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DOI
10.1080/00423114.2025.2504113

Publication date
2025

Document Version
Final published version

Published in
Vehicle System Dynamics

Taylor & Francis
Taylor & Francis Group

Vehicle System Dynamics

International Journal of Vehicle Mechanics and Mobility

ISSN: 0042-3114 (Print) 1744-5159 (Online) Journal homepage: www.tandfonline.com/journals/nvsd20

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To cite this article: Georgios Papaioannou, Chen Shen, Malte Rothhämel & Riender Happee (2025) Occupants' comfort: what about human body dynamics in road and rail vehicles?, Vehicle System Dynamics, 63:7, 1241-1299, DOI: 10.1080/00423114.2025.2504113

To link to this article: https://doi.org/10.1080/00423114.2025.2504113

VEHICLE SYSTEM DYNAMICS
2025, VOL. 63, NO. 7, 1241–1299
https://doi.org/10.1080/00423114.2025.2504113

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Occupants' comfort: what about human body dynamics in road and rail vehicles?

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ABSTRACT

Transportation and mobility are experiencing a significant transformation the recent years, which is evident in road (vehicles and bicycles) and rail vehicles. This transformation includes the introduction of automated vehicles (AVs), the increase of active transportation modes (e.g. cycling and walking) and the extended use of trains for commuting to work or travelling. However, despite this great transition, there are significant challenges that can hamper the wide use of these transport means, with comfort being one of them. In this paper, we explore physical comfort in these transport modes, examining ride comfort and motion sickness definitions and assessment, environmental influences, occupant postures, human body dynamics, and postural control strategies for adapting to motion. We conclude that while established comfort guidelines exist for conventional vehicles, substantial gaps persist in understanding and evaluating comfort in emerging modes like bicycles and automated vehicles with varied seating. Further research into modelling human body dynamics and the central nervous system's role in postural control, especially for cyclists and non-conventional postures, is essential for designing future transportation systems that prioritise comfort and health.

ARTICLE HISTORY
Received 11 February 2025
Revised 16 April 2025
Accepted 29 April 2025

KEYWORDS
Ride comfort; motion sickness; human body dynamics; automated vehicles; rail vehicles; bicycles

1. Introduction

Transportation and mobility are experiencing a significant transformation the recent years aiming to increase safety, enhance accessibility and decrease environmental impact. The transformation is evident in road (vehicles and bicycles) and rail vehicles, which are part of our daily life, including the introduction of automated vehicles (AVs), the increase of active transportation modes such as cycling and walking and the extended use of trains for commute or travelling among others. According to Fiorello et al. [1], road vehicles are used by 56%, trains and other public transport by 27%, and bicycles by 6% for the most frequent trips in the EU members. More recently, transport by car accounted for 79.7% of passenger-kilometres across the EU, 7.1% for coaches, buses or trolley buses and 5.6% for trains [2]. Among all journeys in EU, 20–40% are by bike or on foot, with bicycle trips being

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most frequent in the Netherlands, Denmark and Sweden and least frequent in Finland [3]. However, despite this great transition, there are significant challenges that can hamper the wide use of these transport means. This review paper will focus on exploring the literature about motion comfort, an important factor that is proven critical in all types of transport.

Comfort while being driven in any type of vehicle (rail and road vehicles) is a highly complex concept, affected by environmental, physical and psychological factors [4–7]. Attempts to define comfort in the context of different vehicle types have converged to similar definitions. According to Peng et al. [4], comfort in Automated Vehicles (AVs) is divided into two layers: the physical (driving dynamics which lead to vehicle kinematics and proxemics [8], human body kinematics [9] and motion sickness [10]) and the psychological layer (privacy, trust [11,12], perceived safety [13], naturalness [14], engagement in NDRTs [15] and situation awareness), both of which can affect each other. These are also affected by environmental and traffic influences, interior design [16,17], infrastructure, route geometry [18], road roughness, weather, and other road users. A similar definition for comfort was provided by de Looze et al. [17]. These factors have been also considered critical when defining comfort in rail vehicles [19–21], with limited focus on psychological comfort since rail vehicles are a widely used and accepted technology. In the context of comfort on bicycles, Tool et al. [7] highlighted the importance of physical comfort and the impact of environmental factors (weather, route geometry and road roughness), excluding the impact of psychological comfort. For physical comfort, the mechanical (bicycle design and components), and the biomechanical and physiological (human body dynamics and individual characteristics such age, gender, body size, weight and others) are of critical importance. In this paper, we will explore the physical comfort in road (AVs and bicycles) and rail vehicles, which is the common factor in the definitions identified, delving into the differences in the environmental factors, occupants' postures, the resulting human body dynamics, and their postural control strategies to dynamically adapt their posture based on the external perturbations in road and rail vehicles.

Automated driving is considered one of the major technological developments within the automotive industry and is able to improve road safety [22], reduce environmental impact [23], and make travel more accessible [24]. Automated vehicles (AVs) are expected to constitute around 35% of vehicle sales, and 50% of all vehicle travel by 2050 [25]. At the same time, there are important challenges, which could lead to the disuse of AV technology [11], with motion comfort to be considered as one of them. The engagement in other activities during the ride and the productive use of the commute time are considered by consumers as one of the key reasons for the adoption of AVs [26]. All the envisaged AV designs, i.e. the handing over of vehicle control, seating backwards [27], engaging in non-driving related tasks (NDRTs) [15] or not having a clear view of the road ahead by displays or structures [28], will provoke the incidence of discomfort and motion sickness (MS) to the occupants [10,29]. Meanwhile, this shift in occupant behaviour and experience (i.e. engagement in NDRTs, different interior design, limited horizon view etc.) will introduce new challenges in maintaining postural stability, as unpredictable vehicle maneuvers can provoke excessive head and body motion, and induce more discomfort including motion sickness [30]. Albeit AVs technology is gradually introduced on public roads, insufficient consideration has been given to the occupants' comfort despite being one of the main factors affecting public trust towards AVs [12]. Hence a refocus is required.

Rail travel is a common and green way to commute in urban and suburban areas, while only 0.4% of EU transport greenhouse emissions and 1.9% of EU's energy consumption can be attributed to rail travel. As a result, the EU has set a strategy to double high-speed trains by 2030 [31]. In contrast to manually driven vehicles, trains allow passengers to engage in other activities (e.g. working or others) [32] while travelling due to the lack-off control, the available space, the 'living room' (e.g. tables and more comfortable chairs) concept and the longer routes. The use of travel time for work tasks also allows employees to be more efficient and balance their personal and professional lives better [33]. However, trains are designed for transporting goods and people rather than for providing comfortable and occupational workspace [34], while they do not accommodate working sitting postures (e.g. looking down while seating wide, limited arm movements due to other passengers etc.). Therefore, the engagement in non-driving activities can increase discomfort, affecting both the pleasantness of the drive and travellers' productivity. This highlights the need to focus research on improving and understanding comfort in rail vehicles to secure their widespread use and accommodate the recent needs.

Comfort in various transport means is strongly affected by the transmission of motion from the seat to the head, which varies with factors such as seat compliance, posture, and individual characteristics [35]. Meanwhile, head motion, in particular angular velocities and accelerations, plays a critical role in motion comfort [9,36], as it can diverge substantially from vehicle motion and directly influences motion perception and sickness accumulation through its interaction with sensory systems (vision and vestibular), which are head referenced [37,38]. However, even though head motion directly affects motion sickness prediction [9], existing motion sickness models, including the widely used SVC [39–41] models, overlook the detailed prediction of head and body dynamics. All the above underscore the necessity for a deeper understanding of head-neck-body motions within the context of AVs and rail vehicles, which will allow their efficient design to enhance motion comfort (e.g. in seat suspension systems [42,43], active chassis control, motion planning [44,45] and others).

Cycling, one of the active transportation modes, is healthy [46] and greatly contributes to reducing greenhouse gas emissions, congestion, and air pollution specifically on shorter travel distances [47]. Due to flexibility and cost two-wheelers are also increasingly used to deliver products to consumers. The personal and societal advantages are more evident in the recreational use of the travel time rather than the productive, correlating positively with physical and mental well-being [48], as well as reduced amount of sick days [49]. Therefore, various countries provide incentives to increase the use of bikes, but there are still challenges that need to be addressed to enable their wide and comfortable use. According to surveys and the literature, irregular road surface quality is a modulating factor of safety and comfort of cyclists [50–53]. The transmission of vibrations from the road to the rider's body and head is mainly affected by their posture and the design of the bike. High magnitude vibrations are induced to the bicyclists human body by road irregularities, without any isolation from the wheels since most bicycles, for daily use, do not employ suspension systems, apart from the tires, to isolate them [54]. Meanwhile, the bike type and specific configuration can affect the sitting posture and the vibration transmissibility [55,56]. The intensity of these vibrations is critical also for children being transported by bike, e.g. in a carrier or in a cargo bike, as accelerations are amplified in such vehicles [57,58]. Hence, there is a need to re-focus on the impact of vibrations on children's, adult's and workers'

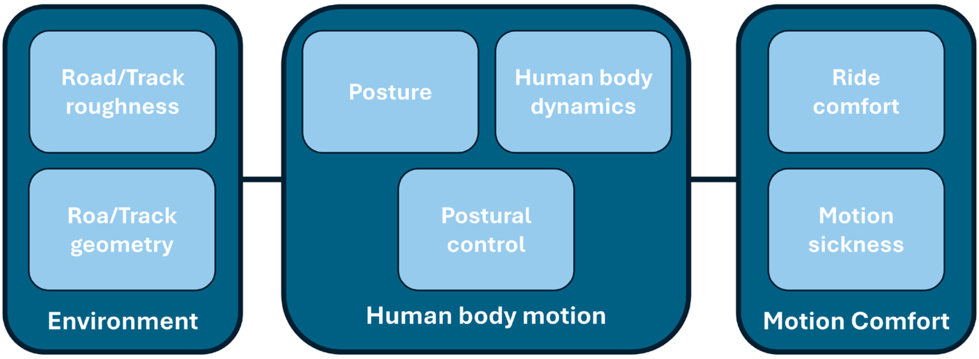

Figure 1. Overall structure of the paper.

health, and comfort [59] to secure the comfortable and wide use of bikes for securing their great environmental impact.

In this paper, we focus on physical comfort by delving into the modulating factors of motion (dis)comfort (i.e. combined symptoms of ride comfort and motion sickness): environment (road/track roughness and geometry) and human body motion (posture, human body dynamics, and postural control) (Figure 1). Motion sickness and ride comfort are widely discussed in various literature reviews. In this paper, we will explore them with regards to their assessment in different transport modes (road and rail vehicles), and the factors affecting them (environment and human body motion).

2. Motion comfort

Comfort is a complex term related to ergonomic factors, ride comfort and whole-body vibrations, thermal conditions (temperature, humidity), noise levels, and air quality within the vehicle [16]. Richards [60] emphasises that comfort is a personal state characterised by a feeling of subjective well-being in response to a particular environment or situation. Zhang et al. [61] build on that and recommended to always consider comfort and discomfort as two independent entities. In this paper, we focus on the aspects of ride comfort and motion sickness, which are part of the wide and complex domain of physical discomfort.

Vibrations cause an immediate perception of discomfort, which is often referred to as ride comfort (RC). Ride comfort, also referred to as vibrational comfort, particularly focuses on the vibrations transmitted by the vehicle structure to the human body in the range of approximately 0–30 Hz, where the relevant frequency range varies somewhat per transport mode. Since ride comfort relates to discomfort in various body regions, it is also referred to as whole-body vibration (WBV). In road transport, RC is often dominated by vertical motion resulting from road unevenness/roughness. However, horizontal accelerations due to abrupt braking or steering also affect ride comfort. The motion of automated vehicles is regulated by controllers along a predefined trajectory, which reduces the likelihood of sudden steering movements. In contrast, rail vehicles rely on track guidance for steering. As a result, rail vehicles may exhibit more pronounced lateral motions caused by lateral track irregularities, as well as self-excited bogie hunting and car body motions.

Meanwhile, prolonged low frequency vibrations (< 1 Hz) can also provoke motion sickness (MS). Motion sickness is a condition identified by symptoms such as sweating, dizziness, nausea, and vomiting. Motion sickness can also occur in conditions with only visual motion (visually induced motion sickness – VIMS), or in driving simulators and flight simulators (simulator sickness) but this is beyond the scope of this paper. MS can occur during travel by land, sea, air, and space. In road and rail transport, the horizontal vehicle accelerations are key in provoking MS with a modest role of vertical motion, whereas in ships vertical motion is key in provoking MS. Ride comfort and motion sickness will be discussed in Sections 2.1–2.3.

2.1. Ride comfort and whole-body vibration

2.1.1. General

Ride comfort generally relates to continuous perturbations, for instance, due to road or track unevenness or, in rail vehicles, to self-excited motion of bogies and car body. Ride comfort is perceived immediately, while prolonged whole body vibrations can also induce drowsiness with negative effects on driving ability, safety and performance. An acute sense of discomfort is also provoked by discrete motions, which are transient and mostly described as discrete pulses with specific acceleration and jerk characteristics [62,63]. In real driving conditions, these motions are discrete events which could include lane changing, accelerating, braking and curve entry. A narrative review [64] reported that

> Relatively short exposures to vibration of 30 min can significantly induce drowsiness and impair performance, where more than half of the cited studies evaluated the effect of vibration on driver drowsiness at lower frequencies (less than 10 Hz), at a low amplitude (less than $0.3\ m/s^2$), and for low durations (within 30 min).

Whole-body vibrations (WBV) result in feelings of discomfort, while there is evidence that, depending on the duration and amplitude, prolonged WBV can cause significant health issues [65] also illustrating adverse relationship between exposure to whole body vibration (WBV) with Musculoskeletal disorders (MSD) [66,67] and low-back pain [68]. Daily and prolonged exposure to whole-body vibrations was related with functional impairments and postmortem structural changes in animals' brains [69].

The whole-body vibrations induced by the road surface and path are also critical for balance and orientation, which is a challenging task, particularly in dynamic environments such as moving (road and rail) vehicles where this research is focussed. Difficulty in stabilising the body in a moving vehicle can induce a perception of discomfort directly, and hamper precision when manually operating vehicle controls and NDRT. The central nervous system (CNS) integrates sensory information from visual, vestibular, and somatosensory systems to produce coordinated motor responses that ensure body stability and orientation awareness. The integration of this sensory information and the postural instability are greatly affected by the whole-body vibrations and eventually the head motion, where our visual and vestibular sensory systems are referenced. In this paper, we refer to this process as postural control which will be explored in relation to motion comfort in Sections 5 and 6. Meanwhile, the head motion has been proven to be a key-determinant for discomfort, while the differences between expected and perceived motions/vibrations as perceived by our head-referenced sensory systems result in motion sickness occurrence.

