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Review article

Health effects of railway-induced vibration combined with railway noise – A systematic review with exposure-effect curves

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ABSTRACT

Background: The combined health impact of concurrent railway noise and railway vibration exposure is not yet well understood.
Objectives: This systematic review gives an overview of epidemiological studies on health effects from railway vibration, aiming to quantify this association with exposure-effect curves. Moreover, the combined health effects of vibration and concurrent noise were investigated.
Methods: We converted the vibration metric to an equivalent noise level and calculated an overall noise level by energetically summing the equivalent and railway noise level. The combined health effect was determined by using published evidence-based exposure-effect formulas.
Results: Studies included in this systematic review predominately investigated annoyance and self-reported sleep disturbances; no studies on manifest diseases were identified. For the combined effects of vibration and noise on "total" annoyance, the results based on the pooled analysis of CargoVibes project are recommended as conservative approach.
Discussion: Converting railway vibration into equivalent noise levels in dB may offer a pragmatic approach to assess the combined health effects of railway noise and railway vibration exposure. Future studies should include cardiovascular and mental diseases in addition to vibration-induced annoyance and sleep disturbances. Furthermore, future studies should include in-depth investigations of the interaction between railway noise and railway vibration to allow for a more accurate assessment of the railway-induced burden of disease.

1. Introduction

Long-term exposure to railway noise increases the risk of adverse health (World Health Organization, 2011). In Sweden, exposure to railway noise is estimated to be associated with a loss of 4322 disability-adjusted life years (DALYs) per year (Eriksson et al., 2017). Railway vibration is also known to impact health (Aasvang et al., 2007; Öhrström et al., 2009), but the combined impact of concurrent railway noise and vibration exposure is less clear.

A systematic review of scientific literature published between 2000 and 2013 on the health effects associated with railway traffic found 13 publications considering the impact of railway noise or vibration (Schlattjan et al., 2014). Most of the publications considered were based on two field studies: a study commissioned by the British Department for Environment Food and Rural Affairs (DEFRA) (5 publications) and the Swedish TVANE-project (Train Vibration and Noise Effects) (3 publications).

These studies considered the impact of railway noise and/or

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vibration exposures on annoyance, sleep disturbance, attention, heart rate, and cortisol levels. In the DEFRA study, annoyance was found to increase with the magnitude of the vibration (Waddington et al., 2014). The DEFRA study also found an increase in annoyance and sleep disturbances with increasing vibration, as well as with increasing noise exposure (Koziel, 2011). The TVANE-project found a strong relationship between annoyance from vibration and the measured vibration velocity; a vibration velocity of 0.4 mm/s was identified as a quasi-threshold for a strong increase in annoyance (Gidlof-Gunnarsson et al., 2012). Also, this study found a statistically significantly higher average annoyance in a region with high vibration compared to a region with low vibration at comparable sound levels (Öhrström et al., 2009). That is, in an area with high vibration, the same level of average annoyance was attained at approximately 5–7 dB (dB) lower sound levels (Gidlof-Gunnarsson et al., 2012).

Since 2013 (the last year included in the aforementioned literature review), the collaborative CargoVibes project summarized data from over 4000 individuals in 8 European countries, and generated exposure-effect-curves for annoyance caused by vibration (Waddington et al., 2015). CargoVibes also provided new insights into vibration-related sleep disturbances (Persson Waye et al., 2014, 2019). Another recent publication summarized six studies on the effects of vibration associated with the Japanese Shinkansen high-speed-train network (Yokoshima et al., 2017). Annoyance due to vibration was demonstrated, as well as annoyance due to noise. The Swedish EpiVib study examined the long-term health effects of railway vibration in over 6800 people with a residential address within 1 km of a western Swedish railroad line (Maclachlan et al., 2018). EpiVib reports that a significantly higher proportion of people are highly annoyed by railway vibration ensuing from freight trains and diesel trains than by vibrations caused by passenger trains and high-speed trains. Annoyance due to freight trains could also be observed at a distance of up to 400 m from the railroad line.

Since both railway-traffic noise and vibration exert negative health effects, a critical examination of how combined exposures affect health is needed. In addition, practical methods for the comparison and combination of both are currently lacking. Thus, the aims of this study are:

- to examine the exposure-effect relationships reported from studies examining railway vibration and railway noise with health and well-being outcomes, and
- to develop a new approach for estimating the combined impact of railway noise and vibration on health and well-being.

2. Materials and methods

2.1. Systematic literature review

2.1.1. Information sources and search

A systematic review of scientific literature was conducted to determine which health constraints may be associated with railway vibrations and secondary airborne noise. The search had no disease-specific restrictions but we focused on annoyance, sleep disturbance, psychological disorders and cardiovascular disease as probable health outcomes, and sought to answer the following research questions:

1. Is there an increased risk of high annoyance, sleep disorders, psychological disorders or cardiovascular diseases among persons exposed to (nighttime) vibrations and secondary airborne noise from railway traffic, which is not exclusively due to railway traffic equivalent continuous noise levels or maximum noise levels?

   If an association is confirmed in Question 1:

2. How can the exposure-effect relationships between vibrations or airborne sound and the occurrence of annoyance, sleep disorders, psychological diseases or cardiovascular diseases be described?
3. How do vibrations interact with continuous noise levels or maximum noise levels to cause railway traffic-related annoyance, sleep disorders, psychological diseases or cardiovascular diseases?

Our research question 1 was specified according to the population, exposure, comparison, and outcome of interest (PECOS criteria), as shown in Table 1. The review procedures were outlined in a study protocol registered a priori at PROSPERO (CRD42020206055). This study is an update of the literature search by Schlattjan and colleagues (Schlattjan et al., 2014).

