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ENVIRONMENTAL VIBRATION AND PUBLIC HEALTH: A SCOPING REVIEW OF HEALTH EFFECTS, EXPOSURE ASSESSMENT, AND PREVENTIVE STRATEGIES

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- **OBJECTIVE.** To systematically map and synthesize current evidence on the effects of environmental vibration on populations, methods of exposure assessment, exposure–response relationships, regulatory approaches, and preventive strategies, and to identify the main gaps in the evidence base from a public health perspective.
- **MATERIALS AND METHODS.** A scoping review was conducted in accordance with JBI methodology, with reporting guided by PRISMA-ScR and PRISMA-S. PubMed/MEDLINE, Scopus, and Web of Science Core Collection were searched from database inception through 24 August 2026, supplemented by citation searching. Eligibility criteria were structured according to the PCC (Population–Concept–Context) framework. Twenty-four publications were included in the empirical synthesis and grouped into 13 research clusters; regulatory and methodological sources were analyzed separately.
- **RESULTS.** The most developed evidence base concerned railway vibration. The most consistent exposure–response relationships were observed for annoyance. Field and laboratory studies also support associations between nocturnal vibration and sleep disturbance, cortical arousals, awakenings, and acute changes in heart rate; in some experiments, vibration effects were observed independently of noise. Evidence for psychological and cognitive symptoms remains emerging and limited, and adequate prospective data on clinically manifest chronic diseases were not identified. Exposure assessment methods were heterogeneous and included RMS, VDV, vw,95, VdB, PPV, maximum frequency-weighted measures, and modelled exposure. Regulatory systems are primarily oriented toward comfort, annoyance, or structural safety rather than quantitative assessment of long-term health risk.
- **CONCLUSIONS.** Environmental vibration should be regarded as a physical stressor relevant to public health, with the strongest evidence for annoyance and sleep disturbance. Priorities include standardizing exposure assessment, jointly evaluating noise and vibration, investigating nocturnal exposure, vulnerable populations, and long-term clinical outcomes, and preventing exposure through spatial and transport planning.
- **KEYWORDS:** *environmental vibration, public health, railway vibration, annoyance, sleep disturbance, exposure assessment, prevention.*

ВІБРАЦІЯ У НАВКОЛИШНЬОМУ СЕРЕДОВИЩІ ТА ГРОМАДСЬКЕ ЗДОРОВ'Я: SCOPING-ОГЛЯД ВПЛИВУ НА ЗДОРОВ'Я, ОЦІНЮВАННЯ ЕКСПОЗИЦІЇ ТА ПРОФІЛАКТИЧНИХ СТРАТЕГІЙ

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- **МЕТА.** Систематично картувати та узагальнити сучасні наукові дані щодо впливу вібрації навколишнього середовища на населення, методів оцінювання експозиції, залежностей «експозиція–ефект», нормативних підходів і профілактичних стратегій, а також визначити основні прогалини доказової бази з позицій громадського здоров'я.
- **МАТЕРІАЛИ ТА МЕТОДИ.** Проведено scoping-огляд відповідно до методології JBI із дотриманням рекомендацій PRISMA-ScR та PRISMA-S щодо звітності. Пошук здійснювали в базах PubMed/MEDLINE, Scopus і Web of Science Core Collection від початку їх індексації до 24 серпня 2026 року з додатковим пошуком за списками цитувань. Критерії включення сформовано відповідно до моделі PCC (Population–Concept–Context). До емпіричного синтезу включено 24 публікації, згруповані у 13 дослідницьких кластерів; нормативні та методологічні джерела аналізували окремо.
- **РЕЗУЛЬТАТИ.** Найбільш сформована доказова база стосувалася залізничної вібрації. Найпослідовніші залежності «експозиція–ефект» встановлено для роздратування населення. Результати польових і лабораторних досліджень також підтверджують зв'язок нічної вібраційної експозиції з порушенням сну, кортикальними активаціями, пробудженнями та гострими змінами частоти серцевих скорочень; в окремих експериментах ефекти вібрації спостерігалися незалежно від шумового впливу. Докази щодо психологічних і когнітивних симптомів залишаються новими та обмеженими, а достатніх проспективних даних щодо клінічно маніфестних хронічних захворювань не виявлено. Методи оцінювання експозиції характеризувалися значною неоднорідністю та включали RMS, VDV, vw,95, VdB, PPV, максимальні частотно-кориговані показники та модельовану експозицію. Нормативні системи переважно орієнтовані на комфорт, роздратування або конструктивну безпеку, а не на кількісне оцінювання довгострокового ризику для здоров'я.

ВИСНОВКИ. Вібрацію навколишнього середовища доцільно розглядати як фізичний стресор, значущий для громадського здоров'я, з найбільш переконливими доказами щодо роздратування та порушення сну. Пріоритетними напрямами є стандартизація оцінювання експозиції, одночасне оцінювання шуму і вібрації, дослідження нічної експозиції, уразливих груп населення та довгострокових клінічних наслідків, а також профілактика впливу на етапах просторового і транспортного планування.

КЛЮЧОВІ СЛОВА: *вібрація навколишнього середовища, громадське здоров'я, залізнична вібрація, роздратування, порушення сну, оцінювання експозиції, профілактика.*

INTRODUCTION

Environmental vibration is a common physical factor in urban and suburban environments and is associated with railway and road traffic, metro systems, construction activities, and industrial sources. In residential settings, it is often intermittent and co-occurs with transportation noise. Actual human exposure is determined not only by distance from the source but also by soil properties, the frequency content of vibration, rolling-stock characteristics, foundations, building design, and the resonant properties of structures.

Transmission of vibration from the source to the individual is a multistage process: mechanical energy is generated by transport or technological processes, propagates through the ground, is transferred to foundations and structural elements, and may be amplified at specific natural frequencies of the building. Consequently, equal distance from a source does not ensure equal exposure, and field assessment requires simultaneous consideration of source characteristics, the propagation path, and building response.