2.1.2. Objective metrics

Vibration data can be transformed into objective metrics for evaluating the ride comfort of road and rail vehicles. Various evaluation methods and metrics are available in the norms and standards, such as ISO 2631 [70], VDI 2057 [71], and BS 6841 [72], which are widely used for both rail and road vehicles. In addition, EN 12299 [73] and the Sperling index [74,75] are dedicated to assessing the ride comfort of rail vehicles. These methods typically translate 3D translational accelerations and 3D rotational accelerations into one common discomfort exposure signal which varies as function of time. Subsequently the root mean square (RMS) or similar operations are used to summarise discomfort over a certain period. Both the time varying exposure and RMS generally retain the underlying unit of acceleration (m/s^2), which is intuitive for translational motion but debatable for rotational motion. For the latter, weighting factors to convert the units are used and suggested by the ISO standard. The evaluation typically begins by applying a perception filter, which involves frequency weighting, to the vibration signals. This accounts for the varying sensitivity of the human body to vibrations at different frequencies. Figure 2 compares the different filters for ride comfort (RC), which are explained below, and for motion sickness (MS), which are explained in Section 2.3.

Regarding the comfort filters, W_b is defined in BS 6841 [72] for vertical seat vibration based on the experimental comfort contours in the frequency range of 2–100 Hz [76] and 0.5–5 Hz [77]. In ISO 2631-1 [70], a different weighting curve, W_k, is defined. This weighting curve is a compromise between W_b and another weighting curve W_i, which is derived from data collected by Seidel (in an unpublished report 1988) [78]. Although W_k is almost identical to W_b, it is not derived from experimental studies and appears to be a less satisfactory predictor of discomfort [79]. For rail vehicles, W_b is more commonly used, as specified in ISO 2631-4 [80] and EN 12299 [73]. Comparison of W_b and W_k (Figure 2(a)) shows that W_k places more weight on low-frequency vibrations and less on high-frequency vibrations. One possible explanation [81] for this difference is that the studies leading to the W_b curve involved female subjects, who are generally more sensitive to higher-frequency vibrations [77], while the studies that led to W_k (W_i) only considered male subjects. This illustrates the need for considering gender balanced human participants for the development of such metrics.

Furthermore, different frequency weightings are used for vibrations measured in different body positions and motion directions, as the perception of discomfort can vary. For example, W_d is defined in ISO 2631 as the frequency weighting curve for vibrations in horizontal directions (Figure 2(b)). The maximum sensitivity range of horizontal vibrations is lower (between 0.5 and 2 Hz for W_d) compared to that of vertical vibrations (between 4 and 8 Hz for W_k and between 5 and 12.5 Hz for W_b). In addition, ISO 2631 specified that different weighting curves with different 'multiplying factors' should be used for measurements at the feet (floor), seat, and seat back in different directions.

To establish a standard for ride comfort in rail vehicles, Helberg and Sperling conducted tests with 25 participants using a vibration test platform [74,75]. Through this dataset, they extracted frequency weightings for vertical (W_v, Figure 2(a)) and horizontal (W_h, Figure 2(b)) motions, which allowed the derivation of the Sperling Index. According to the figures, the most sensitive frequency ranges are the same for vertical and horizontal vibrations, while a higher overall weight is assigned to horizontal vibrations. Compared to W_b and W_k, the Sperling index places more emphasis on vibrations between 1 and 2 Hz and less

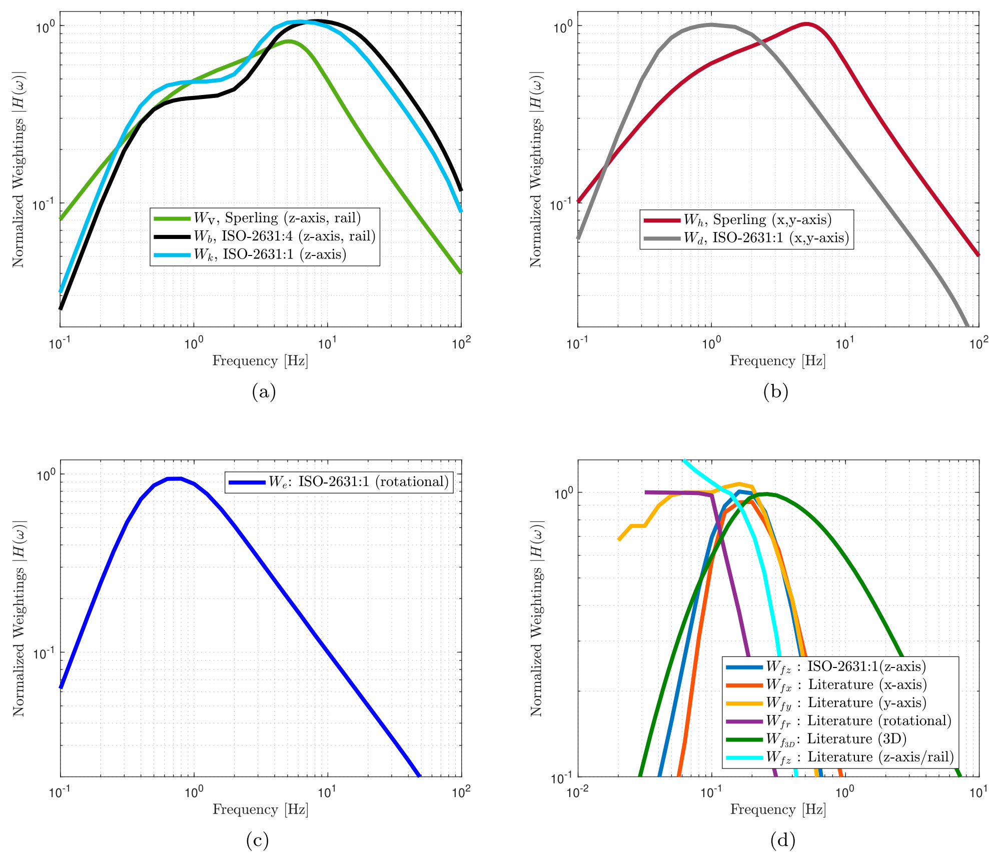

Figure 2. Filters for vertical, horizontal and rotational ride comfort (a,b) described in Section 2.1 and motion sickness (c) described in Section 2.3. (a) Vertical filters for ride comfort. (b) Horizontal filters for ride comfort. (c) Rotational filters for ride comfort and (d) Motion sickness filters.

on vibrations above approximately 4 Hz. We conclude that frequency weighting filters for road and rail vehicles are not fundamentally different and are based on the same or similar experimental data involving single-axis sinusoidal motion in laboratory conditions.

Frequency weightings specified in standards, such as those in ISO 2631-1, are widely used but show limitations in certain contexts. Many factors, such as vibration magnitude, point and direction of measurements, type of excitations, etc., may influence comfort perception and thus the frequency weightings. For example, multi-axis vibrations generally cause more discomfort than single-axis vibrations for similar magnitudes, and shocks are rated as more severe than continuous vibrations. Additionally, variables like body posture and seat-back inclination also affect comfort perception and WBV, which will be discussed in Section 6. A more detailed review of the factors and their effects on frequency weightings has been conducted by Deubel et al. [82]. Despite these limitations, the studies of Enders et al. [83] show that the conventional filters defined in the ISO and BS standards perform better than non-standardised filters. Therefore, the ISO weightings remain a valid baseline for most applications.

The key metrics used across these standards to assess comfort over a certain time period include Root-mean-squared (RMS) acceleration and Vibration Dose Value (VDV). These metrics serve complementary purposes: RMS acceleration measures vibration intensity over time and can be used as a general indication of passenger or driver comfort under steady-state conditions. VDV, on the other hand, is designed to capture the effects of intermittent, high-intensity vibrations that are common in real-world scenarios, such as when a train encounters short-wave track irregularities or a vehicle passes over a pothole. VDV is used also to compare vibration exposures of different durations for occupational health e.g. 30 minutes of high vibration vs. 4 hours of moderate vibration. In addition, the crest factor, evaluating the intensity of peak vibrations relative to RMS levels, is used for identifying peak vibration events that might affect passenger comfort or health, even if the overall vibration levels are low. Besides, the point vibration total value (PVTV) is defined as the root-sum-of-squares of the vibrations in all directions at one measurement point and the overall vibration total value (OVTV) is defined as the root-sum-of-squares of the PVTVs at all measurement points.

EN 12299 provide several metrics for ride comfort assessment of rail vehicles, among which the Mean Comfort (N_{mv}) and Continuous Comfort (C_{cx}, C_{cy}, C_{cz}) are most commonly used. Mean Comfort evaluates ride comfort over a five-minute period using a statistical method. During this period, accelerations measured from the floor are divided into 60 segments of 5 seconds each. The RMS acceleration is then calculated for each segment in three directions: vertical, longitudinal, and lateral. The Mean Comfort is defined as the 95th percentile of the 60 RMS values, i.e. the fourth highest value. One of the main advantages of this method is that it is less sensitive to extreme values or large fluctuations, which are more common in rail vehicles than road vehicles, compared to the RMS-based method used in ISO 2631. However, since only one of the 60 RMS values is used, there is a possibility of losing certain information. Therefore, it is recommended to also use the Continuous Comfort (C_{cx}, C_{cy}, C_{cz}), defined as the five-second frequency-weighted RMS values for each direction, which is similar to the RMS values defined in ISO 2631. The above conventional methods and metrics use the vibrations measured either on the floor or seat surface or combined to evaluate passenger ride comfort. However, the comfort index so calculated is independent of the seat characteristics and human parameters, while the data are based on rigid and compliant seats. Thus, whole-body vibration analysis using human biodynamic models [84–88] and/or measurement data [89] is necessary to perform more precise and comprehensive comfort analysis. Another limitation of the above standards is that they apply for continuous perturbations. For brief discrete horizontal acceleration events, similar to sudden braking and steering, de Winkel et al. [63] showed that the ISO norms do not well match subjective discomfort and propose the development of alternative standards.

Despite the existence of clear guidelines for the assessment of comfort in road and rail vehicles, there is no standard or widely used metric for the assessment of comfort on bikes. As a result, researchers usually employ the ISO-2631. Gao et al. [90] explored the validity of ISO-2631 standard and derived new limits with regards to bicyclists comfort (Table 1). Meanwhile, others [91,92] have used metrics, that represent the inverse value of the energy contained in the signal of acceleration greater than the acceleration of gravity, to define the comfort levels on bikes. Therefore, it is critical to re-define standards to assess comfort on bikes, especially now that their use is increasing significantly.

Table 1. Comfort reactions to different vibration environments.

		ISO 2631 (Vehicles)			
		a_{wv}	<	0.315 m/s²	not uncomfortable
0.315 m/s²	<	a_{wv}	<	0.630 m/s²	a little uncomfortable
0.500 m/s²	<	a_{wv}	<	1.000 m/s²	fairly uncomfortable
0.800 m/s²	<	a_{wv}	<	1.600 m/s²	uncomfortable
1.250 m/s²	<	a_{wv}	<	2.500 m/s²	very uncomfortable
2.000 m/s²	<	a_{wv}			extremely uncomfortable
		EN 12299 (Rail)			
		C_{Cy}, C_{Cz}	<	0.200 m/s²	very comfortable
0.200 m/s²	<	C_{Cy}, C_{Cz}	<	0.300 m/s²	comfortable
0.300 m/s²	<	C_{Cy}, C_{Cz}	<	0.400 m/s²	medium comfortable
0.400 m/s²	<	C_{Cy}, C_{Cz}			less comfortable
		Gao et al. [90] (Bicycles) (based on ISO 2631)			
		a_{wv}	<	1.780 m/s²	very comfortable
1.780 m/s²	<	a_{wv}	<	2.200 m/s²	comfortable
2.200 m/s²	<	a_{wv}			uncomfortable

The translation of acceleration levels in the different vibrations environments (i.e. transport modes) into perceived comfort by occupants is illustrated in Table 1. According to the table, 2.0 m/s^2 could be translated as very uncomfortable in road vehicles, while such intensity could be considered as comfortable in bicycles. Similarly, for rail vehicles, all accelerations above 0.4 m/s^2 could be considered uncomfortable, whereas for bikes the accelerations should exceed 2.2 m/s^2.

2.1.3. Subjective metrics

Various approaches are adopted to subjectively test discomfort. Matsumoto et al. [93] identified there are no significant differences in the perception thresholds for WBV between male and female subjects, while the thresholds of young subjects tended to be significantly lower than the thresholds of old subjects. After each exposure, the subjects were asked to inform the parts in the body where they felt the exposure. The subjects were asked to inform the body parts by selecting from eight body parts (head, shoulder, chest and upper back, arms, abdomen and lower back, buttocks, thighs, calves, and feet) indicated in a diagram of the body presented by the experimenter. The subjects were allowed to select more than one body part.

DeShaw at al. [36] tested 12 young males on a non-automotive seat in a lab-environment in different postures on different vibration levels to develop a statistical model predicting subjective discomfort based on ISO2631 metrics. Each participant evaluated every test condition involving different vibration directions, magnitudes, and postures using the Borg CR-10 scale [94]. This scale, which ranges from 0 to 10, includes descriptive anchor points, with higher ratings corresponding to greater exertion or discomfort. Since a rating of 0 represents the absence of vibration, the Borg CR-10 scale serves as an absolute measure, enabling comparisons across various postures and vibration conditions. DeShaw et al. [36] identified significant correlations ($R^2 = 0.93$) with the predictive discomfort model. The evaluation according to ISO 2631-1 correlated also well with discomfort ($R^2 = 0.89$) but was not able to predict the effect of posture.

