances to the left and right of the tracks are 50 and 100 metres (i.e. approximately 25 and 50 metres from the tracks).

The participants in the 2013 survey whose addresses were not located in an exclusion zone lived on average closer to a railway line. We therefore expect to find slightly higher exposure levels for those participants than for participants at addresses within an exclusion zone. The DR relationships derived on the basis of the 2013 survey data are therefore likely to be somewhat steeper after removing the participants living in the exclusion zones.

9.1.4 *How do physical, contextual and personal factors influence high annoyance and high sleep disturbance due to vibrations from railway traffic?*

High annoyance

The analyses show that, besides exposure to railway-induced *vibrations*, annoyance due to *noise* produced by railway traffic affects the reported levels of annoyance due to railway-induced vibrations.

In addition, social and personal factors play an important role. These factors involve concerns regarding a decrease in property value and/or property damage, hearing, feeling or seeing windows, doors or crockery (‘rattle’), acceptance of vibrations and expectations regarding railway-induced vibrations in the future.

Socio-demographic factors such as age, gender, level of education and degree of urbanisation were found to be of minor influence on the reported levels of annoyance due to railway-induced vibrations.

Exposure to noise produced by railway traffic (L_{den}) only proved to be associated with high annoyance due to railway-induced vibrations from the different railway sources after exclusion of high annoyance due to the noise of the corresponding source .

After adjustment for potentially confounding factors, we found that people report more high annoyance due to vibrations from total railway traffic and freight trains as their exposure to vibration levels (expressed as V_{max}, V_{per} or RMS) increases or their distance from the railway line decreases. After adjustment for potentially confounding factors, we found that people do *not* report more high annoyance due to vibrations from passenger trains as their exposure to vibration levels (expressed as V_{max}, V_{per} or RMS) increases or their distance from the railway line decreases.

High sleep disturbance

High sleep disturbance due to *noise* produced by railway traffic heavily affects the reported levels of sleep disturbance due to railway-induced vibrations.

Several social and personal factors are also associated with high sleep disturbance. This mainly concerns factors related to acceptance of vibrations from railway traffic, expectations regarding such vibrations and concerns about loss of property value, potential property damage and potential negative health effects of vibrations. Hearing, feeling or seeing windows, doors or crockery rattle and a negative attitude toward plans to increase railway traffic in some parts of the Netherlands are positively associated with severe annoyance due to train-related vibrations, but none of those associations were found to be statistically significant.

Socio-demographic factors, such as age, gender and level of education, were found to be of little influence on the reported levels of sleep disturbance due to railway-induced vibration. Degree of urbanisation only appeared to influence the reported levels of high sleep disturbance due to vibrations from total railway traffic. We also found that women are more likely than men to report high sleep disturbance due to vibrations from total railway traffic and freight trains.

The results as regards to the location of the bedroom were ambiguous: persons whose bedroom is located on the third floor or higher are more likely to experience sleep disturbance due to vibrations from total railway traffic and passenger trains, but less high sleep disturbance due to vibrations from freight trains, compared persons whose bedroom is located on the first floor or ground floor. Finally, associations were also found between high sleep disturbance and closing or opening windows in summer and/or winter.

Exposure to night-time noise produced by railway traffic (L_{night}) only proved to be associated with high sleep disturbance due to railway-induced vibrations after exclusion of high sleep disturbance due to the noise of the railway traffic.

After adjustment for potentially confounding factors, we found that people who fall into the second or third quartiles for exposure to vibrations (expressed as V_{max}, $V_{per\ night}$ or RMS_{night}) report more high sleep disturbance due to vibrations from passenger trains than their counterparts in the first quartile. However, this was only statistically significant for the difference between the first and the third quartile. For both total railway traffic and freight trains, persons who are exposed to higher vibration levels (expressed as V_{max}, $V_{per\ night}$ or RMS_{night}) are not more likely to report high sleep disturbance due to railway-induced vibrations from either of these sources.

9.2 Strengths and weaknesses of the Follow-Up Study

9.2.1 *Strengths*

Sample size

To answer the research questions of the Follow-Up Study, we conducted a survey. The main benefit of this approach is that it offers a relatively simple method for approaching and questioning a large group of people about a very wide range of aspects of their perception of railway-induced vibrations and health. Thanks to its size, the survey makes it possible to formulate statements with sufficient statistical power about experienced levels of annoyance, sleep disturbance and other health aspects potentially associated with railway-induced vibrations.

Sampling method

While selecting our participants we took into account the address distribution across the various exposure classes. Since it was impossible to estimate exposure to vibrations in advance, we used a combination of distance from the railway line and building year as a proxy. This was found to be an effective sampling method, both in the Follow-Up Study and in the 2013 study. Moreover, research has shown that the construction of the dwelling, the foundation technique and its structural condition are important predictors of vibration exposure. For example, the study by Öhrström and Skånberg [45] found that persons who lived in houses with a wooden structure were more likely to experience vibration-induced annoyance than persons of houses with a concrete structure. A house built without a proper foundation will vibrate with the soil, but a building with foundation beams anchored in concrete piles will vibrate much less. As a proxy for the structure of a building and its structural condition, we used the building year of the participants' dwelling. Distance from the railway line is relevant as regards to the transfer of vibrations from source to recipient. The influence of vibrations decreases as the distance from the vibration source increases.

Use of an improved model
For the purpose of the Follow-Up Study, we used the OURS model to determine exposure to railway-induced vibrations. In contrast, the 2013 study based exposure on the SRM-t model. One key difference between these two models is the underlying data they use to estimate exposure. In addition, OURS uses a different calculation method. See Van Kamp et al.[19] for an overview of the differences between the two models. In the calculation of the vibration exposure, assumptions were made and choices were made (sometimes for practical reasons).This means that there may be discrepancies between the calculated and the actual exposure for each individual address. These discrepancies are caused by variations in floor characteristics, building structures, train types, railway construction etc. Since the SRM-t model mainly uses standard values and less detailed input data than the OURS model, we expect that the discrepancies between exposure estimated using SRM-t and the actual exposure values are larger than those using OURS. A previous comparison had already shown that OURS yields lower vibration levels than the SRM-t model [19]. Those lower values more closely reflect the range of measured values found in other vibration studies. In other words, for the Follow-Up Study we have been able to use a more suitable exposure model than for the 2013 study. The OURS model offered the added advantage of being capable of calculating more exposure parameters. One good example of that is the calculation of exposure indicators with and without ISO 2631 weighting. In addition, the OURS model was capable of estimating average exposure (expressed as V_{per} or RMS) for different parts of the day. This was not possible with the SRM-t model.

Type of ER relationship
To build the ER relationships, we used methods that are capable of describing both linear (logistic regression with continuous outcomes) and non-linear (logistic regression with categorical outcomes) relationships. The use of exposure as a categorical variable generally yielded the strongest relationship with the best fit, which suggests a non-linear relationship between exposure and response. This is further suggested by the curves of the ER relationships. At high exposure levels, the categorical models predict more high annoyance or sleep disturbance than the continuous models. Therefore, non-linear effects must be considered when establishing ER relationships. If it is taken for granted that the relationship between exposure to vibrations and annoyance or sleep disturbance is linear, resulting in the choice for a specific method that is only capable of describing linear relationships, this may lead to an underestimation of risk at higher exposure levels.

9.2.2 *Weaknesses*

However, the present study also has several limitations which will be addressed in the following sections.

Potentially selective non-response

Over the past decades, overall willingness to take part in surveys has decreased. This is reflected in a persistent decline in response rates. The present study (Group I) achieved a response rate of 30%, which is slightly lower than the 32% achieved during the 2013 study. Although we have used population weighting methods to minimise the influence of differences in composition between the respondent group and the study area population, the results should still be interpreted while considering the potential differences between the research group and the population of the study area.

The possible influence of selective non-response on the study results should also be taken in account. Selective non-response occurs when, specific groups are under- or overrepresented in the study because these groups are more or less likely to participate in the study. If the outcome-related behaviour in these groups are markedly different from the total population, this will bias the outcomes of the study and result in estimates that are systematically too high or too low.

The separate study among non-respondents demonstrated that their non-response was not arbitrary. For example, the annoyance score among participants of the study was higher than among the participants of non-respondent study. Therefore, the participants of the study are not entirely representative of the total population of the study area, potentially resulting in a slight bias of the outcomes. This should be taken in into account when considering the percentages of high annoyance and sleep disturbance reported in the current study. Unfortunately, due to the low response rate of the non-response survey (19%), it is not possible to reliably weigh the overall outcomes for the influence of selective non-response.

The COVID-19 pandemic

We conducted the Follow-up Study in the fall of 2021 during the COVID-19 pandemic. This was a period in which the Dutch government took a large number of measures that were intended to curb the spread of the coronavirus. Those measures affected the timetables for passenger trains. The annual reports of the Dutch railway operator NS (Dutch Railways) show that the company introduced a basic timetable in March 2020, with fewer train services during peak-hours. A minimal service of two trains per hour in both directions from each station was implemented. Although the trains services where scaled up again through the year, the services was again reduced in October 2020 to approximately 90% of regular capacity. This continued into the first months of 2021, during which the Netherlands was in a COVID-19 lockdown. Starting from late April 2021, the lockdown measures were relaxed and the NS gradually increased train frequences again and returned to full capacity by August 2021. This included the additional trains are deployed during alleviate peak-hour demand. Starting from December 2021, the NS temporarily operated fewer trains in the evening, during the night and at peak hours, and the regular evening timetable began two hours earlier [109, 110].

Compared with passenger transport by rail, freight transport by rail was little affected directly by COVID-19 measures. However, the impact of the pandemic did influence the number of freight trains operated in the Dutch railway network. It is important to note that although the introduction of the basic timetable opened up additional space on the railway network due to a reduced number of passenger trains, this space was not used to operate additional freight trains.

A number of factors should be considered regarding the impact of COVID-19 measures on freight transport. First, after Italy went into full lockdown the number of container trains (specific freight trains which transport shipping containers from harbours to the hinterland) to Italy was reduced from six to five shuttles a week to Italy and back. Second, the lockdown also reduced the supply of shipping containers from China. In addition to that, the lockdown in China also caused stagnation in the supply of car manufacturing parts, as a result of which car factories all over Europe ground to a halt. This then resulted in cancellation of freight trains needed to transport car parts and completed cars. As steel is a key material in car production, the number of trains carrying steel also decreased. Freight transport by rail showed a marked recovery in 2021. Despite the fact that the Netherlands and other parts of Europe continued to see lockdowns in 2021, the economy was running at full speed and there were no situations in which production in one or more industrial sectors came to a complete standstill. As a result, the amount of freight transport by rail was greater in 2021 than it was in 2020. For example, the number of freight trains crossing the Dutch-Germany border increased by 7% compared with 2020, and by 3% compared with the pre-COVID-19 period. Likewise, the number of freight trains to and from Rotterdam (the largest generator of freight traffic in the Netherlands due to the Port of Rotterdam) was up 10% in 2021 compared with 2020 and 6% compared with 2019. In contrast, freight traffic at the Dutch-Belgian border decreased by 7% compared to 2020 and 10% compared to 2019 [111-115].