From a public health perspective, exposure in the home is particularly important because the residential environment is expected to support sleep, rest, and recovery. Perception, discomfort, and annoyance have been studied most frequently; a smaller but important body of research has addressed sleep, cortical arousals, awakenings, and acute cardiac responses. A previous systematic review of railway vibration found that epidemiological evidence was largely limited to annoyance and self-reported sleep disturbance, while studies of clinically manifest disease were absent [1]; a corrigendum to that review was published in 2024 [2].

Since 2023, the evidence base has expanded to include new population studies of railway vibration, contemporary experiments on combined noise and vibration, and the first studies linking direct measurements of metro vibration with standardized indicators of mental health. Nevertheless, the literature remains methodologically heterogeneous, using RMS, VDV, statistical maxima of frequency-weighted velocity, VdB, PPV, maximum acceleration, and modelled individual exposure. This heterogeneity complicates direct comparisons across studies and the development of universal health-based criteria.

A further challenge is the combined action of noise and vibration. The two exposures often originate from the same transport source; therefore, their effects are correlated in field studies and may modify each other. Laboratory studies allow better separation of exposure components, whereas population studies better reflect real-life residential conditions. Triangulation across these designs is therefore essential when considering causality.

A gap also exists between the epidemiological evidence base and regulatory practice. International and national standards use different metrics and are primarily oriented toward comfort, annoyance, or structural safety, while universal health-based guideline values for long-term non-occupational vibration exposure have not been established. Standardization of exposure assessment is therefore central to the further development of evidence-based public health practice in this field.

Given the breadth of the topic and the diversity of sources, study designs, exposure metrics, and outcomes, a scoping review approach was selected because it is suitable for systematically mapping evidence, identifying conceptual and methodological gaps, and defining priorities for future research [3].

Objective. The objective of this review was to systematically map and synthesize evidence on the effects of environmental vibration on populations, methods of exposure assessment, exposure–response relationships, regulatory approaches, and preventive strategies, and to identify the main gaps in the evidence base from a public health perspective.

RESEARCH QUESTIONS

1. Which sources of environmental vibration and which non-occupational residential/community contexts are represented in the literature?
2. Which physical metrics and methods are used to assess individual or population-level exposure?

3. Which subjective, functional, physiological, psychological, and clinical outcomes have been investigated, and for which outcomes have exposure–response relationships been established?

4. What roles are played by co-exposure to noise, source type, building characteristics, and individual or situational factors?

5. Which regulatory and preventive approaches are used, and which evidence gaps are priorities for evidence-based public health?

MATERIALS AND METHODS

Review design and conceptual framework. The review was conducted as a scoping review in accordance with JBI methodological guidance [3]. Reporting was guided by PRISMA-ScR [4], and description of the search strategy followed PRISMA-S principles [5]. Eligibility criteria were structured according to the PCC (Population–Concept–Context) framework.

Population: the general population and residents of residential or community settings exposed to non-occupational anthropogenic vibration. Concept: environmental/community vibration, including railway, metro, tram, road traffic, construction, and industrial/community vibration; additional concepts included exposure assessment, perception, annoyance, discomfort, sleep, physiological, psychological/cognitive outcomes, exposure–response relationships, and mitigation. Context: residential, urban, suburban, and other non-occupational community settings.

Inclusion and exclusion criteria. The core evidence base included peer-reviewed publications indexed in PubMed/MEDLINE, Scopus, or Web of Science that: (1) assessed human responses or health-related outcomes associated with environmental vibration; (2) described relevant methods for measuring or modelling exposure; or (3) evaluated preventive or mitigation approaches in residential/community settings. Systematic reviews, methodological studies, and official standards or policy documents were used to contextualize the evidence. No lower date limit was applied; the search was current through 24 August 2026.

By functional purpose, eligible sources were grouped into four categories. Health/human-response studies assessed perception, annoyance, discomfort, sleep disturbance, awakenings/cortical arousal, and physiological, psychological, cognitive, or clinical outcomes. Exposure-assessment studies described or compared methods for measuring and modelling environmental vibration when directly relevant to population assessment. Prevention/mitigation studies addressed technical, building-related, transport, or planning interventions. Review/methodological/policy sources were used to contextualize primary evidence and regulatory practice.

Studies of occupational whole-body vibration or hand–arm vibration, animal or in vitro experiments, therapeutic applications of mechanical vibration, noise-only studies without a separate characterization of vibration, and purely structural or engineering studies without relevance to population exposure or prevention were excluded. The term whole-body vibration was not itself an exclusion criterion; eligibility was determined by the exposure context.

Information sources and search strategy. Searches were conducted in PubMed/MEDLINE, Scopus, and Web of Science Core Collection. Backward and forward citation searching of key studies and previous reviews was also performed. Regulatory documents were identified separately through the official websites of the issuing organizations.

The search strategy combined four conceptual blocks:

(1) *vibration exposure* — vibration*, environmental/community/ground-borne/railway/rail/traffic/road traffic/train-induced vibration;

(2) *residential/community context* — residential, dwelling*, home*, building*, resident*, community, population;

(3) *human response/health* — annoyance, discomfort, perception, acceptability, concern, sleep, awakening, arousal, physiological, heart rate, mental health, depress*, attention, concentration; and

(4) *exposure–response/methodology* — exposure, exposure-response, dose-response, measurement, assessment, prediction. Following a pilot search, the terms «human response», «community response», and «vibration annoyance» were added. Syntax was adapted to each database.

The working PubMed query consisted of three sequential logical components: terms for vibration exposure; residential/community context; and human response/health and exposure–response terms. Equivalent title/abstract/keyword fields and Boolean operators were used in Scopus and Web of Science. A blanket NOT occupational filter was not applied in order to avoid excluding relevant articles in which the term whole-body vibration was used for occupants of buildings; occupational settings were excluded during screening.

Additional citation searching was particularly important for earlier studies whose titles did not consistently use contemporary terms such as «environmental vibration» or «health». It was also used to identify secondary analyses from the same research programmes and to avoid incorrectly treating them as independent populations.