Zhou et al. [95] investigated how the frequency-dependency of vibration discomfort depends on the acceleration and the force at the subject–seat interface. Discomfort ratings were collected using the magnitude estimation method, with the reference motion assigned a baseline value of 100. Participants were instructed to rate test motions relative to this reference (i.e. a motion perceived as half as uncomfortable would be rated 50; one perceived as twice as uncomfortable would receive a rating of 200). If participants could not perceive a test vibration, they were instructed to assign it a value of 0, and such responses were excluded from subsequent analyses. A similar approach was adopted by Morioka et al. [96], who determined equivalent comfort contours for fore-and-aft vibration of the backs of seated persons from 2 to 80 Hz using the method of magnitude estimation, examining the effect of input location, contact area, and body posture. Arnold et al. [97] used also the method of magnitude estimation to explore the equivalent comfort contours for fore-and-aft, lateral, and vertical whole-body vibration in the frequency range 1.0 to 10 Hz. The magnitude estimation method used in the previous studies [95–97] was relative, while the absolute magnitude estimation method can be used where no reference signal is used. Huang et al. [98] conducted a comparison between the reference (RME) and absolute magnitude estimation (AME) methods. Twenty human participants rated the discomfort by different levels of vibrations and noise using both methods. According to the results both RME and AME provided rates of growth of discomfort with high consistency over the repetitions. With regards to noise, RME illustrated less inter-subject variabily than the AME. RME was more consistent than the AME in rating the discomfort levels both by the noise and the vibration. Meanwhile, when judging vibration, RME illustrated greater inter-subject variability than AME. However, Huang et al. [98] concluded that AME may be more appropriate because perceived discomfort caused by the reference stimuli in RME may differ (e.g. occur in a different part of the body) from the perceived discomfort caused by the evaluated stimuli.

Huang et al. [99] explored the subjective discomfort caused by vertical whole-body vibration in the frequency range of 2–100 Hz using the AME method. Subjects also indicated the most uncomfortable body location where the vibration was experienced through a map with 12 body locations (0-no discernible location; 1-head; 2-neck; 3-shoulders; 4-chest; 5-back; 6-arms; 7-abdomen; 8-waist; 9-buttocks; 10-thigh; 11-calves; and 12-feet) similar to [93]. Lantoine et al. [100] used two different subjective methods to compare three car seats (one with soft foam, one with firm foam, one with seat suspension). Whole-body perceived discomfort was first assessed using a Visual Analogue Scale (VAS). One side of the VAS featured a slider that participants could adjust to indicate their level of whole-body discomfort, while the opposite side was marked with numerical values to help the experimenter quantify the discomfort score. The second assessment focussed on local discomfort, with participants verbally reporting their discomfort levels for specific body areas, including the neck, upper back, lower back, arms, buttocks, thighs, legs, and feet. For the rating they used the absolute method estimation rating on a scale from 0 (no discomfort) to 100 (the highest imaginable level of discomfort). Local perceived discomfort was then expressed as a percentage of the maximum score reported by each participant during each driving session. The same approach with regards to the discomfort in the body segments was also used by Cvetkovic et al. [101].

In conclusion, different methods have been used in the literature to assess discomfort subjectively, while new methods have been developed or used, like the VAS [100]. However, the use of existing methods to allow comparisons across the literature would lead to greater scientific contributions.

2.1.4. Across transport modes

Having explored the methods to objectively and subjectively assess ride comfort across transport modes, this section will delve a bit deeper into specific studies exploring ride comfort in the transport modes investigated in this paper (passenger vehicles, bicycles/two wheelers, and rail vehicles).

Passenger vehicles. Ride comfort is technically mainly expressed by means of objective vibration metrics described in Section 2.1.2. An overview of methods to decrease whole-body vibrations was reported by Tiemessen et al. [102]. Strandemar and Thorvald [103] defined the ride diagram (in accordance to the handling diagram for lateral dynamics). Similarly, de Winkel [63] derived standards for comfort and showed that the acceleration amplitude increases discomfort levels, and the direction of motion affects the strength of this effect. More specifically, they identified that higher jerks (shorter duration pulses) are considered more comfortable, and that triangular pulses are more comfortable than sinusoidal pulses.

Paddan and Griffin [104] measured 25 road vehicles and reported that the frequency-weighted RMS for the most severe axis ranges between $0.26\,\mathrm{m/s^2}$ and $0.75\,\mathrm{m/s^2}$, with a median value of $0.39\,\mathrm{m/s^2}$. These values are consistent with the vibration levels typically measured in rail vehicles Table 2. Aladdin et al. [111] explored the ride comfort of seated passengers in a vehicle from noise and whole-body vibration. According to the results, the RMS accelerations with frequency weighting according to ISO-2631, were increasing on the seat pan, backrest, and feet with increasing vehicle velocity. They reported values ranging from $0.05 - 0.6\,\mathrm{m/s^2}$, with the higher magnitudes to be present in the backrest. The vertical vibrations in all points of measurements were the most dominant, with the lateral vibration at the backrest reaching the same levels during the higher velocities. Similar

Table 2. Examples for sum of weighted acceleration (whole-body vibration) for bicycles, motorised road vehicles and rail vehicles.

Vehicle and road surface	Weighted acc.	Velocity	Ref.
	Bicycles		
Bike on asphalt	$a_w = 2.76\,\mathrm{m/s^2}$	v_x unknown	[105]
Bike on stone road	$a_w = 5.59\,\mathrm{m/s^2}$	v_x unknown	[105]
Bike on paved surface	$a_w = 6.37\,\mathrm{m/s^2}$	v_x unknown	[105]
Citybike on asphalt	$a_w = 1 - 3.2\,\mathrm{m/s^2}$	$v_x = 12 \cdots 16\,\mathrm{km/h}$	[90]
Carrier on asphalt	$a_w = 1 - 4.2\,\mathrm{m/s^2}$	$v_x = 10 - 20\,\mathrm{km/h}$	[58]
Carrier on cobble	$a_w = 2.5 - 9.3\,\mathrm{m/s^2}$	$v_x = 10 - 20\,\mathrm{km/h}$	[58]
Cargobike on asphalt	$a_w = 1 - 3\,\mathrm{m/s^2}$	$v_x = 10 - 20\,\mathrm{km/h}$	[58]
	Road vehicles		
Passenger vehicles	$a_w = 0.1 - 1\,\mathrm{m/s^2}$	v_x unknown	[106]
Passenger vehicles at bumps	$a_w < 2\,\mathrm{m/s^2}$	v_x unknown	[106]
Child seat∗ on asphalt	$a_w = 0.77\,\mathrm{m/s^2}$	$v_x = 30\,\mathrm{km/h}$	[58]
Child seat∗ on cobble	$a_w = 1.32\,\mathrm{m/s^2}$	$v_x = 30\,\mathrm{km/h}$	[58]
Heavy trucks on average	$a_w = 0.2 - 1.6\,\mathrm{m/s^2}$	v_x unknown	[106]
Heavy trucks at bumps	$a_w > 2\,\mathrm{m/s^2}$	v_x unknown	[106]
	Rail vehicles		
Locomotives	$a_w = 0.05 - 0.76\,\mathrm{m/s^2}$	v_x unknown	[107]
Rail vehicles	$a_w = 0.08 - 0.27\,\mathrm{m/s^2}$	$v_x = 0 - 90\,\mathrm{km/h}$	[108]
Rail vehicles (curve)	$a_w < 0.9\,\mathrm{m/s^2}$	$v_x = 0 - 90\,\mathrm{km/h}$	[108]
Rail vehicles	$a_w = 0.24 - 0.36\,\mathrm{m/s^2}$	$v_x = 100 \pm 10\,\mathrm{km/h}$	[109]
High speed	$a_w = 0.31 - 0.67\,\mathrm{m/s^2}$	$v_x = 200 - 400\,\mathrm{km/h}$	[110]

Note: * Child seat in passenger vehicle;

results were extracted by Park et al. [112], who collected data from six vehicles on highway and uneven road conditions in a driving test field. The vehicles were driven with a constant speed of 80 km/h on the highway and 40 km/h on the uneven road. They reported levels of total ride comfort around $0.50 - 0.75\,\mathrm{m/s^2}$ with significant differences between the vehicles. Interestingly, they presented increasing levels of the values with the increase of the backrest angles from 10–40°.

Kim et al. [113] assessed the whole-body vibrations in different active seats for heavy vehicles. They illustrated significant increases of the discomfort, and highlighted the need to develop more effective controls to address non-vertical WBV exposures where existing seat design are lacking despite the importance of these vibrations. Mansfield et al. [114] performed a large correlation study with 1203 drivers across two car types and three road surfaces. They used only the vertical acceleration due to its dominance over the other translational and rotational accelerations. They reported comfort levels from $0.32 - 1.10\,\mathrm{m/s^2}$, having significant differences between the three rides and two vehicles tested. They also concluded that there was no significant difference in using the weighted rms of the acceleration or the vibration dose value (VDV).

In an effort to decrease the need for human testing, Penestri et al. [115] designed a multibody dynamics model for testing whole-body vibrations. The multibody dynamic model had minor differences compared to experimental data. In this direction, Harmankaya et al. [116] developed a method to efficiently assess motion sickness, by recreating on-road driving scenarios in a compact test track. The method proved successful in recreating MS, but did not explore the recreation of ride comfort between the conditions.

Two wheelers. Specifically on two-wheelers, discomfort can be part of the operation. For instance, wind, including wind noise, is for many motorcyclists an important part of the driving experience, but it is undesirable in passenger road and rail vehicles. The focus of this paper is on ride comfort, which primarily is experienced through localised pressure on the rider's body and vibrations transmitted to the rider. Ride comfort on two wheelers, specifically on bicycles, can be affected by the following known aspects (saddle soreness, temporary loss of sensation in the limb or hand due to restricted blood flow, high amount of vibration which not lead to soreness directly but decreases the experienced comfort). Discomfort for both men and women occurs even during short bicycle trips (3 – 10 km) [117]. Celestine et al. performed a questionnaire analysis over 129 cyclists in southern India with the aim to customise bicycle design based on musculoskeletal disorder discomfort [118]. According to their results, females experience more pain than males, specifically in the regions around the hip and knee. The highest pain levels were reported in the spine among cyclists using single-suspension bicycles. Overall, they concluded that rigid and geared bicycles are ergonomically better. However, despite the interesting findings, they did not assess the levels of whole body vibrations and ride comfort, which is the focus of this review paper.

Chen et al. [119] investigated light motorcycles and scooters (engine size 125cc) on rural, provincial and urban roads in comparison to passenger vehicles, according to ISO 2631-1 and ISO 2631-5 standards. They found significantly higher measured acceleration values for the riders of two-wheelers than for the passenger vehicles. For sedans they found means of RMS between 0.25 and $0.40\,\mathrm{m/s^2}$ while scooters were in the range of 0.68 and $0.97\,\mathrm{m/s^2}$ and motorcycles ranged from 0.82 to $1.18\,\mathrm{m/s^2}$. Estimated 8-h vibration dose value $VDV_{(8)}$ and 8-h static compression dose S_{ed} showed similar differences. Following the standards and the health guidance caution zones defined in ISO 2631-1 Annex B, the car drivers could manage more than 8 h before reaching the recommended limits while more than 50% of the motorcyclists reached the limits already within 2 h of driving. For bicycles all measured values known to the authors are above the threshold for an 8 h day [57,58,90,105]. This is hardly a problem for occasional riders or commuters but can be concerning for professionals such as letter carriers, delivery riders, urban couriers or even police officers on bicycles or motorbikes. However, even for occasional riders there might not be adverse health risks but significant discomfort levels that hamper the aspect of 'fun to ride'.

Macdermid et al. [120] investigated level of vibration and power output of seven athlete mountain-bikers in a comparative study on single-track climbs where the surface differed (asphalt vs. off-road). As expected, the acceleration level measured at handlebar, left arm, left leg and seat post differed significantly with RMS values between about 15 and 25 m/s^2. Specifically interesting is the fact that the accelerations in longitudinal direction were larger than those in vertical direction. Surprisingly, at lower back and head the differences between road types were not significant. In contrast the power needed to provide the same speed differed with 11%.

Both, Roseiro et al. [105] and Gao et al. [121] showed that the vertical acceleration dominates the combined vibration in utility cycling applications. For cyclists the contact to the vehicle relevant to (dis)comfort is not only the seat but also the handle bar. Therefore, this contact is of high importance for comfort. Drouet et al. [122] found that cyclists can discriminate energy differences measured at the handle bar in the order of 100 mJ. Vasudevan et al. [54] investigated the vibration level of cyclists in comparison to motorcyclists when crossing speed bumps between 4 to 8 cm height. VDV measured on the bike was speed and bump dependent and ranged between 0 and 10 $m/s^{1.75}$, while scooters did not experience higher values than 6 $m/s^{1.75}$, which probably is caused by lack of chassis suspension on bicycles.

In addition to the cyclists and riders, attention has been drawn with regards to the vibration induced to the human body of babies and children being transported by bikes. Some alerting results for the load on the children's body were already presented in a German newspaper [123], but there wasn't any scientific paper related with these outcomes. More recently, Schwanitz et al. [57] and Rothhämel [58] investigated child comfort in bicycle carriers and cargobikes, evaluated according to ISO 2631-1. They found vertical weighted accelerations of normally up to 5 m/s^2, in extreme cases up to 9 m/s^2 where most of the vibration took place in a frequency range up to 10 Hz for a tyre pressure of 300 kPa. Doria et al. [124] investigated the frequency domain of city bikes identifying the area around 15 Hz as the most important in the PSD at the same tyre pressure and similar tyre width. This frequency range was covered in Rothhämel's measurements only on smooth cobbestones.

Kanya investigated whole-body vibration transmissibility of children in bicycle trailers with human subjects [125] in eight different cycle carriers with an average speed between 10.1 and 18.8 km/h. The sum of weighted acceleration (WBV measured at seat) was $0.67 - 1.54$ m/s^2 on paved road and up to 1.79 m/s^2 on gravel road which is significantly lower than the results presented by Schwanitz [57] and Rothhämel [58]. The sum of weighted acceleration measured at the head was $1.66 - 3.18$ m/s^2 on paved road and up to 3.38 m/s^2 on gravel road. Tyre size and inflation pressure were not reported. However, at least some of the carriers owned chassis suspension systems. Recently, Dell' Orto et al. [126] measured the seat pan acceleration of five strollers and two styles of cargo bicycles with dummy infants representing ages of 0 to 9 months over six different road surfaces of varying road roughness at typical travel speeds. They reported average seat pan acceleration for 78 different scenarios and investigated the effects of road surface, vehicle, seat type, and travel speed on comfort and health using the ISO standards. They proved that rough road surfaces, amplified by travel speed, may induce health risks for travel durations as low as 10 min to 30 min. Cargo bicycles ridden at the maximum electric bicycle speed over paver bricks can cause accelerations that should likely be avoided except for only the shortest of durations until more direct evidence of risks to infants is studied.