We searched the Embase (via Ovid) and MEDLINE (via Pubmed) medical literature databases from 2013 through November 23, 2020 using the search strings given in Table S1. Additionally, we searched the conference proceedings of Internoise, Euro-Noise and the German Society for Acoustics (DAGA), as well as the websites of the projects CargoVibes, DEFRA, EpiVib, RIVAS and TVANE. Moreover, we considered studies cited in the DIN 4150–2, the German standard for vibrations on buildings (part 2: effects on people in buildings). Reference lists of included studies were also searched for relevant publications. Older studies from the grey literature search not cited by Schlattjan et al. (2014) were also included in this review. All population-based epidemiological publications investigating railroad noise-related vibration in the general population with regard to annoyance, sleep disturbance, mental ill health, cognitive disorders, and cardiovascular and cancer diseases were included. A description of various vibration metrics is given in Table S2.

2.1.2. Study selection

We used Endnote as reference management system. Study selection was done in two steps: First, title-abstracts were screened independently by two authors for inclusion and exclusion criteria. Afterwards full-texts of included references were screened for relevance by the same authors. Study selection steps were piloted and disagreements were solved in meetings with the study team. Information of included publications was extracted in extraction tables on study design, region, population characteristics (size, age and sex distribution), sampling procedure (recruitment, response and follow-up), definition and measurement of exposure (vibration and noise) and outcome, relevant study results, funding, analysis method and confounder adjustment, conflict of interest. Data extraction was done by one author and checked for accuracy by a second author. Data extraction was piloted in the study team.

Table 1
Eligibility criteria according to population, exposure, comparison, outcome of interest, and study design.

Code	Category	Inclusion criteria	Exclusion criteria
P	Population	General population	Occupational populations, animals
E	Exposure	Railway-related vibration (about 8–40 Hz) and secondary airborne noise	Other noise sources (railway noise only, road traffic noise, aircraft noise)
C	Comparison	No railway-related vibration and/or no secondary airborne noise	
O	Outcome	Annoyance, sleep disorders, cardio-vascular diseases, subclinical risk markers of the cardiovascular system, mental health	
S	Study design	Cohort, case-cohort, case-control, cross-sectional studies	Reviews, editorials, letters to the editor, simulation and laboratory studies, qualitative studies

2.1.3. Risk of bias assessment

Risk of bias was assessed according to Ijaz et al. (2013) and Kuijer et al. (2018) with modifications (Romero Starke et al., 2019). Study quality was rated using the following major and minor domains: major domains: 1) recruitment procedure and follow-up (in cohort studies), 2) exposure definition and measurement, 3) outcome, 4) confounding and effect modification, 5) analysis method; minor domains: 6) blinding of assessors and 7) funding and 8) conflict of interests. The chronological sequence of exposure and outcome indicates a possible “cause and effect” bias and is generally important to consider in quality evaluation. Annoyance from railway vibrations, the mostly studied outcome is directly related to the simultaneous exposure. Thus, cross-sectional studies (which are otherwise considered to have a high risk of bias in the “chronology” domain) are generally suitable for analyzing this association. For this reason, with respect to mainly short-term events as annoyance and sleep disturbance, we did not consider the “chronology” domain in the present study.

By definition, a study was considered to have a low overall risk of bias if all major domains were rated low risk of bias. Two authors independently rated the quality of each study. Disagreements were discussed in the study team. The quality rating was piloted.

2.2. Statistical analysis

The following three-step procedure was applied to estimate the health effects for a given combination of railway-induced vibration and railroad traffic noise:

Step 1. Equivalence Curves for railway noise and vibration. Based on the results of the literature identified in the systematic search of papers, we calculated equivalence curves for noise and vibration. The equivalence curves should depict the levels of railway vibration and railway noise associated with the same likelihood of an outcome. To obtain the equivalence curves we first extracted formulas for exposure-effect curves describing the association between railway vibration and an outcome. Since railway noise and vibration often occur concurrently, exposure-effect curves describing an isolated exposure to railway vibration or noise are helpful for understanding the direct effect of the exposure. Thus, exposure-effect curves obtained from an area where only one exposure (railway vibration or railway noise) predominated, were also preferred. At least railway vibration formulas describing exposure-effect curves should have controlled for railway noise (or vice versa).

We determined the equivalence relationship by setting two exposure-effect formulas for the same outcome equal to each other, and solving for the concurrent exposure. If a single study reported exposure-effect curves both for railway vibration and noise, these two curves from the same study were set as equal to each other using the equal-annoyance approach which determines the noise and vibration levels associated with the same annoyance level. If only a exposure-effect curve for vibration was available, the vibration curve was set equal to existing WHO Guideline on Environmental Noise for the European Region exposure-effect curves for railway noise annoyance (Guski et al., 2017) (estimating %HA = proportion of highly annoyed people given a specific railway noise level) and sleep disturbance (Basner and McGuire, 2018). Our approach implies that high annoyance/high sleep disturbance by noise is comparable to high annoyance by vibration.

With the resulting formulas, a curve can be plotted showing how railway vibration and noise exposures relate to each other, with respect to the outcome. The formula also facilitated the conversion of a vibration metric into an equivalent noise-level in dB for the same likelihood of an outcome.

Step 2. Summation of noise equivalent level and railway noise level. In a second step, we examined how the conversion of vibration into noise can be used to consider the combined impact of noise and vibration. If no other interaction between railway-related vibration and railroad noise could be derived from the included studies, we assumed in the sense of a pragmatic approach that the railway-related vibration converted into a noise level (“equivalent level”) and the railroad noise level can be summed up energetically to the total level (“summation level”) and that, for example, the annoyance for this total level is as high as for an equally high sole noise level. The energetic summation of a vibration level’s equivalent continuous noise-equivalent $L_{vibration}$ in dB with the expected noise levels L_{noise}, also in dB, was accomplished with the following formula:

$$L_{total} = 10\, log\left[10^{L_{vibration}/10} + 10^{L_{noise}/10}\right] \tag{1}$$

We converted the noise values to commonly used weighted noise metric L_{DEN}, when necessary using the conversion of the Nordic prediction method (Ringheim, 1996; Ringheim and Nielsen, 1997).