Therefore, we are under the impression that the levels of vibrations from railway traffic changed very little during the study as a result of the COVID-19 pandemic. This is reflected in the results of the Follow-Up Study, as the majority of the participants (84%) said they did not experience any change in either vibrations or noise from railway traffic as a result of the COVID-19 pandemic (also see Figure 9.2). Over 8% of participants even experienced an *increase* in vibrations from railway traffic as a result of the COVID-19 pandemic. The same picture emerges for train-related noise.

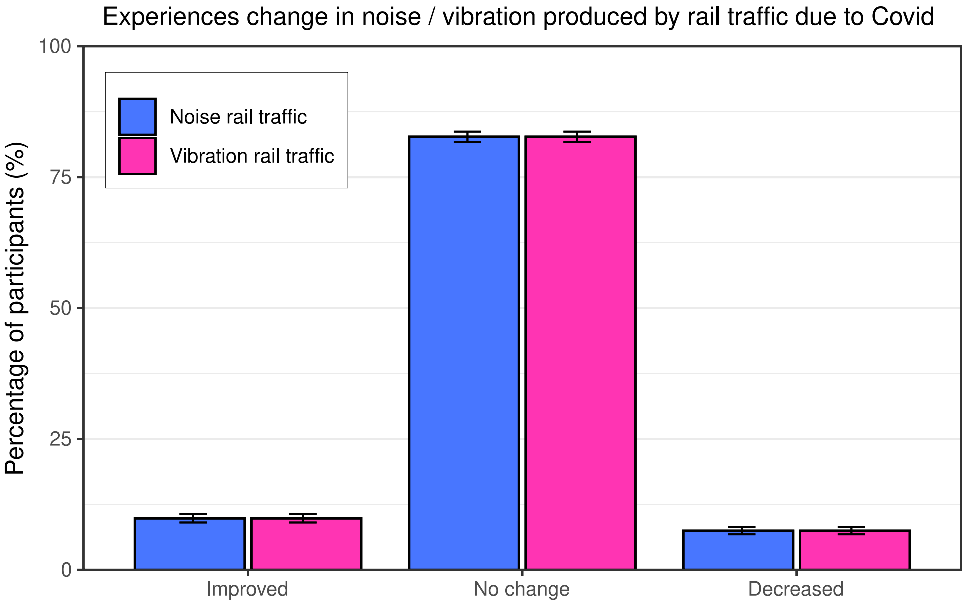

Figure 9.2 Percentages of participants in the Follow-Up Study (N=5,611) indicating changes in their experience of noise and vibrations from railway traffic as a result of the COVID-19 pandemic.

Another factor to consider regarding the impact of the COVID-19 pandemic on railway traffic is that the amount of persons using the trains reduced. Persons spent more time working from home and in addition also relied more on their immediate living environment (e.g. visit local park) than before the pandemic [116]. There are indications that this influenced people's attitudes towards modes of transport, such as trains. Since the outbreak of the pandemic, attitudes towards trains have become more negative and existing positive attitudes towards cars have become slightly more positive. Over the 2014-2018 period, attitudes towards trains were very stable [117, 118]. In addition, the changes in travel behaviour and people's increased reliance on their immediate living environment may have influenced the amount of annoyance and sleep disturbance reported. A national perception survey has shown that during the COVID-19 pandemic, different sources were responsible for annoyance due to noise and vibrations than before the COVID-19 pandemic [119, 120]. Similar results are seen in Follow-up Study, since railway traffic was no longer the principal source of vibration-induced annoyance among the Dutch population aged 16 and over who live within 300 metres of a railway line (excluding zones near railway bridges, tunnels and major stations with many parallel track). Instead, vibrations caused by road traffic and construction work were the main source of annoyance. For high sleep disturbance the pattern is different. The Follow-Up Study showed that railway traffic is the main source of vibration-induced sleep disturbance among people in the Netherlands aged 16 and over who live within 300 metres of a railway line.

Given that the COVID-19 pandemic occurred before and during the field work phase of the Follow-Up Study, there may have been a so-called “change” situation. Research into the relationship between noise and annoyance has shown that when there are changes in environmental noise, people tend to respond more strongly than could be expected based on the existing DR relationships [84, 121]. Incidentally, the opposite is also possible: sometimes people respond much *less* strongly than could be expected based on the applicable DR relationships. This "change" situation can therefore also affect DR relationships based on these outcomes.

Unfortunately, it was not possible to study the extent to which the COVID-19 pandemic affected the relationship between exposure to vibrations and high annoyance or sleep disturbance due to railway traffic. On the other hand, it is important to note that the 2013 study also took place during a period of "change": The Bts was introduced shortly before the 2013 study was conducted, and there were scheduled increases in railway traffic as part of the High-Frequency Rail Transport Programme ("Programma Hoogfrequent spoor" of PHS). These circumstances may have caused people to report more annoyance or sleep disturbance in 2013 but this was not studied.

9.3 Significance for policy: usability of the results

9.3.1 The choice for an exposure indicator

As part of the Follow-up Study, we also studied various vibration exposure indicators: one indicator for maximum exposure, and indicators for average exposure with due regard for the number of trains and/or train length. However, the analyses provide no certainty as to which of those indicators is the most suitable to predict high annoyance and high sleep disturbance. This could suggest that different indicators for exposure to vibrations with various annoyance specifications and limit values offer similar degrees of protection ([21] in [11]). However, a sharp increase in the number of trains or an increase in the duration of train passages (as trains are getting longer) will have a marked effect on some indicators (such as RMS) and a small effect on other indicators (V_{max}). Theoretically, V_{max} could therefore be regarded as a good indicator of the perceptibility of vibrations, while RMS is probably a better annoyance indicator. This could explain why in the Follow-Up Study, V_{max} is slightly better than the other indicators in predicting vibration-induced sleep disturbance, while distance and RMS are better at predicting vibration-induced annoyance. The choice for using a particular indicator depends on the answers to questions such as: What is the indicator intended to assess: the perceptibility of vibrations or the level of annoyance? And to what extent should the effect of night-time exposure be taken into account, according to policymakers?

The limit values and target values in the existing regulations (Bts and SBR) were calculated without ISO weighting. It seems undesirable to use ISO weighting for any new standards to be developed. As seen in the current study, exposure indicators *without* ISO 2631 weighting were better at predicting both annoyance and sleep disturbance due to vibrations from railway traffic. Similar findings emerged from earlier studies [28].

9.3.2 *Application of DR relationships: estimating the magnitude of the problem*

The findings of the current study could be used to estimate the seriousness and impact of railway-induced vibrations compared with other transport-related issues such as air pollution and noise. The results can also provide starting points for estimating the costs and benefits of measures to be taken, aimed at reducing the health effects of railway-induced vibrations. However, such estimates can only be made at population level as the application of DR relationships on individual dwellings, persons or specific sections of railway lines is problematic.

In order to produce estimates of, for example, the reduction in the numbers of people experiencing annoyance and/or sleep disturbance achieved by (policy) measures, several steps have to be made. A full description of those steps is beyond the scope of this report. For a detailed overview of the required steps, see Chapter 5.2 of Van Kamp et al. [11]. In short, the steps needed to produce estimates are a) the SE relationship between vibration exposure and high annoyance and/or sleep disturbance due to railway-induced vibration, and b) the distribution across levels of vibration due to railway traffic.

Re a) Several DR relationships were derived in Chapter 7 that describe the association between exposure to vibrations from various sources of railway-induced vibration and the percentage of high annoyance or sleep disturbance due to these vibrations. In principle, all DR relationships derived in this study can be used to estimate the extent of high annoyance and sleep disturbance due to vibrations from total railway traffic, freight trains and passenger trains. However, it would be preferred to use the DR-relationships which: i) express vibration exposure in terms of distance from the railway line (m), or ii) express vibration exposure in an indicator not subjected to ISO 2631 weighting. The relationship between exposure to railway-induced and high annoyance or sleep disturbance was in most cases, non-linear. Where this is the case, it is therefore preferable to use DR relationships based on the categorical models.

Re b) There are certain aspects to consider regarding the distribution of the population across the levels of vibrations from railway traffic. For the purpose of the Follow-Up Study, exposure to railway-induced vibrations was estimated using the OURS model. In principle, that model can be used to estimate exposure to railway-induced vibrations of *all* dwellings, unless in the absence of soundings. However, the question is whether the results for all dwellings are sufficiently accurate. It is especially difficult to produce sufficiently reliable estimates for dwellings in the vicinity of railway bridges, sunken tracks and major stations with many parallel tracks. For this reasons, those areas were considered exclusion zones in the study. However, in many cases an individual assessment of each address in the exclusion zones does tend to produce a reliable estimate of its exposure. This is however a time-consuming process, as every railway bridge or sunken track section has its own characteristics that potentially requires detailed modelling or even further research per individual site.

9.3.3 *The role of co-determinants*

In the Follow-Up Study we identified additional factors, other than exposure to railway-induced vibrations, that influence reported levels of annoyance and sleep disturbance due to railway-induced vibrations. It's important to note that only the extent to which co-determinants were associated with reported annoyance and sleep disturbance due to railway-induced vibrations was investigated.

We found that the identified associations between vibration exposure and high annoyance and sleep disturbance (as seen in the DR relationships) became weaker and sometimes disappeared altogether after additional adjustment for co-determinants. The cause of these results is however unclear. We did not investigate whether this might be due to effect modification and/or confounding by the various co-determinants. For example, no investigation was performed to see whether the association between vibration exposure and high annoyance due to railway-induced vibrations is different for persons with a negative attitude versus those with a positive attitude (effect modification).

A key finding was the strong association between annoyance and sleep disturbance by noise produced by railway traffic and high annoyance and high sleep disturbance by railway-induced vibrations. Moreover, we found that exposure to noise had a positive association with both reported annoyance and reported sleep disturbance due to vibrations (after eliminating high annoyance or sleep disturbance due to train noise). However, based on the results of the Follow-Up Study and other studies [25, 45-47] it is impossible to determine whether this was due to possible cumulation (noise amplifying the effect of vibrations) or masking effects. This requires further in-depth analysis.