Even if the general interest in child transport in carriers declined to the favour of cargo-bikes, there was still a large investigation by the bicycle magazine *mtb news* in 2022. They tested only carriers with chassis suspension over an own designed test track. The mean acceleration values were in a similar range as Schwanitz and Rothhämel found (max 0.73 g), however with a different evaluation method. Van Driessche [127] in contrast performed measurements in cargo bikes in the context of the design of a seat suspension system. The unweighted accelerations were in the range of 3.5 m/s^2. He concluded that the question probably is not the level of comfort but the level of accumulative injuries based on vibration. Despite the alarming results in the literature, all of them are extracted using standards developed and validated for adults rather than children. In most studies dummies are used to represent children, but these dummies are not validated using measurements in real children. This creates a need to further investigate the interaction of children with such transport systems while developing dedicated comfort standards.

Rail vehicles. Extensive experimental data on WBV measurements from operational rail vehicles worldwide are available in the literature. Most studies follow the ISO standard to evaluate ride comfort, which facilitates comparisons of the general comfort levels between rail and road vehicles, see Table 2. Riesco et al. [107] extracted WBV data measured from locomotives in 11 papers and concluded that the weighted accelerations in the vertical direction range between 0.05 m/s^2 and 0.76 m/s^2. Sadeghi [109] conducted measurements on a commercial line at 100 $\pm$ 10 km/h in Iran and found that the OVTVs were between 0.24 m/s^2 and 0.36 m/s^2. For high-speed trains, Gao and Wang [110] reported that the OVTVs increase from 0.31 m/s^2 at 200 km/h to 0.67 m/s^2 at 400 km/h. In contrast, Peng et al. [128] reported much lower values: the PVTVs measured at the seat surface and backrest at 300 km/h were below 0.12 m/s^2, lower than those typically observed even in conventional-speed trains. However, it should be noted that results obtained under controlled test conditions may not be directly compared to those obtained during commercial operations. In practice, ride comfort on high-speed trains can vary significantly depending on factors such as vehicle design [129], track quality [130], and wheel-rail contact geometry [131].

The variability of measured WBV levels can be attributed to several factors. For example, WBV levels differ across various directions and measurement points. While many experimental studies have shown that the amplitude of weighted accelerations on the seat surface and floor is highest along the z-axis (vertical direction) [107,130,132,133], the lateral motion and RC of rail vehicles are equally important. This is because rail vehicles are guided by the track, and lateral irregularities, transition curves, switches and crossings can result in increased lateral accelerations. Zoccali et al. [108] evaluated the ride comfort of a passenger vehicle on 7 track sections of the Italian railway. They found that, for all track sections, the mean value of the RMS acceleration in the vertical direction (0.058 m/s^2 to 0.25 m/s^2) was slightly larger than in the lateral direction (0.043 m/s^2 to 0.132 m/s^2). However, in curve transitions and railway switches, the lateral RMS acceleration could increase to a maximum of 0.9 m/s^2, exceeding the vertical RMS acceleration.

In addition, due to the conical wheel profile and the resulting wheel-rail contact geometry, rail vehicles are prone to self-excited motions of the wheelset, bogie and car body. These motions, often referred to as hunting or dynamic instability, can cause significant discomfort even on straight tracks. For example, Sun et al. [131] evaluated ride comfort using the Sperling index for a locomotive travelling at speeds up to 150 km/h and observed that car body hunting occurred on straight tracks. This was attributed to low wheel-rail contact conicity, caused by excessive gauge wear and large rail inclination. As a result, the lateral Sperling index was higher on straight tracks than on curves. Furthermore, when the vehicle speed exceeds approximately 120 km/h, the lateral Sperling index becomes greater than the vertical, indicating that lateral ride comfort becomes the dominant factor at higher speeds.

Moreover, the specific measurement location within the cabin also influences WBV levels. Wu and Qiu [134] demonstrated through simulations that ride comfort was worst at two ends of the car body regardless of speed, followed by the car body centre at high speed, while the ride comfort of a seat close to the nodes of the first bending mode was relatively good. This finding was partially verified by the measurements by Gao and Wang [110], who observed that ride comfort was best in the middle of the car body. Second, measurement conditions such as vehicle speed and track conditions can greatly affect WBV levels. Karakasis et al. [135] conducted a multi-factorial analysis based on measurements taken on a track section in Greece, with tests performed at speeds ranging from 30 km/h to over 90 km/h under various track conditions. They concluded that vehicle speed was the most significant factor contributing to ride comfort. In addition, measurements on high-speed trains indicated that the frequency-weighted WBV magnitude typically increases by a factor of 1.5 to 2 when vehicle speed increases from 200 km/h to 300 km/h [110,128,130], and by a factor of 2 to 3.5 at 400 km/h [110,130]. Besides vehicle speed, ride comfort deteriorates with increasing track irregularity. The influence of track irregularity will be discussed in Section 3.

Although the overall magnitude of WBV measurements may vary, the frequency characteristics remain consistent across different measurements. The power spectral density (PSD) of vertical accelerations typically has two dominant frequency bands [110,135–139]: one between 0–4 Hz and another between 8–15 Hz, corresponding to the rigid and flexible modes of the car body, respectively. In some measurements, an additional peak in the 4–6 Hz range was observed on the seat surface, which can be attributed to seat transmissibility [130]. Silva et al. [140] performed output-only modal analysis on the seats of two different types of trains and found that the transmissibility peak around 5 Hz is related either to the bending of the seat frame or to rigid seat movement, depending on the seat design.

In the lateral direction, the dominant vibration frequency is around 0.5–2 Hz [129,131,141], due to the modal coupling between bogie hunting and the rigid eigenmodes of the car body. This frequency range overlaps with the most sensitive range of human vibration perception (see the horizontal weighting curve for ride comfort W_d in Figure 2(b)), and therefore can cause significant discomfort. In addition, bogie hunting, with typical frequency range of 6–8 Hz [142], can also excite flexible eigenmodes of the car body in the same frequency range [143–145].The yaw dampers (and related suspension components) are the main components responsible for this interaction: while they add critical damping to control hunting, they also feed the bogie's dynamic forces into the car body structure [146]. An example of the excited mode is the first torsional bending mode, often called the 'diamond mode' of the car body, which is around 6–9 Hz. This leads to increased lateral acceleration levels on the car body and reduced ride comfort.

2.2. Summary, research gaps and future work

In passenger vehicles and bicycles, tyres effectively mitigate very high frequency vibrations whereas chassis suspensions can also mitigate lower frequencies. Chassis suspensions are established in passenger vehicles and trains, and designed to consider both comfort and safety. However a majority of bicycles does not have any chassis suspension, or have suspension only on front or rear wheel system. As a result, vibrational comfort is becoming a greater issue risking to hamper the wide use of bikes for recreational and occupational reasons, such as delivery bikes.

Seat suspensions provide a cost efficient alternative for isolating vibrations, and are common in bicycles with springs integrated in the saddle and the saddle (stoker). Complex and even active seat suspensions are used in a range of commercial road vehicles such as buses and trucks, and off-road vehicles in agriculture and military. At the same time, active seats are still rare in passenger vehicles and in passenger seats in rail vehicles. However, in passenger vehicles and rail vehicles, seat compliance and seat shape are an essential factor in the transmission of vibrations to body and head, offering scope to enhance ride comfort. Moreover, seat compliance and shape are leading in 'static comfort' as they determine seat pressure and postural comfort including the ability to accommodate different body sizes and postures.

Accelerations measured at the seat surface under the buttocks are predictive of subjective (perceived) comfort. Here frequency weightings as described in the various norms (see Section 2.1.2) provide effective objective metrics of ride comfort. However using the same or similar weightings the tolerable (comfortable) accelerations are much higher on bicycles (see Table 1). For bicycles, saddle pressure is an additional factor determining perceived comfort. In passenger vehicles and rail vehicles, seat back acceleration can also be measured at the seat to body contact area and can be used with established weighting factors in ISO 2631. Head motion is not commonly measured but some studies show additional value of recording head acceleration. In ride comfort, the key unknown factor is posture, where several studies demonstrate significant effects of posture and back support on subjective comfort, but insights and methods are lacking to quantify such effects. Here, the inclusion of head motion is promising, assuming head motion to be a key factor in ride comfort perception. Head motion will also be indicative of our ability to stabilise the entire body and help to design seats which optimally support.

The role of the seat in supporting the body is essential for static comfort and relevant for vertical vibration. With the introduction of automated vehicles horizontal motion due to braking, acceleration and steering is key in designing comfortable vehicle motion control strategies. The design of seats which optimally support is essentially different for active drivers and passive users of automated vehicles and rail vehicles. These passive users will not anticipate future vehicle accelerations which will increase a need for seats assisting in body stabilisation. At the same time, users will want to perform non-driving related activities ranging from resting or sleeping, video watching or performing active tasks on computer systems, challenging the designs of seats and interiors. This holds for all passive vehicle users in AVs, trains, planes and ships but is more critical in AVs and (light) rail vehicles, simply because these will experience higher accelerations in braking and steering manouvres. Active suspension controlling vehicle roll and pitch, can mitigate the resulting body loads but a cheaper solution will be to design seats which optimally support.

Factors related to the comfort of drivers and passengers are complex but differ from one another. On bicycles, in most cases we can assume a single rider on the bike who also controls the vehicle. However, there are some other cases that should also be considered. Specifically children are transported on bikes e.g. on seats behind the driver or in cargo bikes most often in front of the rider or in carriers behind the bicycle. In addition, tandem bikes are becoming more popular again, specifically in the context of inclusion of disabled people. However, independent of any disability the passenger on a tandem usually cannot see the road ahead and can, therefore, not prepare for unevenness by e.g. unloading the saddle. Similar issues challenge the passengers of bicycle rickshaws that have become more common again in larger cities for emission free passenger transport on short distances and in pedestrian-only zones.

2.3. Motion sickness

2.3.1. General

Motion sickness (MS) primarily occurs in passive motion, whereas active drivers do not experience MS. The severity and onset of symptoms vary strongly by individual and eventually lead to nausea and vomiting with initial reactions such as headache, increased salivation, and sensitivity to smells. MS generally develops slowly with prolonged motion exposure and decays when motion exposure is terminated. However complex aftereffects can persist over days including hypersensitivity to new motion stimuli. Meanwhile, occupants' situational (e.g. engagement in NDRT, etc.) and dispositional (e.g. posture, gender, experience, age, etc.) susceptibility greatly affect MS, ride comfort, whole-body vibrations, and postural control [65]. MS is mainly triggered by vestibular motion perception and also occurs in conditions without vision. However, MS is also affected by visual conditions where passive driving with vehicle interior vision (windows closed) was around twice as sickening as being driven with forward out of the windows view [30]. A representative map which includes the factors for MS occurrence is presented in Figure 3.

MS causation has been linked to two main theories: (a) the sensory conflict theory, and (b) the postural instability theory. The sensory conflict theory postulates that conflict accumulates due a mismatch (conflict) between expected and perceived motion from our sensory systems [147–149]. The postural instability theory attributes the inability to

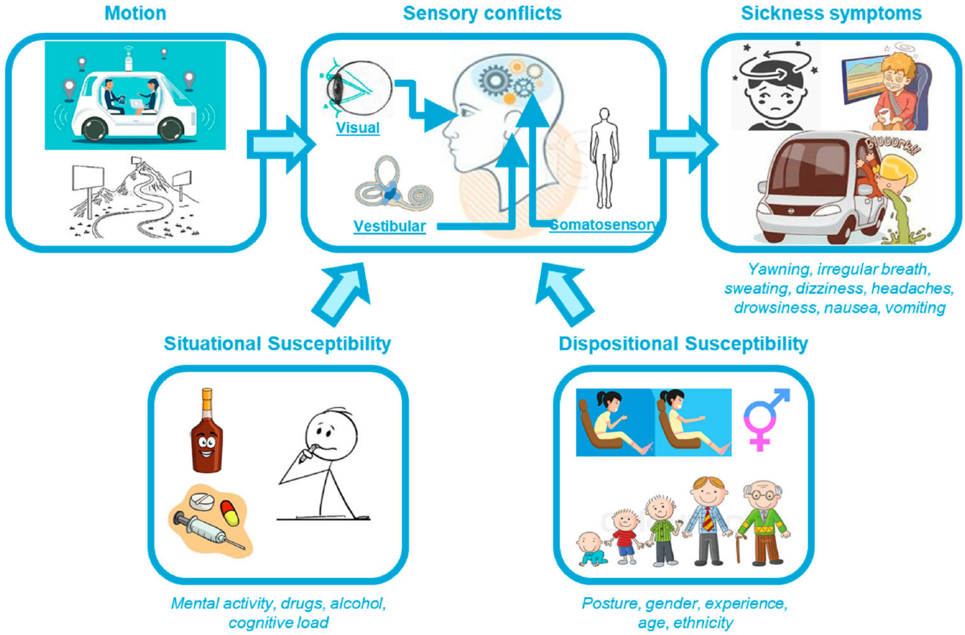

Figure 3. Motion sickness is primarily driven by acceleration and visual condition with substantial individual variations. Re-designed from Griffin [65].

maintain postural stability as the main cause of MS [150]. These theories are not necessarily conflicting as illustrated in a neck simulation study where MS predicting sensory integration models were linked to a neck stabilisation model, showing that conditions eliciting a strong conflict, resulted in inaccurate head rotation perception, hampering precise stabilisation [38].

MS in passive motion can be predicted as a function of motion and the presence and type of visual motion. Such a prediction always includes two components being a conflict or exposure model describing the exposure which rapidly changes in time, and an accumulation model, predicting the slowly evolving sickness level. Advanced models predict a conflict between perceived and anticipated motion, and use this as measure of exposure. Simpler models simply use frequency weighted motion as measure of exposure. Ideally such models take as input the head motion as 3D translation and 3D rotation. As head motion is not always available more often the seat motion is being used. This leads to imprecision in particular due to head rotations which can be substantial even when the seat does not or hardly rotate in pitch and roll (Figures 9–11). As illustrated in Section 5, this can be resolved using biomechanical models or transfer functions predicting head motion as function of seat motion as Papaioannou et al. have done [9,151].