Study selection, data charting, and population overlap. After deduplication, records underwent sequential title/abstract screening and full-text assessment. Reasons for exclusion at full-text review were categorized as occupational exposure, absence of environmental vibration, irrelevant population/context/outcome, purely structural outcomes, or an ineligible publication type. The selection process should be presented in a PRISMA-ScR flow diagram [4].

For each included publication, we extracted country, study design, sample, vibration source, measurement method and location, exposure metric and units, frequency weighting, temporal characteristics, co-exposure to noise, outcome, effect estimate, 95% confidence interval (CI), adjusted confounders, principal findings, and limitations. The functional role of each source was also coded as H — health/human response, E — exposure assessment, P — prevention/mitigation, or C — contextual/review/methodological.

The standardized data-charting form included authors and year; country and Study/Cohort ID; design; sample size and characteristics; source type; measurement location, direction, and method; physical quantity and units; frequency weighting; exposure duration and temporal structure; number of events; concurrent noise; outcome assessment method; effect estimate and 95% CI; covariates/confounders; key findings; and limitations. The form could be refined during piloting when new types of indicators required additional fields.

To avoid double-counting the same populations, Publication ID was distinguished from Study/Cohort ID. Related publications from NANR209, Cargo Vibes, TVANE, EpiVib, and the Japanese Shinkansen surveys were grouped on the basis of country, data-collection period, sample characteristics, authorship, and project descriptions.

Critical appraisal and synthesis. Although formal critical appraisal is not mandatory for a scoping review, it was undertaken to improve interpretation of health outcomes. The revised JBI Critical Appraisal Tool for Analytical Cross-sectional Studies was used for analytical cross-sectional studies [6], with design-specific approaches applied to other study types. No aggregate quality score was calculated; domains were assessed separately. Because of substantial heterogeneity in sources, metrics, units, outcomes, and designs, an overall meta-analysis was not performed; instead, descriptive and narrative evidence mapping was used. Regulatory documents were analyzed separately, with explicit distinction between human-response criteria and building-damage criteria.

Critical appraisal was used not as a mechanical exclusion criterion but as a tool for weighted interpretation. For cross-sectional studies, particular attention was paid to clear inclusion criteria, validity of exposure and outcome measurement, identification and control of confounders, and appropriateness of the statistical analysis [6]. For laboratory experiments, exposure control, protocol standardization, objectivity of outcomes, and external validity were considered; for qualitative studies, methodological congruence with the research question and transparency of analysis were assessed.

RESULTS AND DISCUSSION

Overall characteristics of the evidence base. Within this scoping review, 24 publications were included in the empirical synthesis and grouped into 13 research clusters representing individual studies or research programmes. Several programmes, including NANR209, CargoVibes, TVANE, and EpiVib, were represented by multiple publications with complete or partial overlap of samples, while some publications reported secondary or pooled analyses of several primary studies. Publication ID and Study/Programme ID were therefore analyzed separately to avoid double-counting evidence. Most evidence originated from the United Kingdom, Sweden, Norway, and Japan; more recent studies added data from Malaysia and Iran. Central and Eastern Europe, including Ukraine, remain underrepresented.

Research on railway vibration predominated, including conventional passenger and freight trains, high-speed systems, metro, and light rail. Road traffic, construction, and industrial vibration have been studied far less extensively. Field studies were predominantly cross-sectional and combined questionnaires with measured or modelled exposure; laboratory sleep studies were small but employed polysomnography (PSG) and electrocardiography (ECG). The Norwegian socio-vibration survey included 1,503 respondents [7]; NANR209 comprised 1,281 interviews, including 931 on railway vibration and 350 on construction vibration [8, 9]. EpiVib included 6,894 participants in an early publication [13], while a later analysis included 7,280 adults with modelled exposure [14].

Sample size varied substantially by design. Laboratory sleep studies typically involved 12–24 healthy volunteers [17–20], whereas field socio-vibration studies included hundreds or thousands of residents [7–15]. Most field samples consisted of adults; children, adolescents, older adults, and medically vulnerable individuals were underrepresented. This limitation is particularly relevant to the external validity of laboratory evidence.

A clear hierarchy was evident across outcome domains. Perception, discomfort, and annoyance were assessed most frequently, followed by sleep disturbance. Acute physiological outcomes were represented mainly by laboratory PSG/ECG studies, whereas mental-health, cognitive, and clinically manifest outcomes were uncommon. Consequently, the «health evidence» in this field should not be treated as a homogeneous body of evidence: confidence differs substantially by outcome level.

The number of publications exceeded the number of independent populations. NANR209 generated a series of papers on exposure metrics, railway/construction annoyance, and modifying factors [8–10, 27]; CargoVibes produced laboratory and field analyses of sleep and heart-rate responses [17–21]; TVANE examined interactions between railway noise and vibration [11, 12]; and EpiVib progressed from a distance proxy to modelled individual exposure [13, 14]. This clustering was taken into account when interpreting the strength and consistency of the evidence.

Exposure assessment. Exposure assessment methods were highly heterogeneous. In Norway, exposure was characterized using the statistical maximum frequency-weighted vibration velocity, $v_{w,95}$; exposure was estimated for 1,427 of 1,503 re-