While there were many similarities between the results of the Follow-Up Study and those of the 2013 study, there were also several differences. Those differences could be, among other things, attributed to co-determinants. Although the sites and research methods were fairly similar between the Follow-Up study and the 2013 study, it should be noted that the two measurements were eight years apart. Studies into the relationship between aircraft noise and annoyance have taught us that the role of co-determinants can vary significantly depending on population, location and time - as illustrated, for example, by Smetsers et al. [122]. A similar effect might be at play in connection with annoyance and/or sleep disturbance due to railway-induced vibrations.

More research into the role of co-determinants in annoyance by railway-induced vibration could give further insight. One complicating factor is that the connections and interactions between exposure to railway-induced vibrations, co-determinants and annoyance due to railway-induced vibrations are not clear. Persons living near a railway line may experience high annoyance due railway-induced vibration and, for that reason, may also have developed a negative attitude. It is not possible to establish causal relationships in a cross-sectional study (one-off measurement).

In addition, co-determinants themselves may be closely interrelated. This means that we should not ignore co-determinants that have a weak effect on annoyance or are difficult to influence (less modifiable). This can be illustrated by an example from the field of environmental noise research [82]: ‘Although aviation generates long-term economic and social benefits across the globe, it is the local residents who mainly experience the negative effects of environmental noise. This contributes to a general sense of injustice. While the influence of this factor on the level of annoyance may be less pronounced, it is also related to other factors, such as “perceived control”. Perceived control has a significant influence on the level of annoyance and, on top of that, is a factor that can be influenced.’

10 Conclusions and recommendations

10.1 Conclusions

The study area of the Follow-up Study has an estimated population of over 1.1 million, who live in approximately 533,000 dwellings. Zones in the vicinity of railway bridges, tunnels and major stations with many parallel tracks have been excluded.

Based on the Follow-up Study, it has been estimated that around 11% of the Dutch population aged 16 and over who live within 300 metres of a railway line (excluding zones near railway bridges, tunnels and major stations with many parallel tracks) experience high annoyance due to railway-induced vibrations. This amounts to an estimated 126,500 persons. As regards high sleep disturbance due to railway-induced vibrations, the estimate is just under 13%.

Most of the annoyance and sleep disturbance is caused by freight trains and to a lesser extent by passenger trains: 22.6% and 18% of residents of the study area report high annoyance and high sleep disturbance, respectively, due to freight trains. The extent of high annoyance and sleep disturbance due to vibrations from passenger trains is estimated at 8% and 6%, respectively.

Under current regulations (Bts and SBR), no ISO 2631 weighting is applied. The Follow-up Study has shown that vibration indicators *without* directional frequency weighting in accordance with ISO 2631 more reliably predict both annoyance and sleep disturbance due to railway-induced vibrations. This confirms the results from previous research into the influence of directional frequency weighting. Therefore, it seems undesirable to apply ISO weighting under any new regulations to be developed.

In the Follow-up Study we studied various types of vibration exposure indicators: one indicator for maximum exposure (V_{max}) and indicators for average exposure with due regard for the number of trains and/or train length (e.g. RMS). No single indicator has been found that is clearly preferable to the others for predicting high annoyance or sleep disturbance. This is because there were very few differences between the predictive models based on the different indicators in terms of model fit and model accuracy. In addition, the exposure indicators were strongly correlated with each other. This means that, for the purposes of further development of regulations in the field of railway-induced vibrations, consideration is given to what the policy wants to focus on with regard to exposure: on the perceptibility of vibrations and/or the nuisance of annoyance, or on other aspects.

For both total railway traffic and freight trains, there was a clear relationship between vibration exposure and the percentage of people experiencing high annoyance: the percentage of high annoyance due to railway-induced vibrations increases with increasing levels of exposure to these vibrations. The relationships were found to be the strongest for freight trains, and were far less pronounced for passenger trains. Similar results were obtained for sleep disturbance.

Besides vibration exposure, several other factors were associated with reported high annoyance and sleep disturbance due to railway-induced vibrations. For high annoyance, the strongest associated factor was annoyance due to the noise produced by trains. Sleep disturbance due to the noise produced by railway traffic was the main predictor of high sleep disturbance due to railway-induced vibration. In addition, several social and personal factors were also associated with both high annoyance and sleep disturbance due to vibrations: acceptance of vibrations, concerns, expectations and observing vibrating, moving or rattling objects in the home.

In principle, all DR relationships established based on the Follow-Up Study can be used to estimate the magnitude of people experiencing high annoyance and sleep disturbance due to vibrations from total railway traffic, freight trains and passenger trains. However, preferably the DR relationships should be used which: i) express vibration exposure in terms of distance from the railway line (m), or ii) express vibration exposure in a measure for which *no* ISO 2631 weighting has been applied. The relationship between exposure to railway-induced vibration and high annoyance or sleep disturbance was found to be, in most cases, non-linear. In those cases, it is therefore preferable to use DR relationships based on the categorical models.

The results of the Follow-up Study confirm the results of the 2013 study in a number of important respects. Similar to the 2013 study, the Follow-up Study found that most annoyance is caused by vibrations from freight trains, and to a lesser extent by passenger trains. Apart from vibration exposure, social and personal factors in particular were found to influence the amount of reported annoyance and sleep disturbance due to railway-induced vibrations.

Furthermore, both the Follow-up Study and 2013 study found a clear relationship between the percentage of people experiencing high annoyance and sleep disturbance and exposure to railway-induced vibration produced by both the total railway traffic and freight trains These relationships were far less pronounced for passenger trains.

However, there were also differences between the 2013 and the Follow-Up Study: at equal (maximum) vibration levels, the likelihood of being highly annoyed due to railway-induced vibrations in 2021 was lower than in 2013. In contrast, at equal (maximum) vibration levels, the probability of being highly sleep disturbed due to railway-induced vibrations in 2021 was *higher* than in 2013.

10.2 Recommendations

Based on the Follow-up Study we have formulated the following recommendations:

Five years from now, consider whether it is necessary to renew the DR relationships established in this study based on the knowledge available at that time.
DR relationships are important for Dutch environmental policy as they can be used to set establish policy norms and can play a role in the underlying tools set (such as the effectiveness criterion[25]). In addition, DR relationships can be used to map potential health effects and to assist in answering various types of policy questions such as: which groups and exposure levels are associated with (the most) problems?, which areas are the most suitable for which measures?, and which measures yield the greatest health benefits? However, residential areas are subject to change: new railway lines are built, more dwellings are insulated against vibrations, residents' acceptance of railway traffic may change, new laws and regulations may be introduced, a nationwide crisis may break out etc. In addition, new knowledge and insights may become available in the near future. In order to prevent unnecessary delays between changes in local circumstances, the emergence of new knowledge and its implementation in laws and regulations - delays which are all too frequent in the case of environmental noise [107, 123] - we recommend not only keeping the knowledge on railway-induced vibrations and health up to date, but also conducting new studies in future within the framework of the 'Living along the railway line' study. At the same time we are aware that policy makers are not likely to be pleased - if only for practical reasons - with the prospect of new DR relationships being established every year. For that reason we recommend conducting a comprehensive assessment, at least every five years, of the need or justification for a revision of existing DR relationships based on the then available knowledge.

We need more insight into the potential influence of co-determinants on the association between exposure to vibrations from railway traffic and the experienced level of annoyance, the interdependencies between those co-determinants and the extent to which they can be influenced. That study should also cover the role of noise.
Research into the influence of co-determinants on annoyance and/or sleep disturbance due to vibrations from railway traffic has so far been limited. The overview produced by Van Kempen et al. [10], the results of Van Kamp et al.[11] and of the Follow-Up Study yielded a number of demographic, contextual and personal factors that were found to be associated with high annoyance and/or sleep disturbance due to vibrations from railway traffic. However, the extent to which those co-determinants influence the association between exposure to vibrations from railway traffic and annoyance or sleep disturbance due to such vibrations has not been studied. Studies into the relationship between

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[25] A method for assessing whether measures are sufficient for reducing vibration-induced annoyance. The effectiveness criterion enables the competent authorities to assess whether the costs of a measure are justified by its effect.

aircraft noise and annoyance, for example, have shown that the role of co-determinants can vary significantly depending on population, location and time [122]. This could also apply in connection with annoyance and/or sleep disturbance due to vibrations from railway traffic. If so, this might explain part of the observed differences between the results of the Follow-Up Study and the first 'Living along the railway line' study from 2013. Moreover, knowledge about co-determinants can offer important areas of focus and intervention options for reducing exposure to railway-induced vibrations. In addition, such knowledge can have consequences for the ways in which measures and/or policies to reduce vibrations are implemented, and for the ways in which local residents are informed about and/or involved in those measures and policies to ensure their success. Within the framework of the 'Living along the railway line' survey, over the years RIVM has performed multiple measurements among residents living along a railway line, which means it has a wealth of data on exposure to vibrations from railway traffic, co-determinants, annoyance, sleep disturbance and self-reported sleep quality.

As in the Follow-up Study, use techniques that can also describe non-linear relationships when establishing *future* DR relationships

Within this study we used multiple methods to establish DR relationships. Studies on environmental noise and annoyance often base DR-relationships on logistic regression models with a continuous exposure which always assume a linear relationship [123]. However, the relationship between exposure and response is not always linear, as illustrated by the figures for DR relationships in Chapter 7. In the Follow-Up Study, we were able to observe these non-linear relationships by using logistic regression models with a categorical exposure. If a relationship between exposure to vibration and annoyance or sleep disturbance is incorrectly assumed to be linear, using a linear DR-relationship may lead to an underestimation of the amount of annoyance or sleep disturbance at higher exposure levels.