2.3.2. Objective metrics

The simplest MS prediction model is the motion sickness dosage value (MSDV) which simply combines empirical functions on the sickness susceptibility as function of frequency for 3D translation and 3D rotation. These functions are shown in Figure 2(d) and discussed below. The MSDV can predict sickness in passive motion, but does not consider effects of vision, and does not consider interaction between motion directions. Diels et al. [152] and Bos et al. [153] highlighted that existing motion sickness evaluation methods (e.g. ISO 2631 [70]) are have multiple limitations, creating a need for revised motion sickness norms. The vertical ISO norm and weighting factor W_{fz} derives from extensive vertical motion experiments with sinusoidal motion between 0.03 and 0.63 Hz, and from 0.1–0.7 g quantifying motion sickness incidence (MSI) over a large population [154]. This dataset only reported the incidence of severe motion sickness (vomiting) and did not report lower sickness levels. Due to a lack of detailed MS data for horizontal motion, the vertical MS functions have also been applied for horizontal motion. Nevertheless, filters have been designed in the literature to capture the horizontal and rotational motion, but they are neglected. More specifically, a longitudinal acceleration weighting filter (WP_{f_x}) is approximately designed according to Griffin et al. [155], the lateral acceleration weighting filter (WP_{f_y}) is extracted from Donohew et al. [156] and the rotational vibration weighting filter (WP_{f_r}) is designed based on Howarth et al. [157]. All are presented in Figure 2(d). Identifying the gap of sufficient data to design the horizontal filters, recently experiments systematically varied not only vertical but also horizontal motion covering an extended frequency range of 0.06–3.2 Hz up to 2 m/s^2 [158]. These experiments showed limited differences in susceptibility for horizontal and vertical motion. For these experiments not only the motion sickness incidence but also lower sickness levels (pre-vomiting) were briefly reported [158]. For all motion directions it was shown that the ISO motion sickness frequency weighting function W_f needs to be adapted and a new weighting factor W_{f3D} was proposed jointly capturing vertical and horizontal loading. As shown in Figure 2(d), the ISO function is reasonable for low frequencies up to around 0.2 Hz but needs to be widened for higher frequencies up to around 2 Hz in particular for lower sickness levels. This motivates a revision of vibration discomfort norms capturing MS. For railway applications, Persson [159] conducted on-track tests to correlate measured vertical acceleration and motion sickness, showing an increased sensitivity at lower frequencies, see W_{fz}, *rail* in Figure 2(d).

A more advanced approach is to use models capturing sensory integration of vestibular and visual motion cues, and the resulting conflict. Here most common are the so called subjective vertical conflict (SVC) models which assume a mismatch between anticipated and perceived verticality to drive motion sickness development. SVC models with increasing levels of complexity including both vestibular and visual loops were introduced and validated for specific conditions [160–164]. Kotian et al. [165] recently validated such models across a wide range of conditions in their ability to predict sickness and motion perception. The subjective vertical conflict (SVC) model best predicted sickness in simple experiments and in passive driving. However, the multisensory observer model (MSOM) [41] best predicted motion perception. Such validations mainly predicted trends between conditions and motion sickness incidence over a population. Recently the SVC model, combined with a sickness accumulation model based on Oman [166] was extended to also predict lower sickness levels using the MISC scale [167–169]. Individual accumulation parameters were estimated using passive driving experiments and driving simulator experiments. Based on these individual parameters a stochastic population model was developed, which well predicted new (unseen) passive driving data. Thus, this model uniquely predicts lower MISC values and their variance across a population. For rail applications, Braccesi et al. [170] developed a UNIPG model based on SVC theory and validated it through experiments on operational trains by comparing the predicted MSI with those obtained by subjective measures (questionnaire). This model was further developed [171] by taking an objective metric related to ride comfort in curves (P_{ct} defined in EN 12299) as input, instead of accelerations, to better predict MSI in curves.

Significant work has been conducted also to explore motion sickness with regards to physiological signals. Koohestani et al. [172] examined the symptoms of motion sickness alongside physiological responses, evaluating different approaches for assessing motion sickness severity using physiological data. Their study considered techniques such as Electroencephalography (EEG), Galvanic Skin Response (GSR), and Heart Rate (HR) monitoring. They found that a definitive correlation between motion sickness and physiological parameters might not always exist. In passive driving, GSR correlated to sickness but also increased in time in participants developing no or marginal sickness [173]. Nonetheless, prior research has demonstrated that motion sickness can be detected through mathematical modelling and data analysis of physiological signals [174,175]. Furthermore, integrating multiple physiological indicators, especially with advanced methodologies such as machine learning, has been shown to enhance motion sickness detection [176,177].

2.3.3. Subjective metrics

Motion sickness is typically evaluated with subjective scales such as the Motion Illness Symptoms Classification scale (MISC) [178] and the fast motion sickness scale (FMS) [179]. These one-dimensional scales are generally applied in auditory form where participants are asked to report their sickness and provide a numerical verbal rating. This allows repeated ratings within experiments with typical intervals of 30–60 seconds. Scales probing specific symptoms in more detail such as the motion sickness assessment scale (MSAQ) are typically probed on paper or a computer after experimental testing. While reporting of specific symptoms is of apparent scientific value, in the design of sickness countermeasures one-dimensional scales are more practical. Moreover we are not aware of any model predicting sickness using multidimensional scales.

In the context of subjective scales we also mention the motion sickness susceptibility questionnaire (MSSQ) [180]. The MSSQ queries a participant's historical experience of motion sickness on various modes of transport. Here, the sum of the scores yields a (self-reported) representation of individual susceptibility. The MSSQ is commonly used in prescreening to select representative participants for experiments. For simple laboratory experiments a correlation of 0.45 was found averaged over ten studies [181]. However, for passive driving [182] reports a Spearman rank correlation of only 0.266 between MSSQ Total and MISC and 0.212 between MSSQ Car and MISC, making the MSSQ an imperfect prescreening tool (see also [183]). Hartmann et al. [184] compared three methods for assessing individual susceptibility to carsickness – two questionnaires focussing on motion sickness experiences and a motion sickness provoking lab test – with the development of kinetosis during real car driving tests. They concluded that lab-based of susceptibility remains highly reliable, especially considering men's tendency to underestimate their carsickness susceptibility in questionnaires

2.3.4. Across transport modes

Motion sickness in car passengers has been evaluated with large scale surveys. According to Schmidt et al. [29], 46% of passengers occasionally suffer from MS. Motion sickness as occurring to passengers in road vehicles is mainly influenced by the driving style (aggressive or smooth) and road conditions (e.g. urban versus curvy cross-country roads versus highway), which determine horizontal motions [28,185,186]. Females were more likely to report feeling ill during coach travel than males by a ratio of four to three. Poor forward visibility was found to increase sickness. Passenger sickness occurrence was approximately three times higher for passengers with no view of the road ahead (mean, 34.6%) compared to passengers who could see the road ahead extremely well (mean, 12.7%). No relationships were found between the occurrence of travel sickness and temperature or time of travel. Variations in motion sickness responses among coach passengers suggest that increased travel frequency may lead to habituation, independent of the age-related decline in travel sickness. Additionally, females appear to be more affected by poor forward visibility compared to males, and improving external visibility for passengers could significantly reduce the incidence of travel sickness. Engaging in non-driving-related tasks (NDRTs) has also been shown to exacerbate motion sickness, particularly when involving visual engagement, such as watching an in-car screen [187]. A recent paper [15] provides an overview of the effect of NDRTs and reports a new experiment showing somewhat increased sickness with a visual dynamic task compared to an auditory task. Travelling in a rearward-facing direction [27] also leads to higher levels of MS.

Motion sickness does occur in rail vehicles but statistics indicate that this is less common than in road vehicles [159]. The majority of the research on MS in rail vehicles focuses on tilting trains. Railway tracks are designed with cant in curves, where the outer rail is elevated higher than the inner rail to counteract the centrifugal forces. Cant alone may not be sufficient for higher speeds or on tight curves. Tilting trains are designed to lean into curves through a tilting mechanism to reduce the lateral forces passenger experience, thus allowing higher speeds on curves while maintaining passenger comfort. Despite being designed to enhance comfort, tilting trains often cause more motion sickness for passengers compared to conventional trains. Ueno et al. [188] found that 26.1% of passengers in tilting trains reported nausea compared to 4.2% in conventional trains. Similarly, Suzuki et al. demonstrated that the rate of motion sickness was higher in tilting trains (27.1%) than in non-tilting trains (17.7%) in a subjective evaluation among approximately 4000 passengers [189].

The main causes of motion sickness in tilting trains include lateral and roll motions, and improper tilting control strategies, presumably inducing sensory conflict. Low-frequency lateral vibrations (0.5–1 Hz) were identified as the primary cause of motion sickness in high-curve-speed railway vehicles in Japan [188]. Suzuki et al. [189] also identified low-frequency lateral vibrations (0.25–0.32 Hz) as the primary cause of motion sickness, with vertical vibrations having negligible effects. Tests conducted by Förstberg [62] showed that reduced tilt compensation strategies (lower roll velocity and acceleration) minimised motion sickness but led to increased lateral accelerations, presenting a trade-off between sickness reduction and ride comfort. A field trial conducted by Donohew and Griffin [190] concluded that the combination of coach-lateral acceleration (caused by cant deficiency) and coach roll (caused by track and coach tilt) resulted in passengers experiencing coach-vertical acceleration and coach roll. This combination of motions increased motion sickness.

As described above, vehicle roll can alleviate MS in curves, but results are not always positive. In the transition from straight driving sections to curves, the train is gradually rotating along its roll axis, and this rotation can contribute to sensory conflict. This can be taken into account designing rail tracks with gradual curve entry, and in active roll systems which limit rotational velocity. Passengers perceive themselves as upright due to the inertial alignment of the train, while the external scenery appears to be tilted, causing sensory conflict. Neimer et al. [191] showed that exclusion of the view of the landscape reduced the number of MS incidents, especially when the passengers were walking instead of sitting still. Another sensory conflict that can cause MS in tilting trains is the Coriolis cross-coupling effect. Such effect occurs when a person experiences simultaneous angular motions. In tilting trains, the train's tilting mechanism creates roll motions, and passengers often move their heads (e.g. to look out the window or at a screen), causing the cross-coupling effect. What makes things worse is that if the train's tilt response to track curvature is delayed, it enhances the mismatch between expected and perceived motion, further triggering the effect. For example, controlled experiments [192] demonstrated significant increases in sickness symptoms when tilt delay was introduced, even at low angular velocities.

2.4. Summary, research gaps and future work

We conclude that motion sickness occurs in particular in passengers in road and rail vehicles. Passengers exposed to passive motion on tandem bikes or children in cargo bikes could also suffer from motion sickness, but nothing could be found on any form of motion sickness in such conditions. Presumably passengers will look forward when needed, providing sufficient anticipation to prevent MS.

The introduction of automated cars make this a more pressing issue, as sickness will occur when taking the eyes off the road using the driving time for other activities. However automation can also resolve the MS issue by designing vehicle motion control strategies [193–195], and user interfaces providing anticipatory cues [196,197] which prevent motion sickness. Motion sickness in trains has been effectively minimised designing rail paths with modest curvature with gradual curve entry, canted rails and active roll. This makes MS in AVs and rail similar as an optimal path and vehicle roll can mitigate MS. However where vehicle roll is proven effective in rail, the on-road benefits remain to be established in AVs. Vehicle pitch may alleviate MS in AVs to deal with braking and accelerations dealing with other road users and adapting speed in curves. Interfaces providing anticipatory information have only been investigated for AVs.

In both domains a further reduction of MS may benefit from advanced objective MS metrics taking into account 6D vehicle motion such as the SVC, capturing other modulating factors in the model (Figure 3) and incorporating 6D seat to head transmissibility (STHT) as discussed in Section 5. Head motion, in particular angular velocities and accelerations, diverges substantially from vehicle motion and directly influences motion perception and sickness accumulation through its interaction with sensory systems (vision and vestibular), which are head referenced. However, even though head motion directly affects motion sickness prediction, existing motion sickness models overlook the detailed prediction of head and body dynamics. Section 5 will further unravel the importance of the STHT.

3. Road environment

3.1. Across transport modes

3.1.1. Passenger Vehicles

Longitudinal profiles show the design grade, roughness, and texture, whose classifications are based on ISO 8608:1995 [198]. ISO 8608:1995 is based on the assumption that a given road has equal statistical properties everywhere along a section and that the road surface is a combination of a large number of longer and shorter periodic bumps with different amplitudes. ISO 8608 has proposed road roughness classification using the power spectral density (PSD) values, with paved roads being considered to be among road classes A to D. More details can be found in Agostinacchio et al. [199]. This road roughness classification is also used for two wheelers. Regarding the impact of road roughness on comfort in passenger vehicles, Cantisani et al. [200] conducted a road roughness and whole body vibration analysis exploring different evaluation tools and comfort limits. The obtained results, in terms of weighted vertical acceleration, according to ISO standards [70], show good correlations to road roughness index (IRI) depending on vehicle speed. Papaioannou et al. [85,201] explored seat comfort for different seat designs under various road profiles and optimised the seat designs to secure optimal comfort in different road profiles.

Ahlin et al. [202] established a relationship between road roughness (characterized by IRI and the PSD parameters), vehicle speed, and the vertical whole-body vibration (WBV) experienced in a basic vehicle ride simulation. According to the results, the conversion of IRI to vertical WBV in a passenger car can be estimated using a factor of 0.16. However, this factor can vary significantly, ranging from 0.04 to 1.4, depending on the specific roughness wavelength and vehicle speed. This variation indicates that, for the same IRI value, the difference between the best and worst ride experiences can be as much as a factor of 30. Consequently, in certain applications, the derived relationships may not accurately reflect actual ride quality. Therefore, it is recommended that Pavement Management Systems (PMS) incorporate direct calculations of reference ride quality based on road roughness profiles, bypassing the use of IRI and PSD in this process. More recently, Muvcka et al. [203] examined the relationship between road roughness, quantified by the International Roughness Index (IRI), and whole-body vibration (WBV) experienced by passengers. They established IRI thresholds that correspond to different levels of WBV exposure, thereby informing road maintenance and design standards to enhance passenger comfort and safety.

Khorshid et al. [204] explored the impact of speed control humps on whole body vibrations, illustrating the whole-body vibration of the driver's seat for three vehicle categories is greatly affected greatly by hump geometry. The health risk of drivers and passengers greatly increases with the increased hump height, with the rear passengers being in greater risk compared to the front passengers.