Table 1. **Key research programmes and their contribution to the evidence base**

Study/Programme	Source	Design/Sample	Primary outcome	Contribution
Norwegian Socio-Vibrational Survey [7]	Road/rail/tram/metro	Field study, n = 1,503	Annoyance	$v_{w,95}$; exposure–response
NANR209 [8–10, 27, 30]	Rail + construction	Field study, n = 1,281	Annoyance, acceptability	Exposure metrics, source-specific response, modifiers
TVANE [11, 12]	Rail	Field study, n = 1,695; secondary subset, n = 862	Annoyance	Combined noise–vibration response
EpiVib [13, 14, 22]	Rail	Qualitative + cross-sectional; large survey, n = 7,280	Perception, annoyance	Qualitative context; distance proxy → modelled exposure
Rafidah et al. [15]	Rail	Field measurements + survey, n = 208	Annoyance	Train type, speed, distance
Arnberg et al. [16]	Heavy road traffic	Laboratory experiment	Sleep	Direct evidence for road-traffic vibration effects on sleep
CargoVibes [17–21]	Freight rail	3 Laboratory + 2 field studies	Sleep, arousal, heart rate	Psg/ecg and exposure–response
Morihara et al. [23]	Shinkansen	Socio-acoustic survey, n = 1,022	Annoyance/ activity	Activity disturbance
Sadeghi et al., PHQ-9 [24]	Metro	Cross-sectional; one building, n = 144	Depressive symptoms	Emerging mental-health evidence
Sadeghi et al., ASR [25]	Metro	Cross-sectional; 31 buildings, n = 451	Mental-health dimensions	Broader psychological outcomes
Tung et al. [26]	Road + conventional/ high-speed rail	Laboratory experiment	Discomfort	Combined noise–vibration effects
Howarth & Griffin [28]	Rail	Controlled laboratory study	Annoyance	Early combined noise–vibration evidence
Yokoshima et al. [29]	Shinkansen	Secondary analysis of 6 surveys	Annoyance	Pooled japanese evidence on combined effects

spondents by combining measurements with semi-empirical modelling, and annoyance increased with increasing $v_{w,95}$ [7]. In NANR209, 24-hour exposure estimates were obtained for 1,073 cases, and 60 vibration descriptors with six frequency-weighting variants were compared. No single descriptor showed a consistent advantage, whereas the use of appropriate frequency weighting improved the association with population response [8, 9].

For intermittent events, vibration dose value (VDV), which is sensitive to short high-amplitude peaks, was widely used. Sleep studies applied event-based velocity and maximum frequency-weighted acceleration: 0.7 and 1.4 mm/s in Smith et al. [19] and $a_{\mathrm{Wd,\,max}}$ = 0.0204 m/s^2 in the vibration-only condition [20]. For cumulative nocturnal exposure, an 8-hour $\log_{10}$ RMS measure was used; in a pooled analysis, a one-unit increase in this measure was associated with an odds ratio (OR) of 3.51 (95% CI 2.60–4.73) for greater sleep disturbance [21].

VDV differs from RMS in that the fourth-power integration of instantaneous frequency-weighted acceleration makes it particularly sensitive to high-amplitude events, which is relevant to transportation and construction vibration. PPV is more commonly used in engineering and structural assessment, whereas VdB is widely used in transport guidance systems. Thus, the same physical situation may be described using metrics that capture different aspects of exposure and are not interchangeable.

Frequency content is independently important because transmission through soil and buildings, as well as human sensitivity, is frequency dependent. Resonant characteristics of floors can amplify particular frequency bands even when ground vibration is moderate. Consequently, measurements only at the site boundary or the use of distance as a surrogate may substantially misclassify actual indoor exposure.

Metrics also differ in their temporal logic. RMS averages the energy contribution and may dilute short peaks; VDV gives greater weight to intense events; event maxima characterize the potential of individual pass-bys to trigger arousal; and 8- or 24-hour integrated metrics characterize cumulative exposure. The choice of exposure descriptor should therefore match the outcome: an acute sleep event and daytime or 24-hour annoyance represent different research questions.

Measurement location is also critical. Values measured on the ground, foundation, floor slab, and at the point of human contact with the floor may differ. For epidemiological studies, the most informative metric is one that most closely represents actual indoor exposure, but large cohorts often require a balance between measurement precision and population coverage.

Large population studies have sometimes used distance from the railway as a proxy for exposure [13]; however, this approach does not account for geology, rolling stock, track condition, or building transmission. More recent studies have used modelled individual exposure incorporating spatial, transport, and noise data [14]. Accordingly, no universal metric is optimal for all outcomes: daily or dose metrics are relevant to annoyance, while event maxima and cumulative nocturnal exposure are relevant to sleep; comparability is further limited by frequency weighting, vibration direction, and measurement location.

Annoyance and exposure–response relationships. Annoyance is the most extensively studied human-response outcome. In the Norwegian survey, annoyance increased systematically with $v_{w,95}$ [7]. NANR209 established exposure–response relationships, but a common curve for railway and construction vibration was not appropriate; response varied by source [9]. Sharp et al. showed that, at comparable physical exposure, freight vibration was more annoying than passenger vibration [10].

In NANR209, detailed analysis of 60 exposure descriptors showed that statistically significant relationships could be obtained for many metrics, but no universally «best» descriptor existed [9]. This is important for regulatory practice: the relevance of annoyance cannot be reduced to a single number without considering frequency weighting, source type, and the temporal structure of exposure.

Non-exposure factors also played an important role. In the UK sample, concern about damage to the dwelling and expectations of future increases in vibration were among the strongest modifiers; residential area type and age were also relevant [27]. In TVANE, ground-borne vibration increased the overall response to railway traffic [11]. Approximately 20% annoyance corresponded to about 59 dB of railway noise or 0.48 mm/s vibration, while approximately 40% corresponded to about 63 dB or 0.98 mm/s, respectively [12]. These are population-specific exposure–response estimates rather than universal regulatory thresholds.

TVANE also showed that, at the same railway noise level, overall response was greater in areas with strong ground-borne vibration; lower noise levels were required to produce a comparable level of annoyance. This finding supports the concept of combined transportation exposure, in which noise and vibration cannot be treated mechanically as context-independent factors [11].

Differences between freight and passenger traffic are consistent with the fact that an integrated metric does not fully capture the temporal and spectral structure of an event. Longer pass-bys, larger numbers of wagons, night-time operation, different low-frequency content, and event repetition may alter subjective response even at similar aggregate exposure levels [10, 14, 15].

Contemporary findings are consistent with earlier evidence. In EpiVib, modelled vibration showed a dose–response association with annoyance after adjustment for socioeconomic factors; the association was stronger for freight traffic and was modified by noise [14]. In Malaysia, response also varied with train type and speed, distance, and operating time [15]. Overall, annoyance is determined by a combination of amplitude, frequency, event duration and frequency, source type, concurrent noise, housing characteristics, and individual and situational factors.