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Glossary and abbreviations

AIC	Akaike Information Criterion. An indicator used evaluating how well a model fits the data it was generated from. It provides a means for model selection by estimating the quality of each model relative to others. A lower AIC score indicates a better fit.
AUC	Area Under the Curve. A measure of the perfmormance of a statistical model. It is an indicator of precision.
BAG	Key Register of Addresses and Buildings. The BAG contains basic data on all addresses and buildings within a municipality, such as building year, surface area, purpose, or location on the map.
BRO	Basic Register of Subsoils
DR relationship	Dose-response relationship. Expresses the connection between an exposure (e.g. vibrations from railway traffic) and response (e.g. high annoyance) to the exposure within a population.
BS-6472	British Standard for the measurement and assessment of vibrations.
Bts	Beleidsregel Trillinghinder Spoor. It is a policy rule. The purpose is to lay down rules for dealing with several aspects of vibration-induced annoyance.
95% CI	95% confidence interval. This is a statistical range within we are 95% confident that the true parameter lies. 95% CI means that if we were to repeat the study many times, in 95 out of 100 cases we would end up with a result within that interval. Confidence is a measure for the reliability of the calculated value.
CargoVibes	Acronym for ‘Attenuation of ground-borne vibration affecting residents near freight railway lines’. CargoVibes was an EU project performed between 2011 and 2014 as part of the Seventh Framework Programme.
CBS	Statistics Netherlands.
dB	Decibel. Indicator for the intensity of a sound.
Decile	A number associated with a score that indicates the percentage of participants that achieved that score or a lower score. The first decile contains the lowest 10%, while the tenth decile contains the top 10%.
DIN-4150	A standard of the Deutsches Institut für Normung (DIN) that describes which requirements and target values are to be satisfied to ensure that people do not experience major annoyance inside dwellings or spaces use for similar purposes. DIN also comprises a methodology for assessing vibrations produced by railway traffic.
GIS	Geographic Information System. An information system for storing, managing, processing, analysing, interpreting and presenting spatial data or information about geographical objects (geoinformation).

HE glazing	High-efficiency glazing.
I&W	Ministry of Infrastructure and Water Management
IenM	Ministry of Infrastructure and the Environment
ISO 2631	International standard of the International Standards Organization (ISO) which, among other things, describes the methodology for measuring and assessing vibrations to which people may be exposed in buildings.
Lden	Day-evening-night level. It is a descriptor of noise based on the energy equivalent noise level (Leq) over a whole day with a penalty of 10 dB for night time noise (23:00 – 7:00) and an additional penalty of 5 dB for evening noise (i.e. 19:00 – 23:00).
Leefbaarometer]	An instrument for monitoring liveability levels in all inhabited districts, neighbourhoods and streets in the Netherlands. It shows the local liveability situation and how it has evolved in recent years.
Lnight	Annual average A-weighted long-term sound level over the night-time period (23:00 – 7:00), expressed in decibel.
Median	The value exactly in the middle of a data set with values arranged from high to low. The median is a measure of centre that separates the lowest 50% of values from the highest 50%.
NO2	Nitrogen dioxide. An inorganic compound of nitrogen and oxygen.
OBW	Study of Perception of the Home Environment, A nationwide study in which RIVM maps out how residents experience noise, vibrations, odours and safety in their living environment.
Odds Ratio (OR)	A measure of association that yields an approximate value for the extent to which a person subjected to a certain level of exposure (such as vibrations from trains) is more likely (or less likely) to develop an illness or other health effect (such as annoyance) than a person not subjected to that exposure or subjected to lower levels of exposure. One example is the risk of developing lung cancer in relation to whether or not a person smokes. When the OR is 2, the chance of developing lung cancer is twice as high for smokers than for non-smokers in the study group. Another example: developing heart disease in relation to taking regular physical exercise. When the OR is 0.5, the chance of developing a heart disease is half as high for persons who regularly engage in physical exercise than for those in the research group who do not. When the OR is 1, there is no difference between the exposed group and the non-exposed group.
OURS	Acronym for Ontwikkeling Uniform Rekenmodel Spoortrillingen (development of a uniform calculation model for train-related vibrations). This model makes it possible to calculate vibration levels in dwellings from railway traffic. The model was commissioned by the Ministry of infrastructure and Water Management, and developed by a group led by RIVM.

Percentile, px	Percentiles (px) are used to identify the share of participants exposed to, for example, vibration strengths equal to or lower than the value associated with the percentile concerned.
PHS	Short for Programma Hoog-Frequent Spoor (High-Frequency Rail Transport Programme).
PM2.5	Fine particles smaller than 2.5 micrometres.
Polysomnography	A type of sleep research in which several physiological parameters are recorded during a person's sleep. The result is known as a polysomnogram.
Prevalence	Percentage, number of times a particular attribute occurs among 100 respondents at any given moment.
RMS	Frequency-weighted ‘root-mean-square’. Exposure measure (often an average) for vibrations over longer periods of time or to express the magnitude of a vibration event. RMS is used mainly for continuous vibrations.
SBR-B Guideline	Guideline B issued by Stichting Bouw Research. This guideline (not a legal instrument) offers an initial basis for an approach to vibration-induced annoyance. It promotes consultation with all parties involved, with joint consideration of measures and of the extent to which annoyance is acceptable.
SRM-T	Standard Calculation Method for vibrations.
Vdir,max	Maximum vibration level in terms of speed (largely through DIN-4150 and SBR-B, but with directional frequency weighting according to ISO 2631-1). This measure is closely related to Vmax in SBR-B, the only difference being the directional frequency weighting. As a result, vertically Vdir,max values are 15% higher, on average.
Vmax	The highest effective vibration level during the assessment period, on the understanding that the 2% of trains with the highest vibration levels were excluded as outliers.
Vper	The average vibration level during the exposure period, weighted according to exposure duration.
WHO	World Health Organization.
WOoN	The Housing Survey of the Netherlands. A basic survey intended to map out the home situation and residential wishes of households in the Netherlands.
WOZ value	Value under the Value of Immoveable Property Act.

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Annex 1 Determination of weighting factors

Sampling set-up

From the Key Register of Addresses and Buildings (BAG, reference year 2019)[26] we selected all residential buildings located within 300 metres of a railway line. Addresses in the vicinity of railway bridges, sunken tracks and major stations with many parallel tracks were excluded. In total, we selected 532,730 addresses that had not previously been included in a study into railway-induced vibrations. We then added a group of 1,189 addresses from earlier surveys. In total, therefore, the study included 533,919 addresses. Due to a change, nine addresses within the latter group appeared to be located more than 300 metres of a railway line. We set the distance for these addresses at 300 metres.

Next, we defined six strata: three distance from the railway line classes (0-49, 50-99 and 100-300 metres) and two construction year classes (<1950 and 1950+). From the first group of 532,730 addresses we randomly selected a predetermined number of addresses within each stratum, to a total of 16,000 addresses. From the second group we selected all 1,189 addresses. The table below shows the total number of addresses and the number of addresses included in the sample.

Table B1.1 Number of addresses in the population and number of addresses in the sample, per group and per stratum.

Group	Stratum	Distance (m)	Building year	Population	Sample
I	1	0-49	<1950	9,936	4,000
I	2	0-49	1950+	27,424	4,000
I	3	50-99	<1950	18,392	2,400
I	4	50-99	1950+	67,518	2,400
I	5	100-300	<1950	93,901	1,600
I	6	100-300	1950+	315,559	1,600
Subtotal				532,730	16,000
II	1	0-49	<1950	378	378
II	2	0-49	1950+	342	342
II	3	50-99	<1950	168	168
II	4	50-99	1950+	156	156
II	5	100-300	<1950	76	76
II	6	100-300	1950+	69	69
Subtotal				1,189	1,189
Total				533,919	17,189

Since the exact size of the households was unknown, we linked the average household size to each address based on the 6-digit postcode[27]. This produced an estimated 1,151,210 individuals living within 300

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[26] See the Kadaster (Land Registry) website for more information about the BAG: https://www.geobasisregistraties.nl/basisregistraties/adressen-en-gebouwen

[27] We determined average household size by dividing the number of residents in each 6-digit postcode area by the number of addresses in it. For numbers of residents and numbers of addresses per 6-digit postcode area we used data collected by Statistics Netherlands (CBS, 2023).

metres of a railway line. For each address included in the study we randomly invited one person of the household to participate. Potentially, this yielded a group of 17,189 participants.

Initial weightings

Due to the sampling set-up described above, the full set of selected addresses and participants is not representative of the population of residents who live within 300 metres of a railway line. For example, there is an over-representation of addresses in the 0-49 metres category compared with the 100-300 metres category.

In order to make the sample representative for the entire population, we can assign a weight to every participant included in the sample that represents the number of persons in the population. That weight is calculated as 1 divided by the chance of a person being included in the sample. This is known as the initial weighting.

The sample is a two-stage stratified sample. Step 1: the chance of an address from a stratum in a group being included in the sample, is the number of addresses in that group and that stratum in the sample, divided by the number of addresses in that group and that stratum in the population. According to the sampling set-up, for every address in group II this chance equals 1, because every address in this group is included in the sample. Step 2: the chance of a person who lives at an address in a group in a stratum being included is 1 divided by the number of residents at that address. Since these two inclusion chances are independent of each other, we can multiply them with each other to arrive at the total chance of inclusion of an individual resident.

NB Because we use the average household size for every address, based on the 6-digit postcode, instead of the actual household size, for a number of addresses the average household size is smaller than 1 or even 0. This is because not all dwellings are inhabited. As a result, the chance of inclusion for persons at those addresses may be greater than 1 or indeed infinitely high. From a practical perspective this should not be possible, which is why we decided to use the average number of persons per address, for a group and a stratum.

Adjustment for non-response

Non-response results in a smaller number of respondents than planned. While this does not necessarily produce incorrect outcomes, the reliability margins of the estimates are likely to increase. More serious problems present themselves when the non-response is selective. Selective non-response occurs when, due to non-response, specific groups are under- or overrepresented in the study. If the outcome-related behaviour in such a group is markedly different from the total population, this will bias the outcomes. In other words, the estimates are systematically too high or too low.

We can adjust for non-response bias if the chance of non-response is associated with a series of known characteristics of a specific group in the sample. In that case, the adjustment weight for a person in the sample is 1 divided by the chance of response in the sample.

Common explanatory variables for non-response include age, gender and level of education. In this study, characteristics of this type were identified in the questionnaire and are known, therefore, for all respondents. However, we do not know those characteristics for non-respondents, so we cannot adjust for them. The only possible way to adjust for non-response in this study is to use information from the strata. It is reasonable to assume that the response in this study depends on the group (first-time or second-time participant), distance from the railway line and building year of the dwelling. This is why we have calculated the chance of response of a person in the sample as the number of respondents in a group in a stratum, divided by the number of included persons from that group and that stratum.

Final weightings

The final weightings are calculated as the product of the inclusion weightings and non-response weightings. The final weighting denotes the number of persons in the population each respondent represents. The table below presents an overview of weightings per group and per stratum.

Table B1.2 Initial weightings, adjustment weightings and final weightings per group and per stratum.