3.1.2. Two wheelers

For two wheelers, the road roughness classification based on ISO 8608 [198] is also used, together with the estimation of pavement macrotexture as proposed by ISO 13473-1 [205]. In this norm, increasing macrotexture can correspond to a smooth asphalt, a draining asphalt, a city pave and a cobblestones surface. Regarding the impact of road surface on comfort, Verhoeven et al. [52] highlighted the unevenness of the road surface as one of the most important factors. Stinson et al. [50] found road surface quality as a factor favouring the use of the bike. Teixeira et al. [53] showed that rough road surface, such as cobbled and off-road surfaces, increased stress biomarkers in cyclists compared to asphalt. Hagemeister and Schmidt [51] found in an interrogation with open and closed questions that good road surface is the most important factor for route choice of cyclists, where cyclists were willing to chose an up to 20% longer route to avoid a route with bad surface quality. In a comparison of different asphalt road surfaces Gao et al. [90] identified a function to describe experienced ride comfort as function of measured acceleration, weighted according to ISO 2631. This function is based in a new assessment level (see Table 1).

While the vibration level during cycling usually is in the range up to 10 m/s^2 depending on road and bicycle, these values are only valid for summer condition or roads free of ice. Measurements by Shoman et al. [206] showed vertical accelerations over 10 m/s^2 on roads in winter conditions, i.e. with snow and ice. On compacted soil under snow and ice the vertical acceleration increased to peak values around 20 m/s^2. Shoman did not summarise the measurements to a single value since the meaning of his work was to collect data for verification of a bicycle simulator.

Depending on the region or country, the requirements for the evenness of bicycle infrastructure often follow the same standards as those for roads. In practice, however, road maintenance frequently fails to meet these requirements, particularly for bicycle paths. Additionally, motorised road vehicles typically operate at higher speeds and are equipped with chassis suspension systems, resulting in different surface quality needs compared to bicycles. Niska et al. [207] found the highest correlation with test subjects' comfort assessments for a wavelength of 1.9 m, corresponding to a vibration frequency of 3.7 Hz at a speed of 25 km/h, with the correlation decreasing as the wavelength increased. However, the International Roughness Index (IRI) primarily focuses on longer wavelengths, which are more relevant for motorised vehicles travelling at higher speeds.

3.1.3. Rail Vehicles

For rail vehicles, track geometry is an important factor that affects ride comfort as it provides the excitation to the vehicle-track system. Track geometry and roughness is classified based on the values of the PSDs according to the US Federal Railroad Administration (FRA) [208] and the European Rail Research Institute (ERRI, formerly the UIC Office for Research and Experiments (ORE)) [209]. The classification of both is depicted in Figure 4(a), which shows the PSDs for the longitudinal track profiles (vertical alignment). The FRA defines six classes of track profiles for ordinary tracks, with Class 1 corresponding to the lowest line speed (16–24 km/h) and Class 6 corresponding to the highest line speed (177 km/h). ERRI specifies two levels of track irregularities, classified as 'low' and 'high'. Other PSD definitions for track irregularities were used in different countries, e.g. China and France, but the PSD magnitude levels are similar to the ERRI's and FRA's Class 6 irregularity. More details about the PSDs of track irregularities can be found in [210,211]. Compared to road profiles, the track roughness have stricter standards regarding geometry requirements. According to Figure 4(a), the ERRI high class corresponds to a Class A road profile, while the limit for the FRA Class 1 track corresponds to a Class D road profile. These stricter limits might indicate higher risk regarding the induced vibrations from the track to the vehicle than the road, hence higher discomfort. At the same time, these stricter

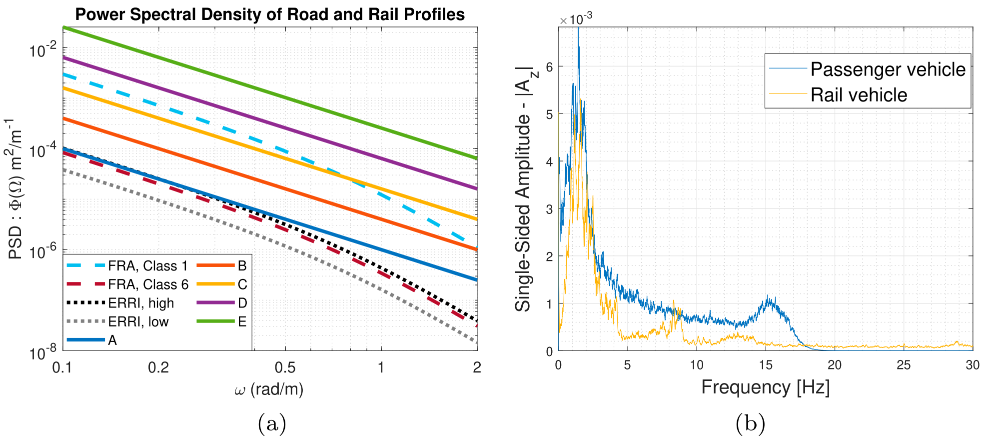

Figure 4. (a) Different road roughness profiles for roads (road vehicles) and tracks (rail vehicles), (b) Acceleration levels in different transport modes. (a) Road and track roughness and (b) Horizontal filters for ride comfort.

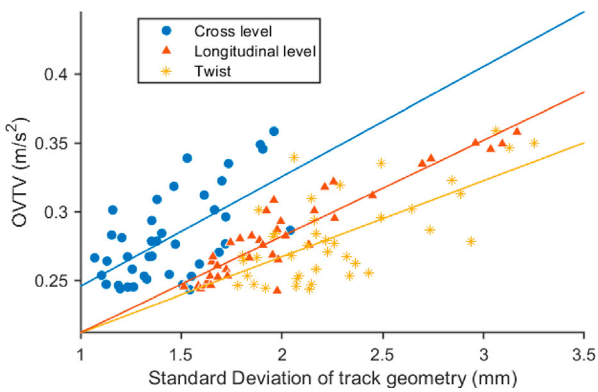

Figure 5. Correlation between ride comfort and track geometry. (Adapted from [109].).

limits on track roughness might be defined to secure contact between the vehicle and the track.

Regarding existing works in the literature that relate the track roughness with comfort, Sadeghi et al. [109] investigated the correlation between track geometry and ride comfort through field measurements. Ride comfort was assessed using the OVTV in accordance with ISO 2631-1 over a track section of 60 kilometers. Track geometry was evaluated by the standard deviation (SD) of five track geometry parameters over a track section, according to EN13848-6 [212]. The five track geometry parameters include longitudinal profile, twist, cross level, alignment, and gauge. The SD represents the dispersion of a track geometry parameter over a given track section, in relation to its mean value. A larger SD indicates a worse track geometry. The correlation between OVTVs and track geometry parameters (Figure 5) showed that ride comfort declines as the SD of the track geometry increases, suggesting a deterioration in track quality.

Liu et al. [130] investigated the contributions of different track geometry parameters to the ride comfort using a dynamic vehicle-track model calibrated by measurements. They found that the longitudinal profiles (i.e. vertical irregularities) and alignment (i.e. lateral irregularities) are the most influential track geometry parameters: the longitudinal profiles are the dominant cause of vibration discomfort, and as speed increases, the alignment becomes as important.

4. Posture

4.1. General

Occupants' sitting posture varies depending on the transport mode, where the physical shape and type of the seat might vary a lot. In this Section, we explore the differences and similarities in adopted postures among road and rail vehicles.

4.2. Across transport modes

4.2.1. Passenger vehicles

The importance of sitting posture, one of the main factors for static comfort [213], has been widely explored for passenger vehicles, while significant efforts have been conducted on predicting drivers' sitting posture [214]. Van Veen et al. [215] investigated various postures with regards to static and dynamic comfort by modifying the position of the head (against the headrest, upright, tilted sidewards), the hands (next to trunk and legs, on the lap, crossed, behind head), and the legs (on footrest, crossed, wide, pulled up). Cvetkovic et al. [101,216] explored the kinematic body responses and perceived discomfort in a bumpy ride and in random vibration, with a focus on the effects of sitting posture. In this work, the postures were categorised (erect, slouched and preferred) based on the flexion – extension angles between the body segments, e.g. head and thorax, and/or thorax and pelvis. According to the results of Cvetkovic et al. [101,216], the average preferred posture across the participants illustrated lower mean head-thorax angle compared to erect and slouched, and larger pelvis-thorax angle than the erect posture but lower than the slouched. However, these studies were conducted with participants not engaged in NDRTs and not with the freedom to adopt different postures. These would probably have resulted in higher head-thorax angles (head down) and more discomfort, and different position of the arms which has proven critical for biomechanical body responses. In conventional vehicles, occupants usually adopt standardised postures due to the limited interior space either as drivers or as passengers. The introduction of AVs, which are expected to revolutionise vehicle interior closer to a living or working space, will expand the range of potential sitting postures by allowing occupants' engagement in NDRTs. AVs interior will move closer to the one of trains allowing multiple postures due to the greater space.

4.2.2. Two wheelers

In sitting position while riding a bicycle, the posture is mainly defined by the three contact points: handlebar, saddle, and pedals. These contact points are indirectly defined by the frame geometry (Figure 6). In addition, fine tuning can be done by means of adaptation (saddle height and forward position) and choice of components (e.g. stem, handlebar,

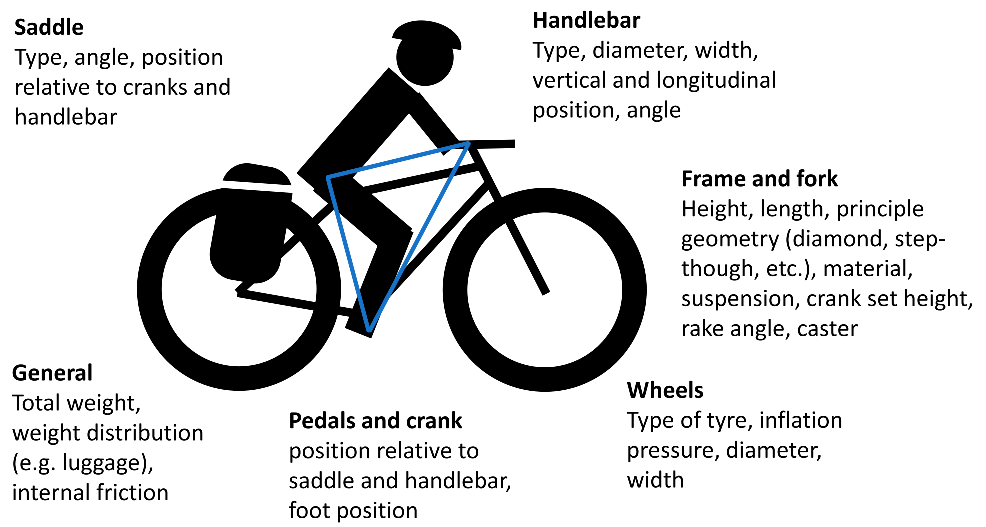

Figure 6. Ride comfort related parameters on a bicycle (inspired by [217]). The blue triangle describes the relation of the contact points between rider and bike.

cranks). This is also evident in city bikes, where the rider/bicyclist adopts a more erect posture since the handlebar height is increased significantly. Amongst the first investigators focussing on bicycle geometry with regard to comfort of utility cyclists were Christiaans et al. [217]. They determined in field and lab experiments that there is hardly any bicycle design metric that could be derived from anthropometric measures with the saddle-to-crank distance as the only exception. However, an interesting trend of their findings was that a significant fraction (about 30%) of the utility riders preferred a frame angle (seat tube angle) lower than what is usually offered in standard frames.

The weight of trunk, head and arms needs to be transferred to saddle and handlebar (and legs in case of significant force on the pedal unloading the saddle). The distribution between saddle and handlebar depends on the angle of the trunk. In an totally upright position as usual on dutch roadster bikes more or less all of the weight is transmitted to the saddle. The opposite extreme might be the time-trial position where a lot of load is on the handlebar. Chen et al. [218] have investigated the trunk flexion angle of 250 cyclists (one third of them female) and the correlation to their ratings regarding discomfort in neck/shoulder and discomfort in buttocks. The larger the trunk flex angle (meaning leaning more forward) the lower the discomfort for the buttocks. The minor the trunk flex angle (meaning sitting more upride) the lower the discomfort for the neck/shoulder area. The calculated compromise was found at 38°. A short investigation of 21 cyclists in Stockholm showed trunk flexion angles between zero and 47° with a mean value of 28° and a standard deviation of 12°.

Scoz et al. [219] suggest a trunk flexion angle of 25° to 40° in their investigation about bike fitting on discomfort of 160 mountain bikers (25% females). During the process they adapted the joint angles of the cyclists into predefined angular ranges by means of modified settings of the bike. After 30 days with the new setting the cyclists reported reduced discomfort, rated according to three different scales (FEEL, OMNI, VAS). However, the trunk flexion angle is often simplified using a straight line connecting hip joint and shoulder joint.

This is not precise due to lumbar spine bending affecting pelvic orientation. According to Neuss [220] this leads to pain in the spine and can be avoided by means of the correct distance between saddle and handlebar, assuming the angle between arm and trunk to be 90°. An important precondition is the freedom of the hip angle. Bressel et al. [221] tested partial and complete cutout saddle designs and investigated the effect on pelvic tilt. Saddles with a complete cutout design increased the trunk flexion angle in their experiments. The saddle with a partial cutout design was rated most comfortable.

For cyclists, posture does not only affect comfort but also propulsion efficiency and performance, which is important also for utility cyclists. Price and Donne [222] found that a steeper seat tube (larger seat tube angle) increases the efficiency during cycling, independent of saddle height. For the saddle height they did not find a maximum, however, a too high saddle decreases the efficiency significantly even if the force applied on the saddle does not change [223]. In contrast to the expectations, changing seat positions over consecutive bouts of cycling does not result in lower discomfort, as Verma et al. [56] realised when measuring pressure distribution and muscle activation.

Posture on bicycles has also been investigated in context of professional racing, often with respect to aerodynamic drag. Chabroux et al. [224] performed an aerodynamic study of different parameters, including both the posture of a cyclist's upper limbs and the saddle position, in time trial (TT) stages. Schaffarczyk et al. [225] as well as Barry et al. [226] investigated different postures on a racing bike and their effect on aerodynamic drag in the application of triathlon and found differences up to factor 2 for $C_d \cdot A$, respectively, and a reduction in cyclist power by up to 16.7%. In addition, other factors, such as accident and injury prevention, have been highlighted as important when investigating the rider's posture [227].

Posture optimisation has also been explored [228] on racing bikes to extract the optimal design of three key points: the handlebar, the saddle and the crank centre. Cyclists usually define their posture according to performance and comfort requirements. However, when modifying their posture, cyclists experience a trade-off between these requirements.