In addition to exposure magnitude, perceived controllability is important. Vibration in one's home may acquire greater significance when residents associate it with a risk of building damage or expect the situation to worsen [27]. Such non-exposure modifiers do not invalidate the physical exposure–response relationship; rather, they explain part of the interindividual variability around it.

Sleep and Acute Physiological Responses. The evidence on sleep is smaller in volume but includes objective PSG/ECG outcomes. In an early experiment involving heavy road traffic, adding vibration to noise increased sleep disturbance; at higher exposure levels, REM sleep decreased and subjective sleep quality worsened [16].

In Arnberg et al., exposure included up to 150 events per night. With peak noise of 50 dB(A) combined with approximately 0.24 m/s^2 vertical and 0.17 m/s^2 horizontal vibration, sleep was more disturbed than under noise-only conditions; at approximately 0.34 and 0.24 m/s^2, respectively, REM sleep was additionally reduced and morning functional performance worsened [16]. Although these exposure levels and laboratory conditions cannot be directly extrapolated to contemporary populations, the study is important in showing that road-traffic vibration may also be relevant to sleep.

In CargoVibes, 12 young healthy participants spent six nights in the laboratory; increasing vibration amplitude was associated with poorer sleep quality and changes in the acute cardiac response [17]. Among 24 volunteers, higher freight-train vibration amplitude (1.4 vs 0.7 mm/s) increased event-related arousals/awakenings and sleep-stage transitions, with the greatest fragmentation observed under the 36-event condition [19].

The subsequent polysomnographic study confirmed that the effect was not limited to subjective assessment: higher vibration exposure significantly increased arousals/awakenings ($p < 0.001$) and the frequency of sleep-stage changes ($p < 0.05$) [19]. Under the 36 high-vibration-event condition, wake time increased, continuous slow-wave sleep decreased, and final awakening occurred earlier. Sleep fragmentation is therefore among the most objectively supported consequences of environmental vibration.

Causal interpretation is strengthened by an experiment in which noise and vibration were separated: vibration alone at $a_{\mathrm{Wd,max}} = 0.0204$ m/s^2 increased the probability of cortical arousal/awakening and accelerated heart rate, while the effects of noise and vibration were largely additive [20]. A separate analysis of 24 participants aged 19–28 years showed a more pronounced heart-rate response at higher vibration exposure; 79% of participants had a mean heart-rate acceleration of at least 3 beats/min [18]. A pooled field/laboratory analysis also confirmed an exposure–response relationship for sleep disturbance (OR 3.51; 95% CI 2.60–4.73 per +1 $\log_{10}$ RMS) [21].

In Croy et al., both an initial and a delayed acceleration in heart rate were observed following the onset of transportation events; the difference between high- and low-vibration conditions was statistically significant ($p = 0.006$), and in the high-vibration condition 79% of participants had a mean acceleration of at least 3 beats/min [18]. This finding demonstrates an acute autonomic response but is not, by itself, a surrogate for future cardiovascular morbidity.

In the pooled CargoVibes analysis, the field component included 233 participants, while the laboratory component included 59 participants and more than 350 person-nights. Differences in exposure–response slopes between laboratory and field settings were not statistically compelling, supporting the ecological relevance of the experimental findings [21].

Thus, the short-term causal relationship with sleep fragmentation and acute autonomic responses is better supported than any relationship with chronic disease. Small samples of young healthy volunteers and the predominance of freight-rail exposure limit external validity, while the long-term clinical significance of repeated responses remains unknown [1].

At the same time, laboratory studies have clear limitations: small samples, predominantly young participants, short exposure periods, and artificial laboratory conditions. In real residential settings, people may be simultaneously exposed to noise, vibration, air pollution, and psychosocial stressors over many years. Large longitudinal cohorts with independent exposure modelling are therefore required to bridge acute mechanistic evidence and chronic public health risk.

Psychological, Cognitive, and Functional Outcomes. Psychological and cognitive outcomes have been studied far less extensively. A qualitative Swedish study described vibration as a factor affecting perceptions of the home through concerns about property, safety, and the possibility of recovery, but could not estimate frequency or causality [22]. Following the opening of the Hokuriku Shinkansen, adverse reactions and activity disturbances were more pronounced at higher vibration exposure, particularly in areas without a pre-existing conventional railway; however, overall residential satisfaction did not deteriorate substantially [23].

Qualitative evidence is important because it indicates a possible pathway from physical perception to broader psychosocial consequences. Residents living near railways described habituation, acceptance, concerns about property and safety, and reduced restorative function of the home [22]. These findings do not demonstrate disease, but they help explain why the same physical exposure may have different significance across individuals and residential contexts.

In 2026, Sadeghi et al. combined indoor metro noise/vibration measurements with the PHQ-9 scale. After adjustment, PHQ-9 scores decreased by $\beta = -0.326$ points per floor (95% CI –0.579 to –0.074), while maximum vibration level was positively associated with PHQ-9 score ($\beta = 0.171$ points per 1 VdB; 95% CI 0.026–0.316) [24]. However, the single-building setting, cross-sectional design, and strong covariance among noise, vibration, and floor level limit causal interpretation. In another study of 451 residents in 31 buildings, attention/concentration and sleep problems were most prominent; the authors reported stronger associations with vibration, but complaint-based selection introduces a risk of selection bias [25].

In the PHQ-9 study, both noise and vibration decreased with increasing floor level; therefore, floor level, noise, and vibration formed a closely correlated spatial gradient. The association between noise and PHQ-9 was weaker and statistically uncertain ($\beta = 0.119$ points per 1 dB; 95% CI –0.016 to 0.254). This does not demonstrate an independently stronger effect of vibration because multicollinearity and residual confounding remain important concerns [24].

In the 31-building study, 13 buildings had no registered complaints, whereas 18 were selected on the basis of complaints about noise or vibration. Simultaneous field measurements and the standardized Adult Self-Report were strengths, but complaint-based sampling may inflate apparent associations. The two 2026 studies should therefore be regarded as hypothesis-generating rather than as confirmation of a causal effect of metro vibration on mental disorders [25].