Group	Stratum	Distance (m)	Building year	Initial weighting	Adjustment weighting	Final weighting
I	1	0-49	<1950	5.62	2.69	15.10
I	2	0-49	1950+	14.10	3.07	43.30
I	3	50-99	<1950	17.30	3.45	59.90
I	4	50-99	1950+	58.40	3.85	225.00
I	5	100-300	<1950	131.00	4.62	608.00
I	6	100-300	1950+	424.00	4.79	2029.00
II	1	0-49	<1950	2.15	1.37	2.94
II	2	0-49	1950+	2.10	1.38	2.90
II	3	50-99	<1950	2.15	1.62	3.47
II	4	50-99	1950+	2.19	1.56	3.42
II	5	100-300	<1950	2.34	1.55	3.64
II	6	100-300	1950+	2.28	1.57	3.58

Given the lower adjustment weightings for group II, it appears that second-time participants are more motivated to take part than first-time participants. The figures also show an effect of distance from the railway line on response: participants who live closer to a railway line have a lower adjustment weighting, meaning that they are more inclined to respond than those living at a greater distance from the railway line.

Annex 2 Untargeted Analysis

Introduction

Van Kamp et al [11] and the literature (also see Chapter 2) report on various factors and exposure indicators that predict the levels of annoyance and sleep disturbance due to railway-induced vibrations. Apart from those known predictors, there may be other, unknown factors that predict or contribute to annoyance or sleep disturbance. To identify such potential but unknown predictors, we also conducted a so-called untargeted analysis (UA) within the study, using a variety of machine-learning techniques. An UA does not involve strict, predefined assumptions as to which variables could influence the outcome measure. Instead, it looks at a large number of factors at the same time and uses data-driven techniques to identify the strongest predictors of the outcome measure.

Method

The datasets used for the UA contain information from the questionnaire and from the modelling of exposure to vibrations (OURS) and noise (RMG-II) from railway traffic at each participant’s home address. Due to the large number of questions in the questionnaire, we did make a prior selection so as to only include relevant questions as predictors. In addition, for each type of outcome measure (high annoyance or sleep disturbance due to vibration) we decided to only use predictors that apply directly to the outcome measure concerned. For example, for the outcome measure high annoyance we did not use variables that have an (expected) impact on sleep disturbance, such as ‘L_{night} railway traffic’ or 'High sleep disturbance due to railway traffic noise’. For each analysis we studied approximately 70 unique predictors.

We used two different methods for performing the UA: Least Absolute Shrinkage and Selections Operator (LASSO) regression and Random Forest (RF). In both the LASSO and the RF method, predictive models are created and then used to identify the best individual predictors. Combining the outcomes of these two methods will produce a reliable estimate of the factors that are the best predictors high annoyance or sleep disturbance due to railway-induced vibrations.

For both methods it is important to be able to reliably the accuracy of the prediction models. Given that the UA uses classification models with a binary outcome measure (participants either do or do not experience annoyance/sleep disturbance), we used the area under the curve (AUC) of the receiver operating characteristic (ROC) curve for the accuracy assessment. AUC values range from 0.5 (wholly arbitrary prediction of outcome) to 1.0 (perfect prediction of outcome based on the model). The more closely the AUC approaches 1, the higher the accuracy of the model.

LASSO

The LASSO regression method involves the use of a penalty parameter λ that is applied to all (normalised) coefficients within a regression model that do not have the value 0. The higher the penalty λ, the more closely the value of a coefficient approaches 0. If λ is sufficiently high, a coefficient will eventually achieve a value of 0, from which point it will no longer add information to the predictive model. Model accuracy metrics then make it possible to estimate the amount of information a coefficient of a variable adds to the model. If the accuracy of the model does not decrease in the absence of that variable, it does not provide any additional information for the model. If we raise λ in steps to a value at which every coefficient has a value of 0 and determine the accuracy of the model at each step, we will be able to identify the variables that contribute most to the accuracy of the model.

The model that eventually emerges as the best in the LASSO regression analysis is the one with the highest λ value whose AUC value is not more than 1 standard error below the maximum AUC value of all models in the analysis. That model is at least as accurate as the most accurate regression model, but also contains the lowest possible number of predictors. The predictors that form part of that model can be regarded as the key predictors of the outcome measure.

The LASSO analysis was performed using the R-package *glmnet* [124]. In all, for each analysis 100 different regression models were created with a λ between 0.001 and 100. We used five-fold cross-validation to estimate the AUC of each model.

Random Forest

Random Forest (RF) is a predictive machine learning algorithm that can be used for classification tasks [125]. The algorithm uses all available predictors within a dataset to create a large number of decision trees for predicting an outcome measure. Every decision tree is based on a different, randomly selected part of the dataset. The predictions of all those individual decision trees are then combined (known as ensemble learning) to arrive at the final prediction. Cross-validation techniques and the AUC values enable us to determine the accuracy of the RF model. To that end, we first build a model based on part of the data (the ‘training data’). Next, we establish how effective the model is in predicting the outcome measure from other data unknown to it (the ‘test data’). The standard error and the AUC value of the RF then indicate the model's accuracy in predicting the outcome measure. Repeating this procedure multiple times using different combinations of training and test data produces a more and more accurate picture of the accuracy of the model.

A ‘variable importance’ (VI) procedure makes it possible to identify the individual predictors that contribute most to the accuracy of the RF model [125]. At each step in the VI procedure, one predictor in the dataset is randomised, as a result of which it provides no further input for the model. That dataset is then used to create a new RF model. By determining the difference in accuracy between the new RF model and the original RF model, we can then estimate the relative importance of the predictor. If the VI procedure is applied to all predictors in the dataset, it is possible to create a ranking of predictors based on their importance within the model. The procedure is repeated several times to optimise the VI ranking. The median VI value can then be used to establish the definitive ranking.

We performed the RF analysis and the VI procedure using the R-packages *caret, random forest* and *iml* [125-128]. We applied a five-fold cross-validation process to estimate the accuracy of each RF model, and repeated the VI procedure eight times for each model.

Individual effects of predictors within Random Forest

To obtain insight into the direction and contributions of individual predictors within the RF model we used 'accumulated local effect' (ALE) plots. The ALE method provides estimates of the conditional contributions of the variables in the model for different values of each variable. A positive ALE value represents a higher chance of an outcome measure; a negative value represents a lower chance [125]. The further from 0 the ALE value, the stronger the effect. When the ALE value is 0, the prediction of the outcome for a specific value of the variable equals the average prediction of the RF model.

The advantages of this method are that it is able to identify non-linear associations and mitigates sensitivity to correlated variables. Disadvantages are that the outcomes cannot be directly quantified (e.g. to the percentage of people experiencing annoyance at a specific value) and that a relatively large number of observations are needed to get a clear picture of the direction of the effect. Within the UA, all ALE plots have been used to identify the effects of four predictors (distance from the railway line, V_{max}, L_{den} or L_{night} and freight trains ratio) within the RF on annoyance and sleep disturbance due to railway-induced vibrations. We used an RF model for this purpose that only included these four predictors. The ALE plots were created using the R-package *iml* [128].

Findings

High annoyance

We conducted an UA for high annoyance and high sleep disturbance due to railway-induced vibrations. Within each analysis, we studied all possible predictors of annoyance or sleep disturbance as well as a sub-group of exposure-related predictors. Below is a discussion of the most important findings. The results of the UA for high annoyance and high sleep disturbance due to vibrations from railway traffic are also presented in Figures B2.1 and B2.2.

The LASSO identified six different variables as key predictors of high annoyance: 'Annoyance due to noise from railway traffic', 'Vibrations are acceptable', 'Concerns about property damage due to vibrations', "Expects decrease in situation regarding vibration", 'Rattle' and 'Attitude towards railway policy'. These six variables were also the six most important variables in the RF analysis (also see Figure B2.1). The fraction of freight trains in total railway traffic is the most important vibration exposure variable, both in the full UA (9th in ranking) and in the exposure specific UA. The exposure indicators V_{max} (15th) and distance from the railway line (19th) also have a moderate performance in RF, but their scores are much lower than those of the noise annoyance and expectation variables. In the exposure-specific UA, the variables with the highest scores are fraction of freight trains in total railway traffic and noise from railway traffic (L_{den}), followed by distance from the railway line, V_{per} and V_{max}.

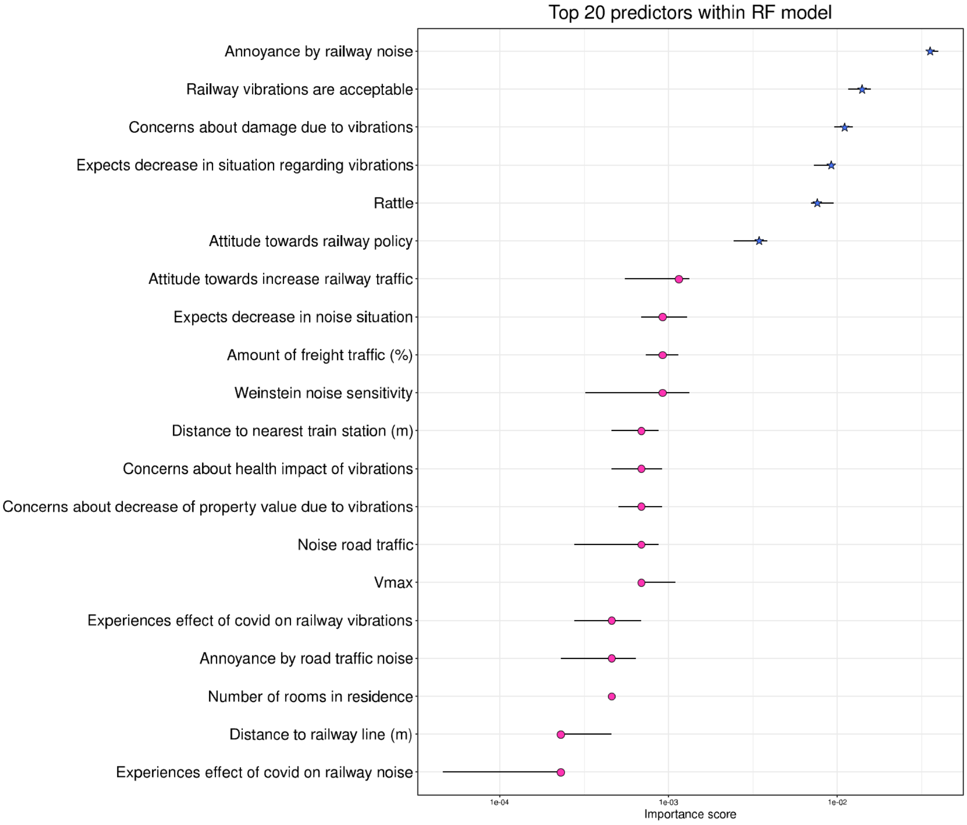

Figure B2.1 The top 20 predictors of high annoyance due to vibrations from railway traffic within the Random Forest model, based on a data set of 4,300 observations and 70 different variables. The predictors identified in the LASSO analysis as the best (n=6) within the data set are marked with an asterisk.