Step 3. Determination of the combined health effects of railway-related vibration and noise. The resulting combined noise level can be inserted into published evidence-based exposure-effect formulas to predict the added impact of vibration on health and well-being. We applied the %HA curve from Guski et al. (2017) to determine the proportion of people who are highly annoyed by the total noise level.

3. Results

3.1. Systematic review

After removal of duplicates, 5063 references were included in the title-abstract screening. We screened the full-texts of 159 articles from electronic database search and 66 full-texts from additional sources. In total, 173 full-texts were excluded from further consideration. The most common reason for exclusion was that studies only considered railway noise, not railway-related vibration. Other exclusion criteria were study design: n = 25 qualitative or laboratory studies and n = 7 reviews. In seven cases, the publication was a short abstract of a conference contribution, or we were unable to locate the full-texts despite extensive efforts by our institute’s librarian. The PRISMA flow diagram shown in Fig. 1 summarizes the literature search. Additionally, references of excluded studies are listed by reason in the supplementary material (Table S3).

Altogether, we included 52 publications from literature search (listed in Table S3). Most articles were published as part of the English DEFRA study “Human Response to Vibration in Residential Environments” (n = 20), followed by CargoVibes (n = 6), a German study on vibration perception and annoyance in residents (“*Erschütterungswirkungen aus dem Schienenverkehr*”) with secondary analysis (n = 5), the Swedish TVANE study “Train Vibration And Noise Effects” (n = 3), the Dutch study “*Wonen langs het spoor*” (n = 2), the EpiVib study (n = 1) and the D-12 study (n = 1). Another eight articles examined the association between vibration from the Shinkansen railway and health study. In addition, two German studies from the DIN 4150-2 guideline and three additional publications without specifying a study name were included. One Norwegian study investigated the effect of secondary airborne noise only.

All studies included women and men, and were conducted in Europe with the exception of the North American D-12 study and the Japanese studies on the Shinkansen railway. The majority of studies investigated the effect of vibration on annoyance. Other outcomes were self-reported sleep disorders, self-reported health and disturbance in daily activities. Different outcome assessment methods and definitions were used by studies. More recent studies (i.e. CargoVibes, TVANE, DEFRA study, EpiVib, and “*Wonen langs het spoor*”) used standardized outcome definitions, while older studies used different questionnaires. Vibration was generally considered over the whole day in the majority of studies, except for studies on high sleep disturbance from CargoVibes, the DEFRA study and the Norwegian study on annoyance from secondary airborne noise which limited exposure to the nighttime. Results of the

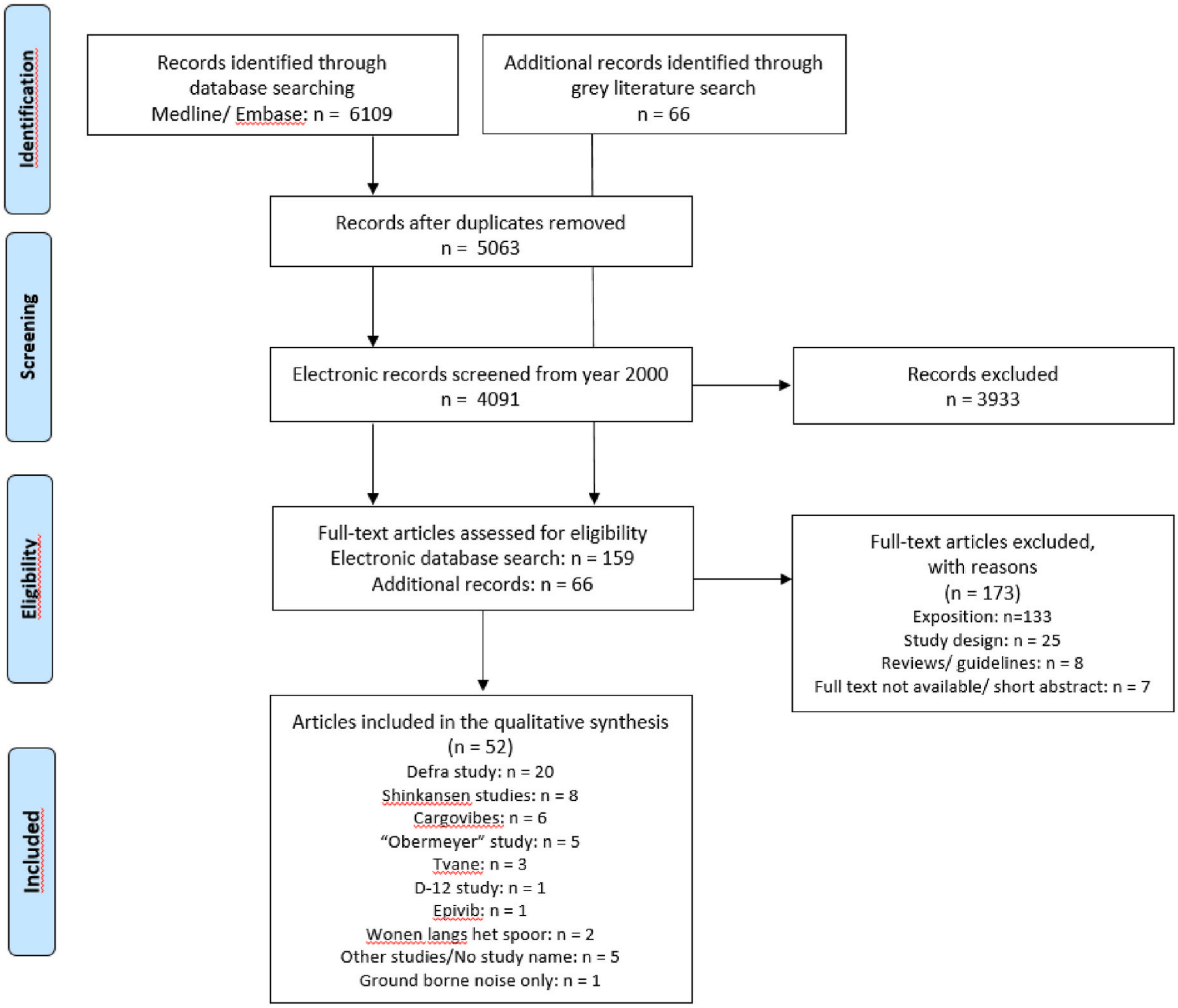

Fig. 1. PRISMA flow diagram (adapted from Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD et al. The PRISMA, 2020 statement: an updated guideline for reporting systematic reviews. BMJ, 2021; 372:n71. https://doi.org/10.1136/bmj.n71).