4.2.3. Rail vehicles

The literature on passenger vehicles about comfort and static posture could be related also with trains. In contract to the limited research on static posture in passenger vehicles, there is significant work trying to unravel the range of sitting posture in trains due to the great flexibility offered by the interior design. The postures of train passengers are associated with specific activities. Figure 7 summarises the typical postures reported in the literature and Table 3 lists the coding of the postures. Branton and Grayson [229] found that passengers were mostly engaged in activities such as reading and conversing, with 1221 and 1222 as the primary postures. Kamp et al. [230] found that the most common activities in trains were talking, relaxing, and reading, with 1211, 2321 and 1212 as the main postures. They also noticed that only less than 5% of the passengers were using small electronic devices, which did not significantly alter the postures. Bao et al. [231] observed that the most frequent postures for relaxing were 2221 and 2222, with heads resting on the headrest. It can be seen from the research above that a key difference between relaxing and other activities is how the head is positioned. Passengers tend to keep their heads upright while talking or reading, but lean their heads against the headrest when relaxing or sleeping. Groenesteijn et al. [232] identified four dominant activities: working on a laptop, reading, talking, and

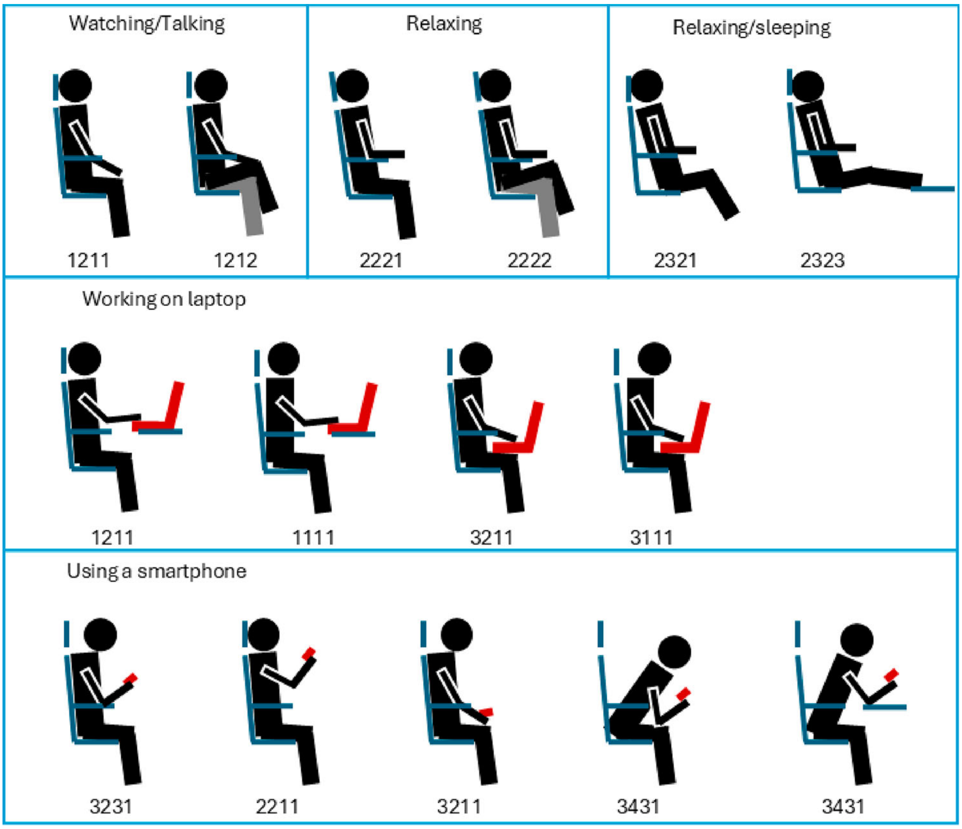

Figure 7. Typical postures for different activities of train passengers. Watching/Talking [230,232], (2221–2222) Relaxing [231], Relaxing/sleeping [230], Working on laptop [232], Using a smartphone [231,233].

Table 3. Coding of postures in trains (adapted from [230]).

Category	Description	Nr.
Head	Free of support (upright)	1
	Against headrest	2
	Lean forward	3
Trunk	Free from backrest (upright)	1
	Against backrest	2
	Lounging (slumped back)	3
	Lean forward	4
Arms	Free from armrest	1
	Upon armrest	2
	Only elbow supported	3
Legs	Free, both feet on floor	1
	Crossed	2
	Other	3

sleeping, with laptop work lasting the longest in duration. Udomboonyanupap et al. [233] observed that 57.4% of train passengers were using smartphones, exceeding the number of traditional activities like reading and talking. The typical posture is with both hands or only the right hand holding the smartphone, and resting their arms on the armrest. Similarly, Bao et al. [231] found that the use of mobile devices is the dominant activity during train trips, and the typical posture is with the body leaning forward and two arms supported by the table.

4.3. Summary, research gaps and future work

According to the literature, posture research methods vary across transport modes. In cycling, the emphasis has been primarily on performance and efficiency, with some consideration given to optimising bike design for a balance between comfort and efficiency. In contrast, train travel has seen more extensive posture studies due to the inherent flexibility in seating arrangements. However, the crucial link between these various postures and their effects on ride comfort and motion sickness remains largely unexplored. Essentially, while posture is clearly important, there's a lack of research comprehensively examining how different postures influence comfort and motion sickness across different modes of transportation. Meanwhile, the long-term effects of sitting postures in vehicle on users' health is under studied, especially in automated vehicles and rail vehicles where occupants may spend extended periods in non-traditional seating positions.

5. Human body dynamics

The environment (route, road surface, traffic etc.) define the vehicle motion and dynamics. The vehicle dynamics are isolated by the different vehicle subsystems (tires, wheels, suspensions, chassis, and seat), and are transferred to the human body inducing whole-body vibrations from the contact points (body-seat surface and back, the feet-floor, feet-pedal unit, hands-steering wheel/handle bar). The transmission and perception of the vibrations is significantly affected by a multitude of factors such as situational (e.g. participation in NDRT, occupants' health and physiological status) and dispositional factors (e.g. posture, gender, experience, age, anthropometric characteristics). The transmission of vibrations from the seat to the occupants' body and head has been extensively researched with the objective to model human body dynamics under different perturbations. The majority of research on this direction has been conducted with seated human participants on motion platforms and simulators, while a few studies explored seated human participants or dummies driven by road vehicles (passenger vehicles and two-wheelers). No research with human participants being driven by rail vehicles has been conducted to explore the transmission of vibrations to the occupants body within the vehicle environment. However, knowledge derived from studies with seated human participants on motion simulators could be expanded to both passenger and rail vehicles depending on the postures. Meanwhile, most of these studies consider that the human body is a passive system which reacts on the perturbation without actively adapting based on sensory feedback received (i.e. presence of postural control). This section will focus on the transmission of the vibrations from the seat to the head, while Section 6 will delve into postural control. More specifically, in this section, we will review the literature about the seat-to-head transmissibilities based on the apparatus used for the collection of experimental data, and the conditions (different seats, perturbations, etc.).

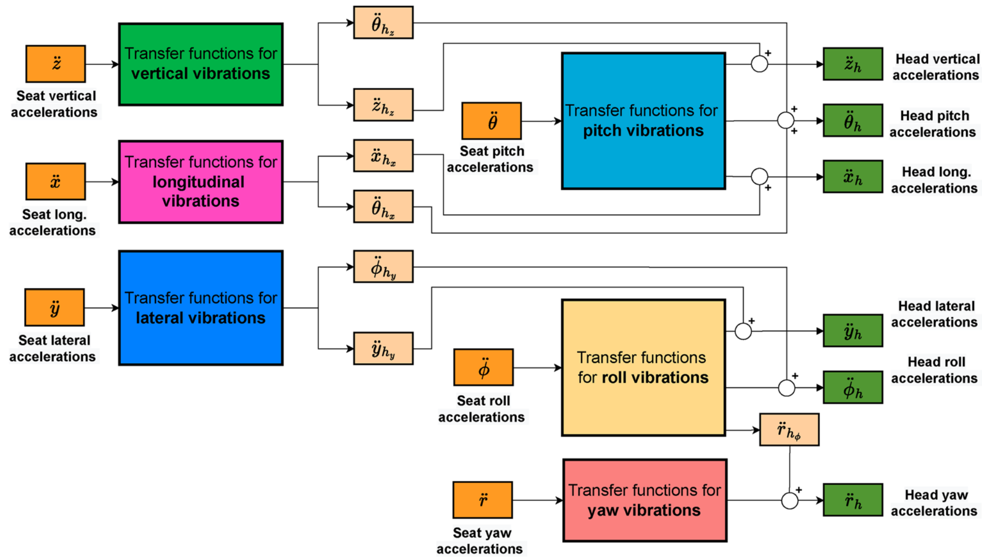

Figure 8. A set of seat-to-head transmissibilities functions combining single-axis, cross-axis and coupled effects. The STHT consist of: (a) T_{zz} and $T_{z\theta}$ for vertical vibrations; T_{xx} and $T_{x\theta}$ for longitudinal vibrations; T_{yy} and $T_{y\phi}$ for lateral vibrations; $T_{\theta z}$, $T_{\theta x}$ and $T_{\theta\theta}$ for pitch vibrations; $T_{\phi y}$, $T_{\phi r}$ and $T_{\phi\phi}$ for roll vibrations; T_{rr} and $T_{x\theta}$ for yaw vibrations.

5.1. Transmission of vibrations from the seat to the head

The human body can be modelled as a multi-body system, with different body segments, which receives perturbations in six degrees of freedom based on the seat vibrations. The human trials where six dimensional transfer functions were developed, could be generalised for assessing occupants' head vibrations based on their excitations. The transmission of the vibration can be studied as single-axis ($x - x, y - y, z - z$), cross axis ($x{-}z$, $z{-}x$, $y{-}x$, etc.) and with coupling effects ($x - \theta, y - \phi$, etc.). The set of single-axis, cross axis and coupled effects transmissibilities can be combined to extract the final 6D head motion (Figure 8). This process is described in the literature [9].

5.2. Motion platforms/simulators

5.2.1. Single/direct axis perturbation

Paddan et al. [35,234,235] explored how vertical, horizontal and rotational acceleration vibrations affect the six axes seat-to-head transmissibilities in frequencies up to 25 Hz. They used a motion platform both with and without a backrest (inclined at an angle of 13° to the vertical). For the translational excitation, the input to the motion platform was a Gaussian random vibration of 60 s duration at 1.75 ± 0.05 m/s² rms, and was applied separately to all different direction (vertical, fore-aft and horizontal). For the rotational excitation, participants were exposed to random motion at frequencies of up to 5 Hz at 1.0 rad/s^2. The random excitation in both cases was used to extract the seat-to-head transmissibilities (STHT) in the frequency domain.

For the vertical excitation [35], head motion occurred principally in the fore-and-aft, vertical and pitch axes of the head, illustrating for the first time the need to consider multiple dimensional seat-to-head transmissibilities for the vertical input. This conclusion was later extended to the other translational perturbations, which were affecting the human body response not on the direct axis of perturbations but on others as well. With the 'back-on' posture, vertical head motion shows a distinct peak around 5 Hz and less variation between subjects than with a 'back-off' posture. These peaks were identified in the fore-aft and pitch head motion. The 'back-off' posture provoked additional peaks in some participants around 8 Hz for the vertical head motion, while second peaks appeared in higher frequencies around 10–15 Hz, when the direct axis of perturbation is the vertical. The seat interaction with the human body ('back-on' posture) amplified the magnitude of the head vibrations due to vertical perturbations in most axes.

For the direct perturbation of horizontal axes [234], the fore-and-aft seat motion mainly resulted in head motion within sagittal (pitch and longitudinal motion) and vertical plane. Without the backrest, transmissibilities for the longitudinal, vertical and pitch axes of the head were greatest at about 2 Hz. The contact with the backrest greatly increased head vibration at frequencies above 4 Hz, causing a second peak in the transmissibility curves at about 6 to 8 Hz. This was partially captured in the vertical excitation study [35] as well. Lateral seat motion without the backrest mainly provoked lateral head motion with a maximum transmissibility at about 3 Hz, affecting also the roll and yaw motion. The backrest had little effect on the transmission of lateral vibration to the head.

For rotational excitations [235], the roll and pitch seat motion mainly resulted in roll, lateral and yaw motion and in fore-and-aft, vertical and pitch motion respectively. During roll excitations with the 'back-on' posture, a peak was identified in the lateral transmissibilities around 0–1.5 Hz. The roll and yaw transmissibilities illustrated peaks in a region around 1–5 Hz. The shift to the 'back-off' posture resulted in significantly lower transmissibilities. Regarding the pitch excitations, the transmissibilities for head pitch vibrations did not illustrate any distinct frequency peaks with frequency, but illustrated an increased amplification from 1 to 5 up to about 2 Hz during 'back-on' posture. The transmissibility of the vertical vibrations illustrated a peak around 2 Hz. These magnitudes were decreased significantly with the 'back-off' posture. For all excitations (intra-subject variability i.e. repeatability measures of a single subject) were small compared to inter-subject variability (differences within a group of subjects).

After Paddan et al. [35,234,235] paved the path for measuring seat-to-head-transmissibilities, more works followed. Matsumoto et al. [236,237] explored the transmissibilities of vertical motion in different human body segments and their non-linear characteristics when seated subjects were exposed to vertical whole-body vibration. The human body responses were measured in the sagittal plane, by perturbing the seated occupants in the vertical direction using a random vibration signal with 0.5–20 Hz frequency range and varying magnitude. The dynamic responses of the body were measured at different locations at the first (L1), fifth (L5), and tenth (L10) thoracic vertebrae, at the first (T1), third (T2), and fifth (L5) lumbar vertebrae, and at the pelvis. Based on the results, the maximum transmissibilities of the vertical vibrations were identified around 5 Hz for all the motions (vertical, pitch and fore-aft). This result was in accordance to Paddan et al. [35] with regards to the 'back-on' transmissibility area. Extending these findings, Matsumoto et al. [237] identified the dependency of the resonance frequency with the magnitude of the perturbation. The resonance frequency in all the transmissibilities (vertical to vertical, pitch and fore-aft) ranged from 5 to 8 Hz with the increase of the magnitude from 0.125 to 2.0 m/s^2 r.m.s.. Similar dependency was identified by Paddan et al. [35] with regards to the posture, where the adoption of the 'back-off' changed the resonance frequency of the seat-to-head-transmissibilities closer to 8 Hz. Furthermore, additional measurements in the human body allowed Matsumoto et al. [237] captured the existence of two resonance frequencies in the pelvis and L5. The first is located around 5 Hz, while the second is located around 8–12 Hz depending on the magnitude of vibration. This shift in the resonance frequencies was attributed to the interaction of the seat with soft tissues of our human body or the body geometry [238]. However, both have not been proven. Finally, they concluded that all the transmissibilities illustrated non-linear characteristics in the responses of the various body segments. This was amongst the first research works after Mertens et al. [239] which identified the nonlinearity in human body responses, implying the need for models considering non-linear characteristics to fully capture human body dynamics.