It is therefore appropriate to describe emerging associations with self-reported psychological symptoms rather than established clinical mental disorders. Similarly, evidence on cognitive effects is based mainly on self-report rather than standardized neuropsychological testing. A controlled experiment published in 2026 confirmed that combined noise–vibration stimuli can increase discomfort and that response may partly depend on sociocultural context [26].

Gaps in the Evidence Base. The principal gap is the absence of an adequate prospective evidence base for clinically manifest chronic diseases. The 2023 systematic review identified no studies of manifest disease associated with railway vibration [1], and the updated evidence does not justify considering vibration an established independent risk factor for hypertension, ischemic heart disease, stroke, or clinically diagnosed mental disorders. Other major gaps include the dominance of railway studies; insufficient research on road, construction, and industrial vibration; limited representation of children, older adults, and medically vulnerable populations; geographic concentration of the evidence; non-standardized exposure metrics; inadequate separation of noise from vibration; and a scarcity of before-and-after studies of mitigation interventions.

By source, the clearest imbalance is between railway vibration and other types of exposure. Construction-vibration studies have focused mainly on annoyance and acceptability, including during light-rail construction [30], with far less evidence on sleep or physiology. Road traffic has early laboratory evidence [16] and a small number of more recent studies, but lacks a comparably developed population evidence base. Industrial/community vibration has been studied even less.

Priorities for future research include prospective cohorts with individual-level assessment of both noise and vibration, objective sleep, cardiovascular, and cognitive outcomes, a standardized minimum exposure dataset (amplitude, spectrum, direction, event maxima, number and duration of events, day/night distribution, and building characteristics), and natural experiments conducted before and after commissioning transport infrastructure or implementing vibration-control measures.

Geographic representation is another important gap. Most of the evidence has been generated in Northern/Western Europe and Japan, whereas data from Central and Eastern Europe remain limited. This is important because differences in geology, housing construction, transport infrastructure, and operational characteristics may substantially alter indoor exposure at the same distance from a source.

Vulnerable populations require dedicated investigation. Young healthy volunteers in laboratory studies do not represent children, older adults, people with chronic diseases, or individuals with sleep disorders. Objective cognitive outcomes and clinical registry data are also largely absent. Mitigation interventions require natural experiments with baseline exposure and repeated assessment not only of the physical reduction in vibration but also of annoyance, sleep, and quality-of-life outcomes.

Regulatory Framework and Prevention. Unlike environmental noise, for which the WHO has issued health-based recommendations [32], no contemporary universal system of health-based guideline values exists for non-occupational environmental vibration. The current ISO 2631-2:2026 addresses comfort and annoyance among building occupants over the 1–80 Hz range, uses Wm frequency weighting, and is not a standard for evaluating health/safety effects or structural damage [33]. General principles for whole-body vibration are provided in ISO 2631-1:1997 [34].

This distinction has practical implications: standards oriented toward comfort and annoyance should not be described as health-based limits, and structural criteria should not be used as a surrogate for public-health acceptability. People may perceive vibration and report sleep disturbance or annoyance at levels far below those associated with risk of structural damage [33, 39, 40].

The British standard BS 6472-1:2008 uses VDV and accounts for time of day [35]; NS 8176:2017 applies vw,95 and vibration classes A–D to road/rail vibration in dwellings [36]; and DIN 4150-2:2025 addresses effects on people in buildings [37]. The FTA Manual applies a staged screening/general/detailed assessment approach and accounts for transport-event frequency; criteria of 72, 75, and 80 VdB are given for residential buildings for frequent, occasional, and infrequent events, respectively [38]. These human-response criteria must be distinguished from structural standards such as ISO 4866:2010 and DIN 4150-3:2016 [39, 40].

The FTA further classifies transport events by frequency as frequent (> 70 events/day), occasional (30–70 events/day), or infrequent (< 30 events/day). This approach reflects the fact that response depends not only on the maximum level of an individual event but also on repetition. These VdB criteria should not be mechanically converted to VDV or PPV because the metrics have different physical and temporal bases [38].

Prevention can be organized according to the hierarchy «source → propagation path → building/receptor → spatial planning». For rail systems, source-control measures include maintenance of

Table 2. **Main regulatory approaches to environmental vibration**

Document	Assessment target	Key approach	Practical relevance
ISO 2631-2:2026 [33]	Building occupants	1–80 Hz; Wm	Comfort/annoyance; not a health limit
BS 6472-1:2008 [35]	Building occupants	VDV; time of day	Dose-based human response
NS 8176:2017 [36]	Road/rail vibration in dwellings	$v_{w,95}$; classes A–D	Socio-vibrational classification
DIN 4150-2:2025 [37]	Building occupants	1–80 Hz	Current german approach
FTA Manual [38]	Transport projects	VdB; event frequency	Screening → detailed assessment + mitigation
ISO 4866 / DIN 4150-3 [39, 40]	Structures	Structural response/ velocity	Do not substitute for human-response criteria

rail and wheel condition, resilient fasteners, ballast mats, floating slabs, and speed optimization; measures along the propagation path include trenches, subsurface barriers, and buffer distance; building-level measures include modification of stiffness, mass, foundations, and resonant characteristics. An engineering review of railway vibration problems confirms the broad need for mitigation and the diversity of metrics used [31]. From a public-health perspective, the preferred strategy is prevention by design: assessing potential exposure before approval of transport routes or residential development, followed by instrumental and, where feasible, population-response monitoring after commissioning.

For selected rail mitigation systems, the FTA reports indicative reductions of approximately 5–10 dB for resilient fasteners in the relevant higher-frequency range and 8–12 dB for ballast mats at frequencies above approximately 25–30 Hz; floating slab track may provide greater attenuation when the system resonance is appropriately designed. Effectiveness is frequency dependent and should not be transferred across sites without engineering analysis [38].

At the spatial-planning level, distance between the source and a sensitive receptor is important but does not by itself guarantee acceptable indoor vibration. Planning decisions should therefore combine screening, geotechnical modelling, building characteristics, and field validation. After a new transport facility is commissioned, post-project monitoring is desirable to verify not only modelled vibration levels but also actual resident response.