single studies are shown in the data extraction tables in the supplementary (Tables S4–S17). All included studies were characterized by a high risk of bias (Table S18). A common source of high risk of bias resulted from the way in which participants were recruited, respectively the number of individuals participating in the study. In addition, most studies did not adjust for the socioeconomic status as an important confounder in their analyses which may affect noise annoyance (Preisendörfer et al., 2022; Romero Starke et al., 2023).

Based on the systematic literature search, we found a positive association predominantly for the outcomes of annoyance and sleep disturbance due to vibration (research question 1): The proportion of highly annoyed and highly sleep disturbed increased with increasing railway vibration exposure. Furthermore, positive exposure-effect relationships were found in the literature for both these outcomes (research question 2). The combined interaction between vibration and rail traffic noise on annoyance (research question 3) was investigated in detail in the DEFRA study, TVANE study, the previous study of Öhrström et al. (Öhrström, 1997; Öhrström and Skånberg, 1996) and the German study "*Erschütterungswirkungen aus dem Schienenverkehr*". The DEFRA study showed that vibration-related annoyance increased with increasing vibration and noise exposure (Koziel, 2011; Woodcock et al., 2011). In the study by Öhrström et al. (Öhrström, 1997; Öhrström and Skånberg, 1996) and the TVANE study (Ögren et al., 2017), a comparison of areas with the same railway noise exposure revealed that more people were annoyed when railway vibration was additionally present. In addition, Zeichart and colleagues (Zeichart, 1998; Zeichart et al., 1993, 1994a) also observed an increase in annoyance with increasing vibration. But they concluded that the relationship between vibration level and annoyance level was not very strong. They observed that the effect of vibration on annoyance was lower at higher noise levels than at lower noise levels. Thus, the results of the epidemiological studies do not allow a clear overall conclusion on the interaction of railway-related vibration and railway noise.

3.2. Annoyance equivalence curves

For annoyance equivalence curves we included the following three studies TVANE, the pooled analysis by Janssen et al. (2013), and the "*Wonen langs het spoor*" study. Studies were characterized by exposure-response curves. We did not include the DEFRA study due to high bias in recruitment (cold calling method, low response: 18%) and the Germany study on vibration for the reason that annoyance was not measured according to standardized methods of the ISO criteria (assessment of annoyance from railway without concrete reference to time).

3.2.1. TVANE study

The TVANE study measured annoyance from vibration and annoyance from noise according to ISO/TS 15666:2003 (International Organization for Standardization, 2003) using the following questions "Thinking about the last 12 months or so, when you are here at home, how much does noise from a railway annoy or disturb you" and

"Thinking about the last 12 months or so, when you are here at home, how much does vibration from a railway annoy or disturb you".

Annoyance curves describing the noise level associated with the same amount of high annoyance at various levels of vibration were published by Ögren et al. (2017). Using logistic regression formulas obtained from the first phase of the TVANE project described by Ögren et al. (2017) for high annoyance due from an area exposed to both noise and vibration and high annoyance due to noise from an area exposed only to noise (personal communication), we obtained an equivalence curve for high annoyance. These formulas examined vibration as the log of vibration velocity [v_v] in mm/s and noise as the 24 h equivalent level ($L_{eq,24h}$) in dB. The formulas are shown in Table 2.

Solving for noise levels resulted in the formula for a curve describing what levels of vibration create an equivalent level of high annoyance due to noise, which we converted to L_{DEN} by adding 7.4 dB based on the Nordic method for Area 1 (Ringheim, 1996; Ringheim and Nielsen, 1997). From the formulas in line 1 and 3, the equivalent noise (L^*_{DEN}) in dB was calculated as follows:

$$L^*_{DEN} = \left[\frac{14.655 + (3.827 \times log_{10} v_v)}{0.2072}\right] + 7.4dB(A) \quad (2)$$

We considered the equal high annoyance curves of noise from Area 1 noise (Table 2, line 3) and vibration from Area 2 (Table 2, line 1) shown in Fig. 2 as our core analysis (step 1). According to this relationship, 0.5 mm/s vibration velocity in Area 2 (exposed to vibration and noise) is associated with the same percentage of high annoyance (ca. 28%) as could be expected from L_{DEN} = 72.6 dB in the area exposed only to railway noise (Area 1). Further examples are shown in Table 3.

The vibration values converted to the equivalent L_{DEN} values in dB based on the Ögren-curves were energetically summed with noise values using formula 1 (step 2). As an example, an energetic addition of the noise equivalent of 72.6 dB for vibration of v_v = 0.5 mm/s with an L_{DEN} of 60 dB results in 72.8 dB. Thus adding vibration of v_v = 0.5 mm/s to an area exposed to noise at a level of L_{DEN} = 60 dB increased the probability of high annoyance to a degree expected by increasing noise by 12.8 dB. The resulting L_{DEN}-equivalents for vibration levels were then inserted into a WHO high noise-annoyance functions published by Guski et al. (2017) shown in equation (3). Using the evidence-based Guski-formula for high annoyance associated with noise as L_{DEN} (step 3),

$$\%HA = 38.1596 - (2.05538 \times L_{DEN}) + (0.0285 \times L_{DEN}^2) \quad (3)$$

shows that this amount of noise and vibration is generally associated with 39.6% probability of being highly annoyed, while the noise alone is associated with 17.4% probability. However, the exposure-effect relationships for L_{DEN} and %HA from Ögren and Guski shown in Table 3

Table 2
Logistic regression model for annoyance in 2 different areas (area 1: noise only, area 2: noise and vibration from Ögren et al. (2017), Table 3).