High sleep disturbance

In the UA, high sleep disturbance due to the noise from railway traffic and concerns about vibration-induced damage/health effects are the main predictors of high sleep disturbance due to vibrations from railway traffic. The high importance score for the predictor high sleep disturbance due to the noise from railway traffic demonstrates the very strong relationship between this predictor and vibration-induced sleep disturbance. Moreover, this variable is responsible for nearly all the accuracy of the LASSO and RF models within the UA analysis.

The UA does not yield any particular exposure variable that is clearly the most important. Night-time exposure L_{night} and distance from the railway line appear in the top 20 of variables of the RF, but there is no marked difference between these two variables in terms of their relevance scores. Within the UA for rail-specific exposures, the main predictor is the fraction of freight trains in night-time railway traffic, followed by night-time noise from railway traffic (L_{night}) and distance from the railway line.

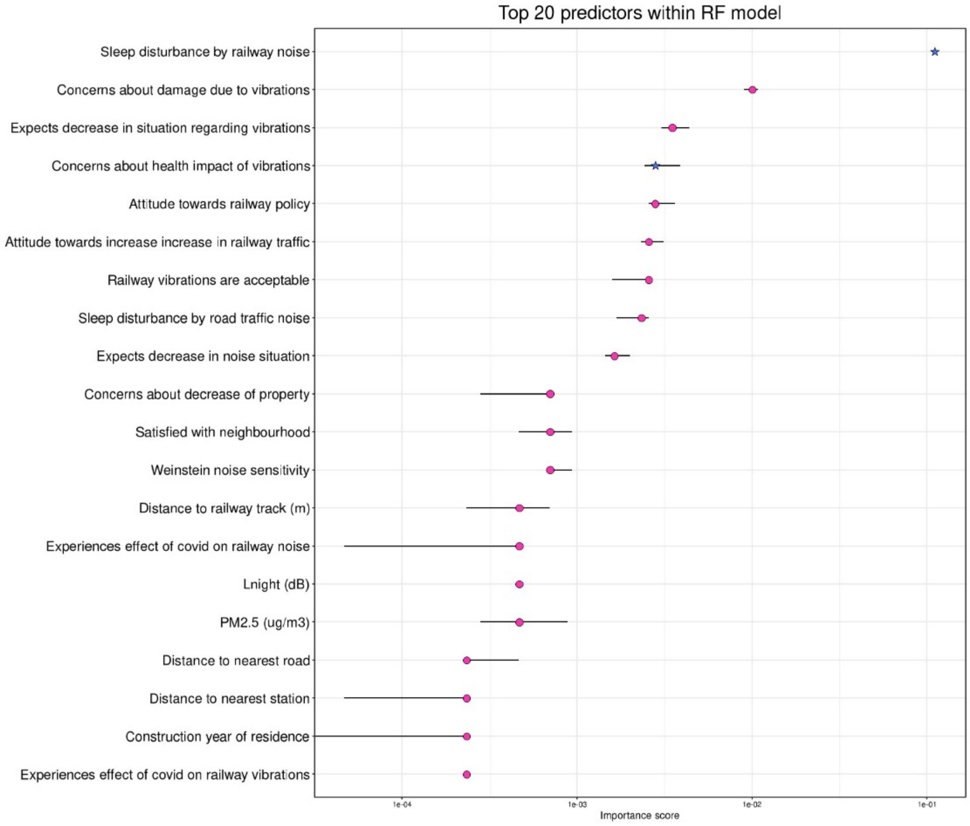

Figure B2.2 The top 20 predictors of high sleep disturbance due to vibrations from railway traffic within the Random Forest model, based on a data set of 4,295 observations and 70 different variables. The predictors identified in the LASSO analysis as the best (n=2) within the data set are marked with an asterisk.

Exploration of directional effects

To explore the directional effects, we created new RF models for high annoyance and sleep disturbance using four predictors: distance from the railway line , V_{max}, the fraction of freight trains in total railway traffic and exposure to noise (L_{den} for high annoyance and L_{night} for high sleep disturbance). We then determined the ALE for each of these predictors, with several different values for each. The results are shown in Figures B2.3 and B2.4. They also include histograms of the different exposures. Since predictions of the ALE are less reliable when there are relatively few observations, we have only presented the values within the 5th and 95th percentiles of total exposures.

Within the RF model for high annoyance due to railway-induced vibrations, the ALE plot for distance from the railway line shows a striking pattern. Persons living within 50 metres of a railway line are less likely to experience high annoyance, but the likeliness of high annoyance actually increases for persons living within 50 to 80 metres from the railway line. The likelihood gradually decreases again from 80 metres. This pattern is non-linear and diverges from the DR relationships observed in the report. There are several possible explanations for this: no weighting is applied in the RF method, the RF model includes multiple predictors, and the methodological differences between RF and logistic regression could all play a role. The ALE for V_{max}

shows that the chance of high annoyance increases with increasing maximum vibration levels. The relationship is non-linear; between the V_{max} values of 0 and 1 the effect gradually increases first, but levels off soon after. Annoyance levels also increase with an increasing share of freight trains in total railway traffic: the more freight trains, the more likely respondents are to report annoyance. This effect, too, seems to be non-linear. For indicator L_{den}, the probability of annoyance increases with increasing levels of noise. The relationship between noise and annoyance is non-linear; the ALE of L_{den} strongly increases in particular at noise levels in excess of 55 dB.

In the RF model for high sleep disturbance due to total railway traffic, the ALE plot for distance from the railway line shows that persons living within 25 metres of a railway track are more likely to report sleep disturbance. Beyond that, the likelihood of sleep disturbance strongly decreases, but oddly enough persons living within 25-50 metres from the railway line appear to report less sleep disturbance than those living further away. As in the case of high annoyance, this pattern diverges from the DR relationship. For V_{max} there is a fairly linear relationship between maximum exposure to noise and high sleep disturbance, with sleep disturbance increasing at higher V_{max} levels. The likelihood of high sleep disturbance also increases with higher percentages of freight trains during the night. Finally, the probability of sleep disturbance increases with increasing levels of night-time noise from trains. Note however that this effect does not really start until 40 dB (L_{night}) and that it levels of around 55 dB (L_{night}). Between these noise levels the increase does seem to be linear.

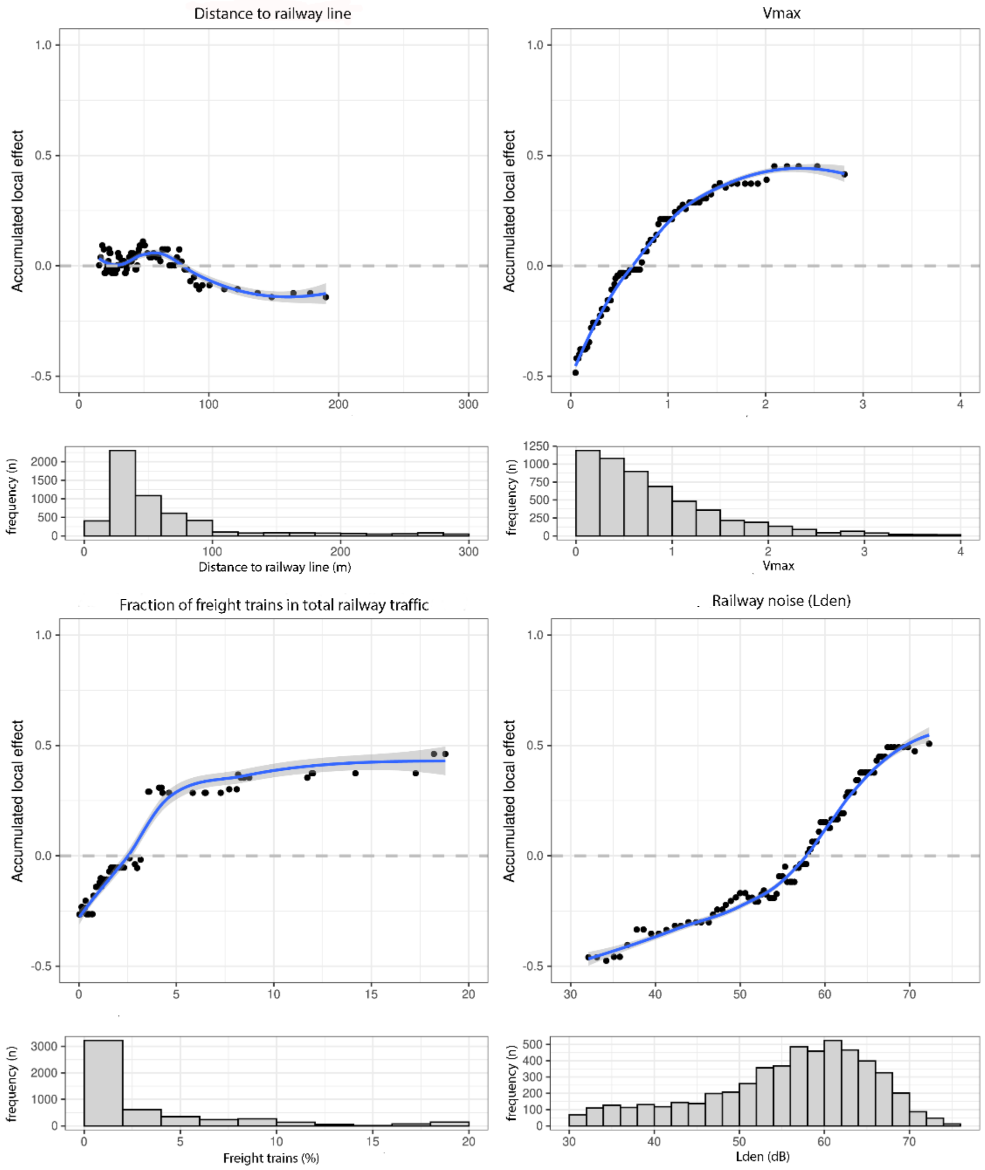

Figure B2.3 The accumulated local effect (ALE) plots of the effects of the predictors Distance from the railway line, Maximum vibration strength V_{max}, fraction of freight trains in total railway traffic and L_{den} for rai traffic in an RF model (n=5,558) for annoyance with exposures only. The figure also shows the histograms of the predictors. Only the values between the 5th and the 95th percentiles are shown.