Evidence Synthesis. Overall, human response is determined by the interaction of exposure magnitude, frequency content, temporal structure, source type, concurrent noise, building characteristics, and individual and situational factors. The strongest evidence concerns annoyance and sleep disturbance; evidence for psychological symptoms is still emerging, while evidence for clinically manifest chronic disease remains insufficient.

Main Findings and Annoyance. This review shows that environmental vibration is an established but methodologically heterogeneous field of research. The most consistent evidence concerns annoyance, followed by sleep disturbance; acute physiological effects are supported by a smaller but methodologically robust body of experimental evidence. Evidence on long-term mental, cardiovascular, and other clinical outcomes remains insufficient [1]. Moreover, much of the overall evidence derives from railway vibration, limiting direct extrapolation to road, construction, and industrial sources.

The most important integrative finding is the unevenness of the evidence chain. At the level of perception and annoyance, large population studies and exposure–response models are available; for sleep, there are fewer studies but stronger objective evidence; for acute physiology, several controlled experiments exist; evidence on mental-health symptoms is only emerging; and a major gap remains for chronic manifest disease. This distinction is essential for accurate communication of the level of certainty.

The consistency of exposure–annoyance associations across independent British, Norwegian, and Swedish programmes increases confidence that this is a genuine population-level outcome [7, 9, 10, 12]. However, annoyance is not a simple function of amplitude. Source type, event structure, noise, residential context, and residents' attitudes have independent importance. In particular, concern about property damage and expectations of future vibration substantially modified response [27]. Annoyance should therefore be interpreted as an

Table 3. **Summary evidence map**

Outcome	State of evidence	Main limitation
Perception/annoyance	Most developed; exposure–response relationships available	Predominantly cross-sectional; source/context modifiers
Sleep disturbance	Moderately strong; psg + field data	Much evidence from freight rail; small laboratory samples
Cortical arousal/heart rate	Limited but objective acute effects	Long-term significance unknown
Activity/attention	Limited	Predominantly self-report
Depressive/other mental-health symptoms	Emerging, weak	Confounding, correlated noise, selection bias
Clinically manifest chronic diseases	Major evidence gap	Lack of adequate prospective cohorts

integrated human response to a physical and socio-contextual stressor, but not as a clinical disease.

This distinction has an important conceptual implication. Annoyance should not be dismissed as «merely a subjective complaint», because it reflects persistent disruption of comfort and the restorative function of the home. At the same time, it is not a clinical outcome and cannot be used as evidence of somatic or mental disease. This distinction allows public-health relevance to be acknowledged without overextending causal conclusions.

Combined Effects of Noise and Vibration. Transportation noise and vibration frequently arise from the same source, making their independent and combined effects difficult to separate in field studies. Early laboratory models showed that joint consideration of noise and vibration better explained overall response than either exposure alone [28]. TVANE, Japanese Shinkansen surveys, and EpiVib confirmed mutual modification of response at the population level [11, 12, 14, 29]. Transport infrastructure should therefore be evaluated as a combined exposure, and epidemiological models should simultaneously include noise, vibration, interaction terms, and source characteristics.

This issue is particularly important for psychological and long-term outcomes because railway and road noise already have an established evidence base for sleep disturbance and cardiovascular outcomes. If noise exposure is assessed imprecisely or omitted from the model, residual confounding may spuriously strengthen an apparent vibration effect. Future studies should examine independent effects, statistical interaction, non-linearity, and source-specific modifiers.

Sleep as the Most Convincing Health-Relevant Pathway. Unlike annoyance research, sleep studies include objective endpoints. The sequence «vibration event → cortical arousal/awakening → sleep fragmentation → acute autonomic response» is supported by PSG/ECG experiments [18–20]. Experimental separation of noise and vibration is particularly important: vibration alone elicited responses, making residual confounding by noise a less plausible explanation [20]. Pooled field/laboratory data provide additional exposure–response support [21].

This pattern is consistent with triangulation of evidence: field surveys show that the problem occurs in real communities; laboratory experiments demonstrate that the vibration component can independently trigger an acute response; and pooled analyses partly bridge these two levels [19–21]. However, triangulation does not replace long-term observation when the outcome of interest is chronic disease.

A mechanistically plausible short-term pathway does not, however, establish progression to hypertension, ischemic heart disease, stroke, or other chronic pathology. This remains the critical missing link [1]. It is therefore appropriate to describe the evidence for acute sleep and physiological effects as causally persuasive, but not to infer an established risk of chronic disease.

Mental Health and Emerging Evidence. Since 2023, a new but still weak evidence domain has emerged for mental health. Studies published in 2026 combined direct metro-vibration measurements with PHQ-9 and Adult Self-Report assessments [24, 25]. They support possible associations with depressive symptoms, sleep problems, and attention/concentration difficulties; however, cross-sectional design, correlated noise exposure, limited study settings, and selection bias preclude causal or clinical etiological inference. These findings broaden the range of outcomes under investigation but do not change the overall conclusion that evidence for clinically diagnosed mental disorders remains insufficient.

Methodological and Regulatory Implications. Heterogeneity in RMS, VDV, vw,95, VdB, PPV, event maxima, and modelled exposure is not merely a technical issue; it impedes meta-analysis and translation of epidemiological evidence into regulatory criteria. Waddington et al. did not identify a universally superior descriptor but demonstrated the importance of appropriate frequency weighting [9]. Standardization should therefore focus not on a single metric but on a minimum dataset comprising amplitude, spectrum, direction, event maxima, event number/duration, day/night distribution, cumulative exposure, and building characteristics.

For future guideline development, epidemiological comparability should precede the establishment of health-based thresholds. Without harmonized reporting, even a large number of new studies may remain difficult to pool. A minimum set of physical descriptors should ideally be supplemented by train/vehicle type, event rate, day/night distribution, building response, and simultaneous noise exposure.