Area	Exposure	Formula
High Annoyance		
1. Area 2, noise and vibration	vibration	$logit(P_1) = 0.2247 + 3.827(\log_{10} v_v)$
2. Area 2, noise and vibration	noise	$logit(P_1) = -11.38 + 0.1789(L_{AEq,24h})$
3. Area 1, noise only	noise	$logit(P_1) = -14.43 + 0.2072(L_{AEq,24h})$
Annoyance		
4. Area 2, noise and vibration	vibration	$logit(P_2) = 0.369 + 3.18(\log_{10} v_v)$
5. Area 2, noise and vibration	noise	$logit(P_2) = -10.2 + 0.168(L_{AEq,24h})$
6. Area 1, noise only	noise	$logit(P_2) = -11.4 + 0.168(L_{AEq,24h})$

P_1 is the probability of "high annoyance" (unpublished); P_2 is the probability of "annoyance" [Ögren et al., 2017].

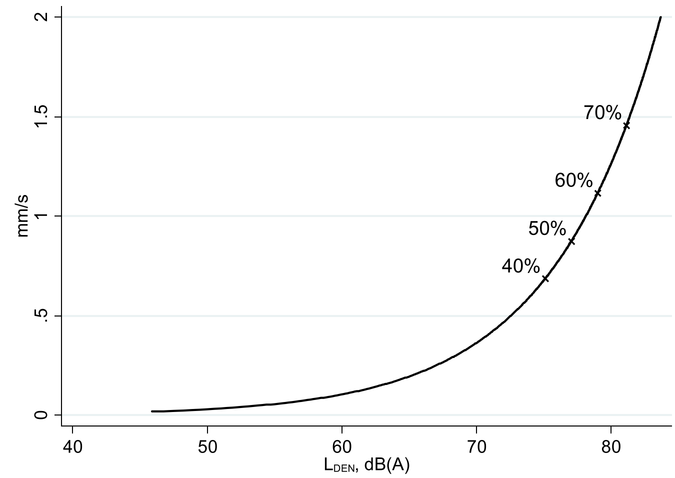

Fig. 2. Equivalence curve for weighted vibration velocity and noise in relation to high annoyance (%Highly Annoyed) in the TVANE study (Ögren et al., 2017). The values on the curves indicate the percentage of people expected to be highly annoyed by noise (Area 1; exposure to noise only) or vibration (Area 2; exposure to vibration and noise).

Table 3
Examples of the noise and vibration equivalence and the corresponding percentage of highly annoyed (%HA) for TVANE.

v_v (mm/s) in Area 2	L^*_{DEN} (dB [A]) noise equivalent based on Area 1	% Highly Annoyed according to the TVANE study (Ögren et al., 2017)	% Highly Annoyed according to WHO (Guski et al., 2017)
0.5	72.6	28.3%	39.2%
1.0	78.1	55.6%	51.5%
1.5	81.4	71.1%	59.7%
2.0	83.7	79.8%	65.8%

vv weighted vibration velocity, L^*_{DEN} noise equivalent in dB

diverge, with the WHO estimates beginning higher but increasing less dramatically.

3.2.2. CargoVibes

In the study "Attenuation of ground-borne vibration affecting residents near railroad", Janssen et al. (2013) produced a pooled analysis using individual data from seven different studies to determine the exposure-effect relationship between vibration and annoyance from rail traffic. The seven studies pooled were:

1. Vibration effects from rail traffic noise from passenger and freight trains (Passchier-Vermeer et al., 1998; Zeichart, 1998; Zeichart et al., 1994a, 1994b)
2. Norwegian study on vibration and road traffic noise in Oslo (Klæboe et al., 2003). *(For the pooled CargoVibes evaluation, only study participants who lived near the railroad line were included.)*
3. Japanese study on Shinkansen high-speed trains (Yano et al., 2005; Yokoshima et al., 2008)
4. North American study "Ground-Borne Noise and Vibration in Buildings Caused by Rail Transit" due to light and heavy rail trains (Zapfe et al., 2009)
5. English DEFRA study "Human Response to Vibration in Residential Environments" of passenger and freight trains and construction sites. *(Only study participants living near the railroad were included in the pooled analysis.)*
6. Swedish study "Train Vibration And Noise Effects" (TVANE) of passenger and freight trains

7. CargoVibes – Dutch city Den Bosch (passenger and freight trains) and Polish city Radzionków (freight trains).

Annoyance was measured standardized according to ISO/ICBEN in the Japanese study (3.), the DEFRAstudy (5.), TVANE (6.) and CargoVibes (7.). The other studies (1., 2. and 4.) used different time windows or did not relate the question to a concrete time window. The questions used by researchers are shown in Janssen et al. (2013) and in the supplementary data extraction table of this publication.

Since the studies used different parameters to represent vibration exposure, a matrix was created to allow the parameters to be converted into each other and to indicate the estimated degree of uncertainty in the conversion. Janssen et al. (2013) estimated coefficients for the exposure-response model using $\log_{10}(Vd,_{max})^3$. We focused on an exposure-effect relationship, which excluded the Japanese Shinkansen studies because high annoyance values were measured even at very low vibrations from the Shinkansen high-speed trains, which were not comparable with the results of the other studies of more traditional train types.