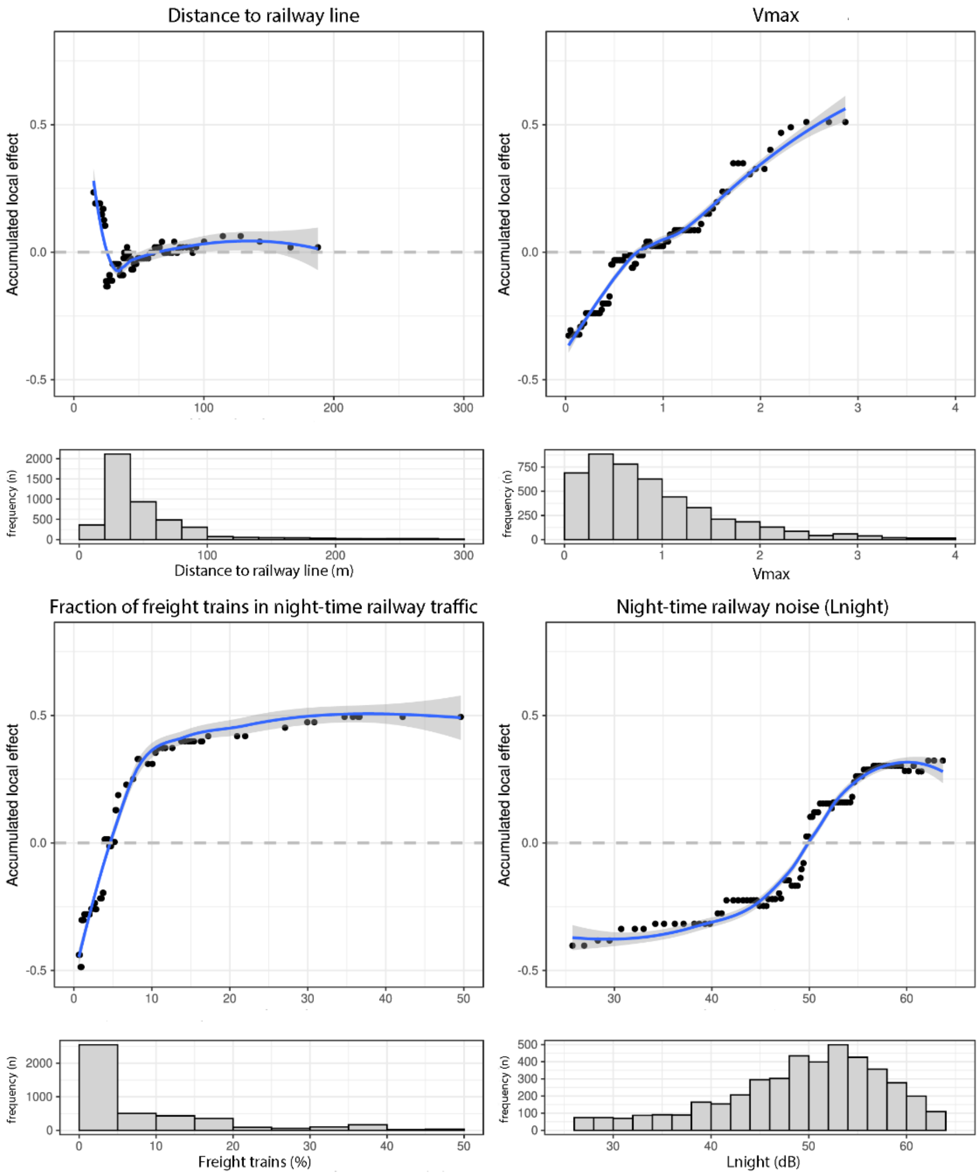

Figure B2.4 The accumulated local effect (ALE) plots of the effects of the predictors Distance from the railway line, Maximum vibration strength V_{max}, fraction of freight trains in night-time railway traffic and L_{night} for railway traffic in the RF model for sleep disturbance with exposures only. The figure also shows the histograms of the predictors. Only the values between the 5th and the 95th percentiles are shown.

Discussion

Below is a brief discussion of the outcomes of the UA. For a more detailed discussion of the overall outcomes, see Chapter 9.

The UA method is used to identify, without assumptions, which factors are good predictors of the outcome measure - in this case, high annoyance and sleep disturbance. One clear difference between the UA of annoyance outcomes and the UA of sleep disturbance outcomes was that the former yielded multiple factors as clear predictors, while the dominant predictive variable for sleep disturbance was sleep disturbance due to noise from railway traffic. The LASSO and RF models that predict sleep disturbance are almost entirely dependent on this sleep disturbance variable for their predictions. This suggests that the experience of vibration-induced annoyance depends on multiple types of factors, while the experience of vibration-induced sleep disturbance mainly depends on sleep disturbance due to noise.

For every type of vibration-induced annoyance or sleep disturbance, we found a strong relationship with annoyance or sleep disturbance due to noise from railway traffic (see Chapter 8). There is a positive correlation between noise and the various types of vibration exposures (r ~ 0.6–0.7) and a negative correlation between noise and distance from the railway (r ~ -0.5) in the data sets (see Chapter 6). It is difficult to determine the influence of these correlations on the basis of the available data sets. The ALE plots for L_{den} and L_{night} do however show a strong effect on the likelihood of high annoyance in a model that also includes distance from the railway line and V_{max}. All these results indicate that noise and annoyance due to noise are factors to be taken into account in studies into vibration-induced annoyance.

A more detailed exploration of the UA is beyond the scope of this study. However, we do intend to elaborate and expand on the UA and include the results in a separate scientific publication. In the future, the UA and ALE methods can be used to gain more insight into the direction of effects and interactions between noise and vibration exposures and distance that contribute to experienced levels of annoyance or sleep disturbance.

Conclusion

The outcomes of the UA gave us cause to decide to include the variable annoyance due to the noise of railway traffic in the logistic regression analysis, as well as the survey questions concerning attitude and expectations regarding railway traffic (see Chapter 8). In addition, the UA strongly suggests the existence of a non-linear relationship between vibration measures on the one hand and high annoyance and sleep disturbance on the other, which is consistent with the results of other components of the study (see Chapter 7).

Annex 3 Coding of variables in the analyses

In this annex we give the definitions of the variables included in the main analyses in Chapters 5, 7 and 8.

Concern about vibrations from railway traffic

Concern about several aspects of railway traffic was measured using questions with 11 answer categories (0-10), asking respondents for concerns regarding: a) loss of property value, b) their health, and c) damage to their property. The answers for the three items were arranged per question. Participants who filled in 8, 9 or 10 were identified as 'seriously concerned' for the purposes of the analysis. Participants who filled in 0, 1, 2, 3, 4, 5, 6 or 7 were identified as 'not seriously concerned'.

Gender

We distinguish between the following groups: men, women and X. The latter group covers all genders not qualifying as either male or female

Annoyance due to vibrations or noise

Annoyance due to noise was measured with a standardised question laid down in the ISO standard: ISO/TS/15666,2003. Annoyance due to vibrations was measured using the adapted version of this ISO question [129].
In both cases, the question had 11 answer categories (from 0 to 10). To determine the percentages of persons reporting annoyance, the extremes of the annoyance scale were assigned the values 0 and 100, respectively. Internationally it has become common practice to identify the percentage of participants who score higher than 72 on this scale as the 'highly annoyed' percentage[130]. To estimate the prevalence of high annoyance, we determined the highly annoyed percentage from the scores of individual participants. The score of a participant was determined as followed: the cut-off score of 72 is in the 8th answer category. All participants who filled in 0, 1, 2, 3, 4, 5 or 6 were assigned a score of 0, and all participants who filled in 8, 9 or 10 were assigned a score of 100. Participants who filled in 7 were assigned a score of 8. Participants who answered that they had not perceived the source at all were regarded as not at all annoyed (score 0). Given that this involved a binary outcome measure (0/1) in a linear regression analysis, only the participants who filled in 8, 9 or 10 were categorised as highly annoyed.

Acceptance of vibrations from railway traffic

We measured acceptance of vibrations using a question with five verbal answer categories. We then used the answer to determine whether a person considered vibrations from railway traffic to be (highly) acceptable (answer categories 'Highly acceptable' or 'Acceptable') or not (answer categories 'Acceptable nor unacceptable', 'Unacceptable' or 'Highly unacceptable').

Attitude towards current train policy

We measured the attitude towards current railway policy using a question with answers on a scale from 0 to 10 (0=very positive and 10=very negative). We used the answer to determine whether a person had a 'negative attitude towards current railway policy' (answers 8, 9 or 10) or not (answers 0, 1, 2, 3, 4, 5, 6 or 7).

Attitude towards growth of railway transport

We measured the attitude towards growth of rail transport using a question with answers on a scale from 0 to 10 (0=very positive and 10=very negative). We used the answer to determine whether a person had a 'negative attitude towards growth' (answers 8, 9 or 10) or not (answers 0, 1, 2, 3, 4, 5, 6 or 7).

Age

For age we distinguished between three groups:
Category 1: participants between 15 and 44 years old;
Category 2: participants between 44 and 64 years old;
Category 3: participants more than 64 years old.

Location of bedroom

We determined at what floor the participants' bedrooms were located. For the purpose of the analysis, we divided the answers into two categories:
Category 1 = Ground floor, 1st floor and 2nd floor;
Category 2 = 3rd floor and higher

Level of education

We distinguished between three levels of education:
Category 1: no education or only primary education;
Category 2: lower general secondary/lower vocational education;
Category 3: higher general secondary/pre-university/senior secondary vocational education;
Category 4: higher professional/university education.

For some analyses/visualisations (Tables 4.6, 4.9 and 4.10) we combined the categories 1 and 2 due to the low numbers of participants in them.

Rattle

'Rattle' refers to situations in which participants hear, feel or see windows, doors and/or crockery. This variable combines the answers to three separate questions . Respondents were asked what they did when they felt, heard or saw vibrations which they believed were due to railway traffic, railway maintenance or any other activity on the tracks. They were also asked to specify whether they saw or heard a) windows, b) doors or c) crockery. The participants could choose one of the following answers: Yes=1, No=2 or Not applicable=3. For the purpose of the analysis, we dividend the participants into two groups based on the answers to these questions:

Group 1: Participants whose answer to at least one of the questions was Yes.
Group 2: Participants whose answer to all three questions was No or Not applicable

Sleep disturbance due to vibrations or noise

Similar to annoyance, sleep disturbance was measured on an 11-point scale (0-10) and it was also calculated in the same way. Respondents who stated that the noise or vibrations were 'imperceptible' were considered not to have experienced any sleep disturbance.

Degree of urbanisation

The degree of urbanisation is based on the Statline data of Statistics Netherlands (CBS). The five urbanisation classes are based on specific address density levels: 2,500, 1,500, 1,000 and 500 addresses per km². We distinguished between the following classes:

- Extremely urbanised (address density 2,500 or more);
- Highly urbanised (address density 1,500 to 2,500);
- Moderately urbanised (address density 1,000 to 1,500);
- Hardly urbanised (address density 500 to 1,000);
- Not urbanised (address density <500).