Regulatory practice is also fragmented. ISO 2631-2:2026, BS 6472-1, NS 8176, DIN 4150-2, and FTA guidance use different metrics and target frameworks [33, 35–38]. It is particularly important not to conflate human-response criteria with structural-damage limits [39, 40]: a level that is safe for the structure may still be perceptible, annoying, or sleep disturbing. For residential settings, nocturnal event maxima, event frequency, and cumulative exposure should be characterized separately.

Public Health Implications. Environmental vibration should be regarded as a health-relevant environmental stressor: the evidence for effects on annoyance and sleep is sufficiently convincing to justify preventive management of exposure even though chronic-disease risk has not been established. The residential setting is especially important because repeated nocturnal or uncontrollable events may impair recovery. Vulnerable populations — including children, older adults, and people with sleep disorders or chronic disease — remain understudied, supporting a precautionary approach to siting sensitive receptors near major vibration sources.

From a public health perspective, the home has a special status: the same physical vibration level may have different implications depending on room function and time of day. A bedroom at night, where repeated events may interrupt sleep, requires a different approach from an office during daytime. Unpredictability, audible rattling, perceived lack of control, and concern about property damage may further increase the relevance of exposure.

In practice, this supports a principle of proportionate prevention: the absence of established chronic-disease risk is not a reason to disregard substantial annoyance or sleep disturbance. At the same time, public-health communication should clearly distinguish established human-response effects, emerging associations, and unconfirmed clinical risks.

The most effective strategy is prevention by design: potential ground-borne vibration should be assessed during transport-infrastructure and residential planning, source/path/building mitigation should be applied where appropriate, and post-project monitoring should be conducted. However, a technical reduction in VdB, VDV, or PPV is not equivalent to a demonstrated public-health benefit; before-and-after intervention studies are needed with repeated assessment of exposure, annoyance, sleep, and other relevant outcomes.

Public-health evaluation of mitigation should therefore include two levels of effectiveness: engineering effectiveness (physical reduction in vibration level) and population effectiveness (reduction in annoyance, sleep disturbance, or other relevant outcomes). The latter remains insufficiently studied. Before-and-after designs with control areas or stepped implementation of mitigation could substantially strengthen the evidence base.

Strengths, Limitations, and Directions for Future Research. Strengths of this review include its broad public-health scope, distinction between Publication ID and Study/Cohort ID, integration of population, laboratory, exposure-methodology, and regulatory evidence, and literature coverage through August 2026. Major limitations include substantial heterogeneity, predominance of railway studies and cross-sectional designs, difficulty controlling for noise, uneven geographic representation, and a search restricted to PubMed/MEDLINE, Scopus, and Web of Science.

Methodological heterogeneity precluded a defensible meta-analysis across all sources and outcomes. In addition, searching the three major databases reduces but does not eliminate the possibility of missing specialized engineering or national literature. Regulatory documents are not epidemiological studies and were therefore analyzed as a separate policy/standards layer rather than as evidence of health effects.

The field requires harmonized terminology and reporting standards. A minimum exposure dataset should support data reuse and cross-study comparison; large cohorts should incorporate GIS/physical modelling, validation measurements, and building characteristics. This would facilitate future pooled analyses and, potentially, the development of health-relevant guideline values.

Priorities for future research include large prospective cohorts; individualized noise and vibration exposure assessment; objective sleep, cardiovascular, and cognitive outcomes; standardized reporting of exposure parameters; dedicated studies of children, older adults, and other vulnerable populations; more research on road, construction, and industrial vibration; and intervention studies linking engineering reductions in vibration to measurable changes in health and well-being.

An optimal prospective design should include repeated or modelled individual exposure, a separate nocturnal component, concomitant noise, socioeconomic and housing covariates, and linkage to clinical registries. Nested substudies could use actigraphy/PSG for sleep, ambulatory blood pressure and heart-rate variability for cardiovascular pathways, and standardized performance tests for cognition. Such multilevel cohorts could determine whether acute sleep/autonomic responses are truly intermediate steps toward long-term risk.

CONCLUSIONS

1. Environmental vibration is a health-relevant physical factor in residential environments, with

the strongest evidence linking it to annoyance and sleep disturbance; objective PSG/ECG evidence is available for sleep-related effects.

2. The most developed evidence base concerns railway vibration. Freight traffic is often associated with a stronger response than passenger traffic at comparable exposure levels; evidence on road, construction, and industrial vibration is substantially more limited.

3. Nocturnal vibration can independently trigger cortical arousal/awakening, sleep fragmentation, and acute changes in heart rate; however, these responses do not demonstrate the development of chronic cardiovascular disease.

4. Population response is determined not only by vibration amplitude but also by frequency content, direction, number and duration of events, time of day, source type, noise, building characteristics, and individual and situational factors.

5. Evidence on mental-health symptoms is recent and preliminary; because of cross-sectional designs, confounding, and correlated noise exposure, a causal relationship with clinically diagnosed mental disorders has not been established.

6. The key evidence gap concerns long-term clinical outcomes. Prospective cohorts with individualized noise/vibration exposure and objective clinical outcomes are required.

7. Regulatory systems are primarily oriented toward comfort/annoyance or structural safety. Human-response criteria should be clearly distinguished from building-damage limits, and prevention should be incorporated at the spatial and transport planning stage.

Overall, current evidence supports preventive reduction of substantial environmental vibration exposure in parallel with the development of standardized epidemiological studies needed to inform future health-based criteria.

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ФІНАНСУВАННЯ

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КОНФЛІКТ ІНТЕРЕСІВ

Автори заявляють про відсутність конфлікту інтересів.

ВИКОРИСТАННЯ ГЕНЕРАТИВНОГО ШТУЧНОГО ІНТЕЛЕКТУ

Генеративний штучний інтелект (GPT-5.2, OpenAI, версія 5.2; використано 26 серпня 2026 року) застосовувався виключно для мовно-стилістичного вдосконалення розділу «Обговорення». Запити до системи обмежувалися проханнями щодо стилістичного редагування. Автори перевірили весь зміст рукопису та підтверджують його точність, оригінальність і відсутність плагіату.

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The authors declare no conflict of interest.

USE OF GENERATIVE ARTIFICIAL INTELLIGENCE

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