The estimated coefficients from the Janssen et al. (2013) pooled analysis were inserted into the annoyance probability distribution formula published by Miedema and Oudshoorn (2001) to determine the proportion of highly annoyed individuals (%HA) for values of $\log_{10}(v_{d,max})$:

$$\%HA = 100 \times 1 - \Phi\left(\frac{72 - 10.72 - (40.53 \times \log_{10} v_{d,max})}{\sqrt{(126.73 + 1528.14)}}\right) \tag{4}$$

In this formula, Φ represents the standard cumulative normal distribution (Probit function). Equating the annoyance level from rail-induced vibrations according to this formula to the annoyance level from rail traffic noise according to the WHO Guideline on Environmental Noise for the European Region (Guski et al., 2017) yields the following formula for determining the noise equivalent (step 1):

$$L^*_{DEN} = 36.0593 + \sqrt{\frac{(\%HA - 38.1596)}{0.0285} + 1300.2731} \tag{5}$$

where Noise L^*_{DEN} is the "noise equivalent" in decibels. The exposure-effect relationship is shown in Fig. 2.

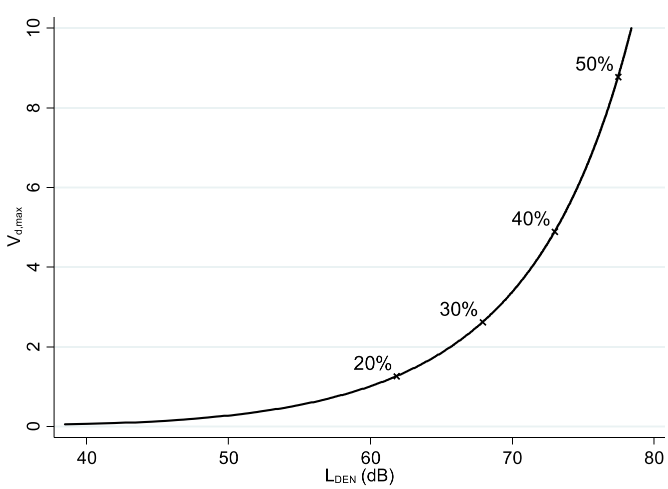

Fig. 3. Equivalence curve for weighted vibration velocity and noise in relation to high annoyance (%Highly Annoyed) in the pooled analysis by Janssen et al. (2013). The values on the curves indicate the percentage of people expected to be highly annoyed.

This equivalence relationship is shown in Fig. 3. According to this equivalence relationship, for example, a V_{max}[1] of 1.0 corresponds to a L^*_{DEN} of 61.1 dB. Table 4 shows four examples of the equivalence of railroad vibration and rail traffic noise with regard to the proportion of highly annoyed persons.

Again, the vibration-related noise equivalents were energetically summed with noise values using formula 1 (step 2), and the resulting L_{DEN}-equivalents were then inserted into the WHO high noise-annoyance functions published by Guski et al. (2017) (step 3). For example, the energetic addition of vibration of $Vmax = 1.0$ (equivalent to 61.1 dB [A] L^*_{DEN}) with an L_{DEN} of 60 dB results in 63.6 dB which corresponds to 22.7% of highly annoyed according to the formula (Equation (3)) from Guski et al. (2017).

3.2.3. *Wonen langs het spoor*

Furthermore, we used the cross-sectional results of the "*Wonen langs het spoor*" study (van Kamp et al., 2014). The study assessed annoyance standardized with the following question "Thinking about the last 12 months, when you are at home, what number from 0 to 10 best shows how bothered, annoyed or disturbed you have been by vibration from railway" (van Kamp et al., 2014).

In the study report, the equations for the unadjusted models and the constants (intercepts) of the regression models are not reported but information was provided via personal communication with Irene van Kamp (Table 5).

The formula for the exposure-response function including all railway traffic (Table 6, line 1) is:

$$\%HA = 6.3315 \times \ln(Vmax) + 35.555 \tag{6}$$

Equating the annoyance level from rail-induced vibrations according to this formula to the annoyance level from rail traffic noise according to the WHO Guideline (Guski et al., 2017) yields the following formula for determining the noise equivalent (step 1):

$$L^*_{DEN} = 36.0593 + \sqrt{\frac{(6.3315 \times \ln(V_{max}) + 35.555) - 38.1596}{0.0285} + 1300.2731} \tag{7}$$

According to this equivalence relationship, for example, a V_{max} of 1.0 corresponds to a L^*_{DEN} of 70.8 dB. Table 6 gives four examples of the equivalence of railroad vibration and rail traffic noise with regard to the proportion of highly annoyed persons.

As for the TVANE and for the CargoVibes study, we energetically summed up the vibration-related noise equivalents with noise values using formula 1 (step 2), and we inserted the resulting L_{DEN}-equivalents into the WHO high noise-annoyance functions published by Guski et al. (2017) (step 3). The energetic addition of vibration of $Vmax = 0.5$ with an L_{DEN} of 60 dB corresponds to 32.2% of highly annoyed.

Table 4
Examples of the noise and vibration equivalence and the corresponding percentage of highly annoyed for CargoVibes.

V_{max}	L^*_{DEN} (dB [A]) noise equivalent	Highly Annoyed according to WHO (Guski et al., 2017)
0.5	55.6	12.0%
1.0	61.1	19.0%
1.5	64.4	24.0%
2.0	66.8	28.1%

[1] Unitless.

Table 5
Functions of the different exposure-effect curves (*Wonen langs het spoor* data from the 2013 initial survey; van Kamp, personal communication, Nov. 23, 2021) for V_{max} values ranging from 0.001 to 10.

Railway Traffic	Exposure-effect Curves
Unadjusted Linear Functions	
All railway traffic	%HA = 35.555 + 6.3315 ln (Vmax)
Passenger trains	%HA = 7.5987 + 1.9009 ln (Vmax)
Freight trains	%HA = 43.521 + 7.2234 ln (Vmax)

Table 6
Examples of the noise and vibration equivalence and the corresponding percentage of highly annoyed.