Expectations

We identified participants' expectations, asking them whether they felt the situation regarding train-related vibrations was improving, deteriorating or stable. For the purpose of the analysis, we combined the participants who expected stabilisation and those who expected improvement.

Windows open/closed

Participants were asked to indicate whether they kept their bedroom windows open or closed when using the bedroom, in winter and in summer. Based on the answers to these two questions we created three groups:

1. Closed (always) = windows closed in winter and in summer
2. Closed (summer or winter) = windows closed in summer or in winter
3. Open (always) = windows open in summer and in winter

HE glazing in bedroom

Participants were asked whether they had HE glazing in their bedrooms. They could choose one of the following answers: Yes=1, No=2 or Don't know=3.

Annex 4 Comparison of DR relationships with and without ISO weighting

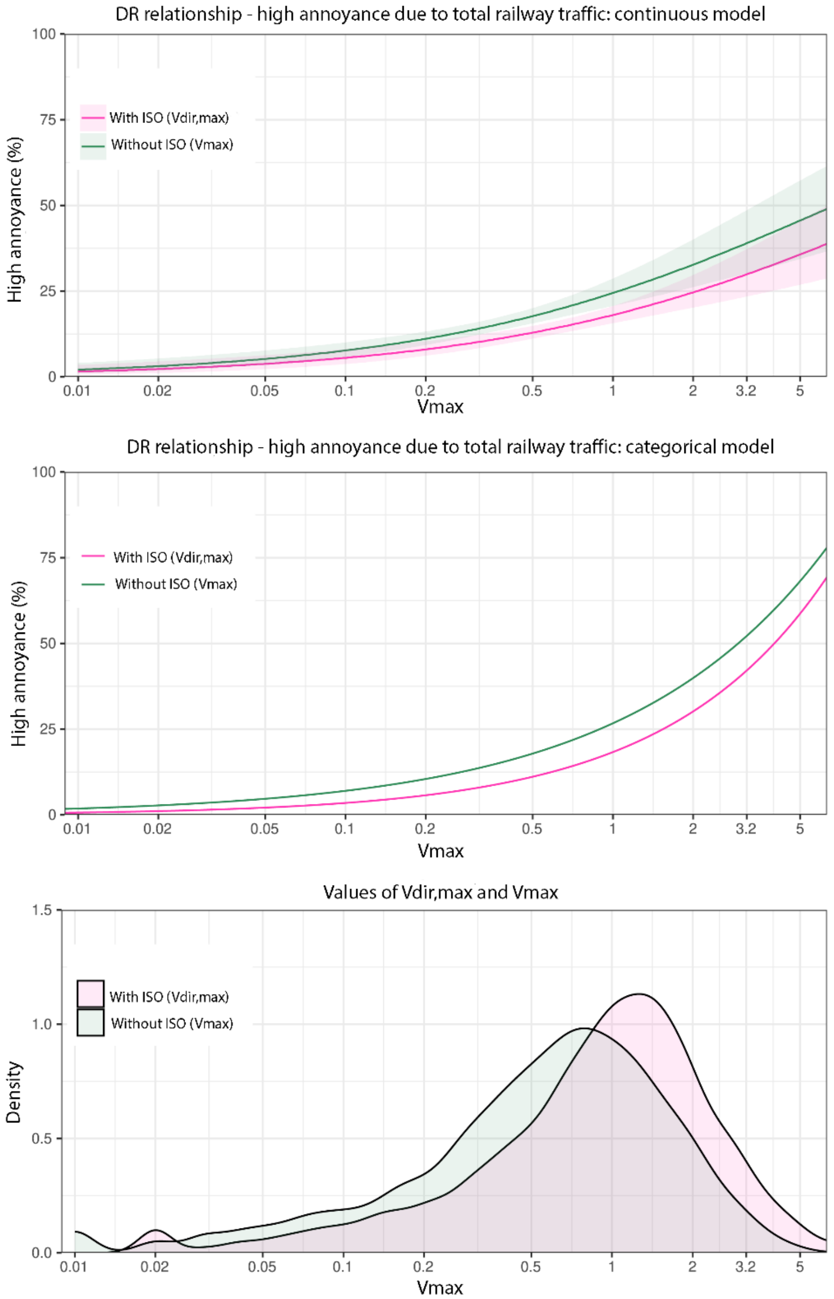

Figure B4.1 The DR relationships for V_{max} and $V_{dir,max}$ and high annoyance due to vibrations from total railway traffic, estimated using a continuous (top) and a categorical (centre) logistic regression model. In addition, the table presents the exposure distribution for V_{max} (without ISO weighting) and $V_{dir,max}$ (with ISO weighting) within the data set using a density plot (bottom). The plot shows that the values of $V_{dir,max}$ are higher than those of V_{max}.

Annex 5 DR relationship formulas

In principle, all DR relationships established in this study can be used to estimate the magnitude of the number of people reporting high annoyance and sleep disturbance due to vibrations from total railway traffic, freight trains and passenger trains. However, the preferred option is to use DR relationships which i) express vibration exposure in terms of distance from the railway line (m), or ii) express vibration exposure in a measure not subjected to ISO 2631 weighting. The relationship between exposure to railway-induced vibrations and high annoyance or sleep disturbance was found to be, in most cases, non-linear. Where this is the case, it is preferable to use DR relationships based on categorical models.

For that reason, in this annex we have only presented the formulas of the DR relationships between exposure to vibrations from total railway traffic, freight trains and passenger trains and high annoyance and high sleep disturbance due to vibrations from those sources *without* ISO weighting. The formulas shown always represent the DR relationship based on the model (continuous or categorical exposure) with the best fit. Where there was no demonstrable difference in fit, the formulas of both the linear and the categorical models are given. The formulas of the continuous models represent a logistic regression model. For the categorical models, the formula presents the trend line of the ten individual predictions of the categorical model (see section 3.9.3 and Chapter 7). As a result, the formulas are different in terms of their structure.

The table also presents the exposure range of the formula, i.e. the range of exposure values within which the formula can be applied reliably. If formulas are used with values outside of this range, considerable deviations may occur.

Table B5.1 Formulas of BR relationships between exposure to railway-induced vibrations and the percentage of participants reporting high annoyance due to railway traffic

Indicator	Formula	Formula range	Model type
Total railway traffic			
Distance from the railway (m)	% high annoyance = e^(3,84225 – 0,01271 * distance)	5 to 300 metres	Categorical
V_{max}	% high annoyance = e^(3.28509+ 1.33892* log10(V_{max})	0.05 to 3.2	Categorical
V_{per}	% high annoyance = e^(4.37632+ 1.10652* log10(V_{per})	0.0005 to 0.5	Categorical
RMS	% high annoyance = e^(6.8129+ 1.1341* log10(RMS)	0.00001 to 0.002	Categorical
Passenger trains			
Distance from the railway (m)	% high annoyance = (1/ (1 + e^(-(-1.5525 - 0.0082*distance))) * 100	5 to 300 metres	Continuous
V_{max} passenger trains	% high annoyance = (1/ (1 + e^(-(-1.8389 + 1.0498 log10(V_{max}))) * 100	0.01 to 3.2	Continuous
V_{max} passenger trains*	% high annoyance = e^(2.6305+ 0.6979* log10(V_{max})	0.05 to 3.2	Categorical
V_{per} passenger trains	% high annoyance = (1/ (1 + e^(-(-1.3207 + 0.6040 * log10(V_{per}))) * 100	0.0005 to 0.5	Continuous
RMS passenger trains	% high annoyance = (1/ (1 + e^(-(-0.0171 + 0.6070 * log10(RMS))) * 100	0.00001 to 0.002	Continuous
Freight trains			
Distance from the railway (m)	% high annoyance = (1/ (1 + e^(-(-0.0610 - 0.0086*distance))) * 100	5 to 300 metres	Continuous
V_{max} freight trains	% high annoyance = e^(4.0303+ 0.9743* log10(V_{max})	0.01 to 2.0	Categorical
V_{per} freight trains	% high annoyance = e^(5.1764+ 0.7947* log10(V_{per})	0.0005 to 0.1	Categorical
RMS freight trains	% high annoyance = e^(6.8149+ 0.8233* log10(RMS)	0.00001 to 0.001	Categorical

*No difference in fit was found between the continuous and categorical models for high annoyance due to vibrations from passenger trains based on V_{max} passenger trains. This is why both formulas are shown.

Table B5.2 Formulas of DR relationships between exposure to train-related vibrations and the percentage of participants reporting high sleep disturbance due to railway traffic

Indicator	Formula	Formula range	Model type
Total railway traffic			
Distance from the railway (m)	% high sleep disturbance = (1/ (1 + e^(-(-1.3782 - 0.0049*distance)) * 100	5 to 300 metres	Continuous
V_{max}	% high sleep disturbance = e^(2.9971+ 0.8058* log10(V_{max})	0.05 to 3.2	Categorical
$V_{per\ night}$	% high sleep disturbance = e^(3.9094+ 0.7572* log10($V_{per,\ night}$)	0.0005 to 0.5	Categorical
RMS night	% high sleep disturbance = e^(5.3411+ 0.7109* log10(RMS_{night})	0.00001 to 0.0125	Categorical
Passenger trains			
Distance from the railway (m)	% high sleep disturbance = (1/ (1 + e^(-(-2.0625 - 0.0068*distance)) * 100	5 to 300 metres	Continuous
V_{max} passenger trains	% high sleep disturbance = e^(2.3443+ 0.6963* log10(V_{max})	0.05 to 3.2	Categorical
V_{per} passenger trains night	% high sleep disturbance = e^(2.9980+ 0.5951* log10($V_{per,\ night}$)	0.0005 to 0.5	Categorical
RMS passenger trains night	% high sleep disturbance = e^(4.1741+ 0.5159* log10(RMS_{night})	0.00001 to 0.0125	Categorical
Freight trains			
Distance from the railway (m)	% high sleep disturbance = (1/ (1 + e^(-(-0.6448 – 0.0058*distance)) * 100	5 to 300 metres	Continuous
V_{max} freight trains	% high sleep disturbance = e^(3.7039+ 0.8714* log10(V_{max})	0.01 to 2.0	Categorical
V_{per} freight trains night	% high sleep disturbance = e^(4.7459+ 0.7080* log10(V_{per})	0.001 to 0.1	Categorical
RMS freight trains night	% high sleep disturbance = e^(5.9928+ 0.6747* log10(RMS_{night})	0.00001 to 0.001	Categorical

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