V_{max}	L^*_{DEN} (dB [A]) noise equivalent	Highly Annoyed according to WHO (Guski et al., 2017)
0.5	68.5	31,1%
1.0	70.8	35.5%
1.5	72.1	38.1%
2.0	73.0	40.0%

3.3. Sleep disturbance

3.3.1. CargoVibes

We could not derive the proportion of highly sleep-disturbed persons (%HSD) due to railway-induced vibration from the available published studies. In principle, applying the above mentioned three-step procedure, we could have estimated the %HSD-formula on the basis of the Netherlands CargoVibes study (Persson Waye et al., 2019). However, we would like to point out that the corresponding Polish CargoVibes does not find a relationship between railway-induced vibration and severe sleep disturbance. Thus, the CargoVibes study does not allow a clear conclusion on railway-induced vibration effects. The "*Wonen langs het spoor*" study finds a positive exposure-effect relationship between railway-induced vibrations and severe sleep disturbances; however, quantification of the proportion of highly sleep-disturbed persons would only be possible separately for passenger trains and freight trains.

For manifest cardiovascular diseases as well as for other diseases, we could not identify any studies that would allow quantification of the exposure-effect relationship.

4. Discussion

In the present study, we investigated health-related effects of vibration from railway traffic using a systematic literature search and subsequent quantification of the exposure-effect curves by considering concurrent traffic noise to vibration levels. Most included studies investigated vibration annoyance and self-reported sleep disturbances from railway vibration. Overall, results suggest that railway vibration increases high vibration annoyance and self-reported high sleep disturbance. We calculated study-specific equal annoyance curves for noise and vibration. As the results of the epidemiological studies did not allow a clear overall conclusion on the combined health effect of railway vibration and noise, in a pragmatic approach, we summed up energetically the railway-related vibration converted into a noise level and the railroad noise level to a total level ("summation level"). Finally, we inserted the resulting summation level into published evidence-based exposure-effect formulas to predict the added impact of vibration on annoyance.

The TVANE study (Ögren et al., 2017) introduced the "equal annoyance procedure". Here the equivalent noise levels were calculated on the basis of a study region that was characterized by exposure to railway-noise with no railway-related vibration and an area that was exposed to railway noise and vibration. In contrast, in this study we determined the combined noise and vibration effect by mathematical equation. In order to achieve the best possible comparability of annoyance values between the included studies, all three studies were assigned the %HA values resulting from the WHO curve (not from the original studies) at a given noise level. Accordingly, the %HA values resulting from the WHO formula for the respective noise equivalent were also assigned to the "equivalent" vibration exposures. The resulting %HA values may differ from the %HA values reported in the individual studies. For example, in the TVANE study, the %HA value (48.2%) according to the WHO formula and according to the "original" TVANE %HA value is identical for an L_{DEN} of 76.7 dB only. L_{DEN} values < 76.7 dB result in higher %HA values according to the WHO formula (Table 3, right column) than in the original TVANE study (Table 3, second column from right); L_{DEN} values > 76.7 dB result in lower %HA values according to the WHO formula than in the original TVANE study. Consequently, weighted vibration velocity values < 0.83 mm/s according to the WHO formula result in higher, weighted vibration velocity values > 0.84 mm/s result in lower %HA values than in the original TVANE study. In principle, the estimation of annoyance vibration and railway noise (as well as for the sum level) could have also been calculated based on the original %HA curve of the TVANE study. However, we see in the choice of the WHO exposure-effect curve the advantage of a better scientific validation (by deriving the WHO exposure-effect curve with a systematic review), thus also the advantage of a higher generalizability. We were able to derive equivalence curves for railway-induced vibration and noise from three studies (TVANE, CargoVibes and *Wonen lang het spoor*): As a result, the pooled analysis of CargoVibes showed the lowest, and the TVANE study the highest annoyance effect for a given noise-induced railway vibration. In TVANE the maximum velocity was used. For example, for a maximum velocity of 1 mm/s, the %HA was about 52% (Table 3) based on the WHO curve. Janssen et al. (2013) converted all vibration metrics in their pooled analysis to $V_{d,max}$ in the CargoVibes study which we converted to V_{max} for our analysis. The V_{max} was also used in the *Wonen langs het spoor study*. For example, an exposure of 1 V_{max} vibration would lead to a proportion of 19% HA in the CargoVibes study (Table 4), respectively 36% HA in the *Wonen langs het spoor study* (Table 6). The results of the TVANE study and the last mentioned two studies are not directly comparable since different metrics were used. For a given maximum velocity value, it can be assumed that the V_{max} value is higher for a typical train pass-by; thus the %HA values in the TVANE study would slightly decrease, if they were related to V_{max} of the same magnitude.

The combined effect of traffic noise and vibration was studied in the DEFRA study (Koziel, 2011; Woodcock et al., 2011), TVANE (Gidlof--Gunnarsson et al., 2012; Ögren et al., 2017; Öhrström et al., 2009), the previous study by Öhrström et al. (Öhrström, 1997; Öhrström and Skånberg, 1996) and in the study by Zeichart (Passchier-Vermeer et al., 1998; Zeichart, 1998; Zeichart et al., 1993, 1994a). The study-specific results on the interaction between railway noise and railway-induced vibration are not consistent: in the DEFRA study vibration-related annoyance increased with increasing vibration and noise exposure (Koziel, 2011; Woodcock et al., –28), but in the Swedish study railway-related annoyance was suggested to be independent of the railway noise level (Gidlof-Gunnarsson et al., 2012; Ögren et al., 2017; Öhrström, 1997; Öhrström et al., 2009; Öhrström and Skånberg, 1996). In contrast, Zeichart (Zeichart, 1998; Zeichart et al., 1993, 1994a) observed that the effect of vibration on annoyance was lower at higher noise levels than at lower noise levels. Altogether, the available epidemiological studies do not allow a clear determination of the interaction between noise and vibration. The respective results from laboratory studies are also inconclusive; some studies indicate that noise annoyance is not affected by vibration and only observed weak association between noise level and vibration annoyance at high vibration levels (Howart and Griffin, 1990; Maigrot et al., 2017). In contrast, others found that vibration levels influenced noise annoyance (Morihara and Matsumoto, 2016), though this effect might only be limited to low noise levels (Paulsen and Kastka, 1995). Differences in laboratory results may have also arisen from methodological differences (Maigrot et al., 2017). Thus, currently it is not known how railway noise and railway-induced vibration interact with respect to annoyance. Therefore, in a pragmatic approach, we energetically summed up the equivalent noise level with the railway noise level. The energetic addition of noise levels represents the conventional approach used by official authorities. Thus for a conservative approach, we considered the energetic summation of the equivalent noise level and the railway noise level as appropriate. However, it is not known whether the combined effect is really better reflected by energetically summation, or by "epidemiological multiplication" (Seidler et al., 2019). Different models have been proposed for the assessment of total annoyance from different noise source. It has been assumed that each single noise source leads to the same annoyance level at equal exposure levels (Taylor, 1982). In addition, Miedema and colleagues (Miedema, 2004) estimated the combined effect with an annoyance equivalence model. Further, the dominant source model (Rice and Izumi, 1986) is based on the assumption that the most annoying traffic source determines the combined effect. Recently, we determined the combined effect of different traffic types (i.e. road, rail and air) on cardiovascular disease risks and depression by comparing different approaches using health claims data (Seidler et al., 2019). Results indicate that the "epidemiological risk multiplication" of different types of traffic may provide a better estimate than energetic addition of noise levels. In addition, several laboratory studies proposed models to estimate the effect of noise and vibration on total annoyance (Howarth and Griffin, 1990, 1991; Maigrot et al., 2017; Paulsen and Kastka, 1995). Here, the variance of the total annoyance model explained by noise was 40% compared to 11% explained by vibration (Maigrot et al., 2017). We encourage future research on the interaction between vibration and noise and their effect on health.

As the equivalence curves considerably differ between the three mentioned studies (TVANE, CargoVibes and *Wonen lang het spoor*), the resulting %HA for the combined effects of noise and vibration also considerably differ (particularly in the case of low noise levels), with CargoVibes leading to the lowest and TVANE study leading to the highest annoyance effects. A clear preference for one of the three studies cannot be derived on the basis of the quality assessment (risk of bias assessment). We therefore encourage future epidemiological research on this topic. In the meanwhile, as a kind of conservative approach, we recommend to apply our formulas derived from the TVANE study to assess the combined annoyance effect of railway noise and railway-induced vibration.

4.1. Strengths and limitations

There were differences in methodological approaches between the studies and all studies were characterized by a high risk of bias. One main reason for a high risk of bias was the way how participants were recruited, in particular, the use of a convenience sample in the DEFRA study, the lack of information given for the recruitment procedure (Eickschen and Brandenburger, 1984; Gottlob, 1987; Zapfe et al., 2009) or a response of less than 50% which was set as minimum for risk of bias assessment (DEFRA study, CargoVibes, EpiVib, *Wonen langs het spoor*). In addition, most studies did not adjust for socioeconomic status, which is a major confounder and closely related to health (Adler and Ostrove, 1999; Preisendörfer et al., 2022; Romero Starke et al., 2023). Furthermore, people with a low socioeconomic status live in more disadvantaged areas which are generally characterized by a higher road traffic load than those with a higher socioeconomic status (Dreger et al., 2019).

Moreover, most included studies investigated the effect of vibration on vibration annoyance, not on total railway annoyance. Thus, in the first step, we based our calculations on the source-specific annoyance (vibration or noise-related annoyance). The equating of noise- and vibration-related annoyance implies that high annoyance by noise is comparable to high annoyance by vibration. Energetic summation of vibration-related "equivalent noise levels" and noise levels should then in fact lead to "total railway annoyance". We believe that energetic summation of noise equivalent levels and noise levels constitutes a rather conservative approach. Further studies should verify whether the implicit assumptions of this approach (comparability of annoyance due to noise and vibration; energetic summation of noise equivalent levels and noise levels) are valid. As an important strength of this study we introduce a new pragmatic approach to estimate the combined effect of noise and vibration on health risks based on energetic summation. Previously, equal annoyance curves were only based on the comparison of an area with a single exposure (vibration alone) and an area with combined exposure (noise and vibration) (Ögren et al., 2017). Against the background of lacking scientific data on health effects of combined environmental exposures, we had to make pragmatic assumptions for this approach. Therefore, our approach should be tested in future epidemiological studies. This is of particular importance, since humans are usually facing a combination of several environmental exposures at the same time.

5. Conclusions

Overall, the results of our systematic review point to an increasing risk of high annoyance with increasing railway-related vibration. As far as we know, we developed the first pragmatic approach for estimating the proportion of highly annoyed people for a given combination of railway-related vibration and railway noise.

The exposure-effect curves for vibration-induce annoyance differed considerably between the included studies. To estimate the "total" annoyance resulting from combined railway noise and vibration, we determined the vibration exposure which led to the same proportion of highly annoyed individuals at a given noise exposure and set them equal. Energetic summation of the vibration-induced noise equivalents derived from the pooled CargoVibes study (Janssen et al., 2013) and of railway noise is recommended as a conservative approach.

Applying a sensitive search string in two databases, complemented by a grey literature search, we could not identify epidemiological studies on the association between railway-related vibration and other manifest diseases (e.g., cardiovascular diseases, mental illnesses) yet. Future research on the health effects of vibration should investigate cardiovascular and mental disorders in addition to annoyance and sleep disturbances, with a particular focus on the interaction of vibration and noise.

Author contributions

Conceptualization, A.S., J.H., C.P., K. K., M.Ö. and M.S.; methodology, A.S., J.H., C.P., K. K., M.Ö., I. v. K. and M.S.; software, J.H.; validation, A.S., J.H., M. Ö., I. v. K. and K.K.; formal analysis, J.H., M. Ö. And I. v. K.; investigation, Y.M., J.H. K.K. and M.S.; resources, A.S. and C.P.; writing—original draft preparation, J.H., A.S. and M.S.; writing—review and editing, Y.M., K. K., C. P., M. Ö., I. v. K., J.H., A.S. and M.S.; visualization, J.H. and M.S.; supervision, A.S.; project administration, M.S.; funding acquisition, A.S. and C.P.

All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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