Zimmerman et al. [240] focussed on the single direction vertical seat-to-head transmissibility, exploring the effects of vibration frequency in seated whole-body vibration exposure, at 4.5, 5, 6, 8, 10, 12 and 16 Hz. Anterior, neutral, and posterior pelvic orientations were evaluated in the study. The different pelvic orientations did not change the peak frequency at the average seat-to-head transmissibilities ($\sim$5 Hz), but had an impact on their magnitude. The transmissibility magnitude was increased and decreased compared to the neutral pelvic position when anterior or posterior orientation was adopted, respectively.

Hinz et al. [241] explored seat-to-head transmissibilities under different magnitudes. The human subjects were exposed to random whole body vibration with various r.m.s magnitudes consisting of frequencies ranging from 0.5 to 20 Hz. Three excitations were used with the subjects being exposed at three vibration magnitudes to direct axis vibration (fore-aft, lateral, and vertical) and a triaxial vibration (components from all axis) simultaneously. According to the results, Hinz et al. [241] identified a similar dependence of the resonance frequencies with the vibration magnitude, similar to Mastumoto et al. [236,237]. The peak frequencies were similar as identified by other researchers, but minor differences occurred in the amplitudes due the seat vibration, postures, seating conditions of the tested subjects, and the location of the measurement at the head. This also points out the need of standardising the process and the equipment used for this measurements for comparable outcomes.

M-Pranesh et al. [242] explored the impact of various postures and support conditions on the transmission of vertical vibrations to along the vertical and fore-aft vibrations at the head and body segments of seated occupants. The perturbation was a random vertical excitation in the 0.5–20 Hz range, similarly as the previous research on the field. The averaged corrected responses revealed that the back support attenuates vibration in direct perturbation axis (i.e. the vertical) to all the body locations, while increasing the fore-aft transmissibility of the vertical vibrations at the C7 and T5 locations. The effect of back support was observed to be very small on the horizontal vibration of the lower thoracic and lumbar regions. According to the results, the hand position generally has a relatively small effect. Sitting without a back support resulted in very low magnitude fore-aft vibration at T5, which was substantially higher with a back support. M-Pranesh et al. [242] highlighted the need to assess distinctly different target body segment transmissibility functions for the development of efficient and accurate human body models, which will be able to capture the unique contribution each body segment.

Mandapuram et al. explored the seat-to-head transmissibility responses of seated occupants under single and dual axis horizontal vibration [243,244], and evaluated also the direct and cross-axis STHT [245] using the same experimental data. They explored different conditions with regards to back support (with and without), hands position (on steering wheel or on lap) and the r.m.s. amplitude of the random vibration signal (0.5–20 Hz) applied along the single axis (*x*-, *y*- and *z*-axis) and along the dual or three-axis. Mandapuram et al. [244] revealed significant effects of hand and back support conditions on the coupling effects and the measured responses, on contrary with M-Pranesh et al. [242]. The back support shifted the maximum fore-aft and lateral transmissibility from around 2–3 Hz to 1–2 Hz, without great differences in magnitude of the transmissibilities. Meanwhile, the placement of the hands on the steering wheel increased the magnitude of the single axis fore-aft and lateral transmissibilities in the area of 2–6 Hz and 2–4 Hz, being more pronounced in the fore-aft direction. The hands condition was with hands on the steer, but this could be translated also with the engagement in a NDRT were the hands are extended, such as reading a book or watching a movie on a tablet. Therefore, we can expect similar effects in such conditions. The position of the arms has proven to affect biomechanics in other works as well [246] by providing an addition vibration input, if the arms are holding a steering wheel/a tablet/a book and others, or acting as a vibration absorber. Mandapuram et al. [245] extended their analysis of single axis STHT also exploring cross-axis STHT. The result matched the previous literature, illustrating the maximum transmissiblity of the vibrations in the horizontal (fore-aft and lateral) and vertical direction around 2 and 5 Hz respectively without back support and hands in lap.

Bhiwapurkar et al. [247] explored the effects of vibration magnitude and posture on STHT responses of seated occupants exposed to lateral vibration. The perturbation was a random excitation in the range of 1–20 Hz with varying amplitude. The STHT was assessed in two different postures: (a) backrest and hands on the lap, and (b) leaning forward with hands on the table. The latter condition aimed on simulating working on a train while commuting. In both sitting postures, the STHT illustrated maximum amplitude at 2 Hz, while it illustrated an additional peak around 6 Hz only in forward lean posture. The additional peak was related with the motion of other body parts [248] or the existence of hand activities [65]. The posture had only a minimal effect on the STHT response. This magnitude of the lateral and vertical STHT was significantly different (lower with increasing magnitude) between the different perturbations around the first resonance peak, and no significant difference was identified after 4 Hz. Negligible differences were identified in the fore-aft STHT.

Despite the various efforts on evaluating and analysing single axis STHT and cross-axis STHT, no previous work extracted all of them in three dimensions. More recently, Mirakhorlo et al. [249] evaluated the single and cross-axis transmissibilities of seated occupants under single axis perturbation (fore-aft, lateral, and vertical), and explored the effects of seat back height and posture on 3D vibration transmission to pelvis, trunk and head. The stimuli of the experiment comprised random noise with a frequency bandwidth of 0.1–12.0 Hz and 0.3 m/s^2 r.m.s. According to the results, seat back support height and sitting posture affect trunk and head postural stabilisation in all motion directions with a more evident effect in fore-aft and vertical responses. Head motion decreased significantly

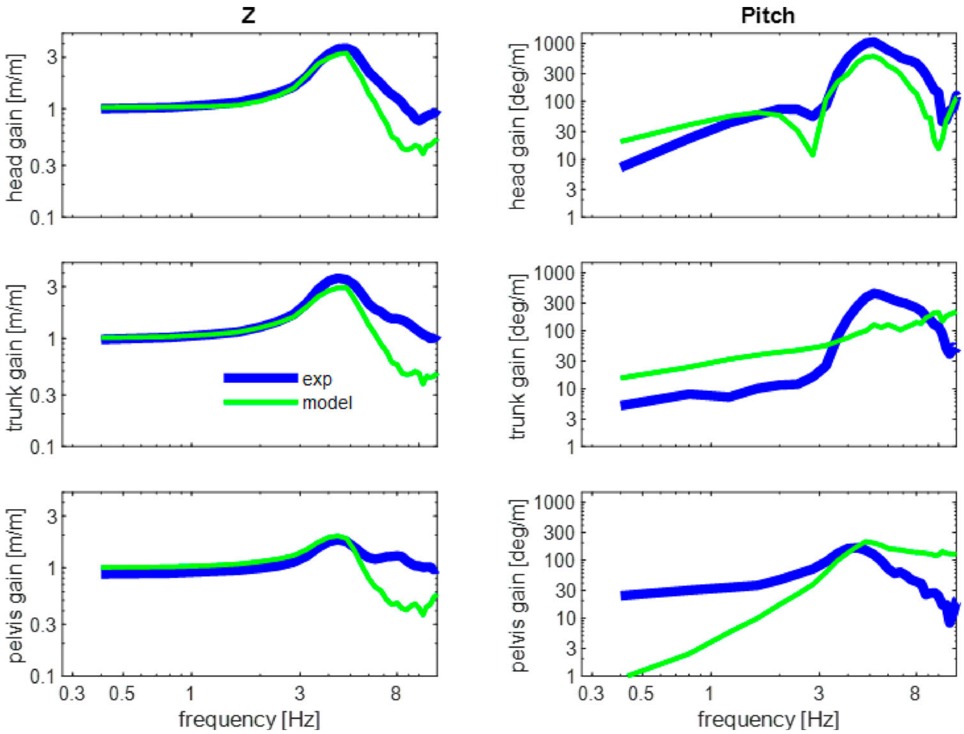

Figure 9. Vertical body dynamics. Transmission from vertical seat motion to pelvis (lower), trunk (mid) and head (upper) for vertical translation (left) and pitch rotation (right). The human data was measured with 0.3 m/s^2 vertical motion of a compliant car seat on a motion platform [249]. The model response was obtained with a 3D computationally efficient multibody model [88,250].

with low back support, proving that low back support allowed for more efficient head stabilisation. The head motion increased significantly in fore-aft and pitch responses when head-down posture was adopted. Desai et al. [88,250] developed a 3D computationally efficient multibody model and validated its response using this dataset (Figures 9–11). The model combines two postural control mechanisms: (1) joint angle control capturing reflexive and intrinsic stabilisation for each degree of freedom with PID controllers, including integration to eliminate drift, and (2) head-in-space control minimising 3D head rotation. This model is computationally efficient, with a 0.9 real time factor, which is much faster than the real time factor of 280 of a more detailed active human body model [251]. This speedup is essential because such efficient human body models could be added in the control modules of active seats or vehicle control algorithms to directly aim at head and body vibrations to enhance ride comfort and mitigate MS.

5.2.2. Multiple axis perturbation

The human body and head responses to simultaneous multi-axis vibrations are more representative for dynamic driving but this is investigated in few studies. However, according to the research, there is a notable difference between the STHT of single and multi-axis vibration. Hinz et al. [241] highlighted the need to explored seat-to-head transmissibilities with

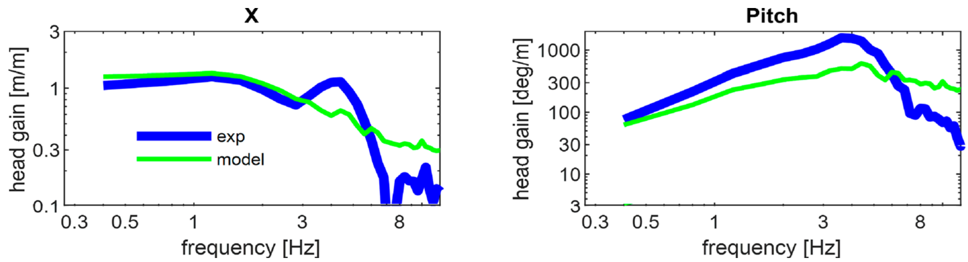

Figure 10. Fore-aft Seat to Head Transmission (STHT) with fore-aft head translation (left) and head pitch rotation (right). The human data was measured with a compliant car seat on a motion platform [249]. The model response was obtained with a 3D computationally efficient multibody model [88,250].

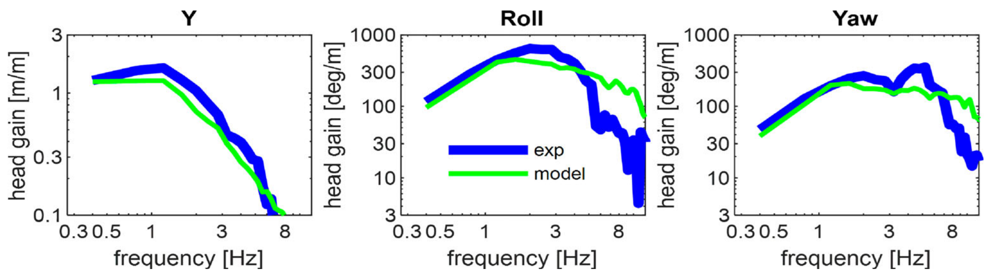

Figure 11. Lateral Seat to Head Transmission (STHT) with lateral head translation (left), head roll (mid) and yaw (right) rotation. The human data was measured with a compliant car seat on a motion platform [249] The model response was obtained with a 3D computationally efficient multibody model [88,250].

not only single but also three axis excitations at different magnitudes. The triaxial perturbation, including components on x-, y- and z-axis, affected slightly the resonance frequency of the transmissibilities, but decreased their amplitude compared to single axis transmissibilities. This illustrated for the first time the need to develop multi-dimensional human body models and seat-to-head-transmissibilities for multi-axial perturbations, which are more realistic.

According to the results, Mandapuram et al. [243] suggested negligible effects of dual-axis (fore-aft and lateral) vibration on the biodynamic responses of the seated body, even though substantial coupled motions of the body have been observed in the sagittal plane under single-axis vibration along the fore-aft and vertical axis. The different hands position (from lap to steering wheel) affected the dual-axis transmissiblity similarly with the single axis. Mandapuram et al. [244], using the same data, explored the seat-to-head transmissibility of the human body under single (fore-aft, lateral, and vertical) and multi-axis perturbations. The results illustrated significant differences on the magnitude of the transmissibilities in all direction (fore-aft, lateral and vertical) but without provoking any shift in the frequencies where their maximum values located.

Zheng et al. [252] assessed the fore-aft and dual-axis vibration of the seated human body, emphasising the nonlinearities and the cross-axis coupling. More specifically, they tested human participants during fore-and-aft random vibration excitation (0.25 – 20 Hz) at three vibration amplitudes (0.25, 0.5 and 1.0 ms^{-2} r.m.s.). During the highest amplitude fore-aft excitation, vertical vibration was added at 0.25, 0.5, or 1.0 ms^{-2} r.m.s. During fore-and-aft excitation, a principal and a secondary resonance occurred around 1 Hz and 2–3 Hz. The magnitude of the resonance frequencies was reduced when dual axis vibrations was considered or the magnitude of the single axis vibrations increased. At the primary resonance frequency, fore-and-aft excitation primarily induces a dominant mode characterised by bending of the lumbar and lower thoracic spine, along with shear deformation of tissues at the ischial tuberosities. The contribution of each body segment, particularly the pelvis and lower thoracic spine, to this mode varies depending on the vibration magnitude. Nonlinearities observed in transmissibility during dual-axis excitation suggest an interaction between the principal mode of the seated human body under fore-and-aft excitation and the cross-axis effects of vertical excitation.

Nawayseh et al. [253] evaluated the triaxial transmissibility to the head and spine of seated human subjects exposed to fore-and-aft whole-body vibration. Sixteen seated male subjects were exposed to sinusoidal fore-and-aft vibration with magnitudes 0.311–0.246 ms^{-2} r.m.s. and frequency range 2–6 Hz. A peak in the range 2–2.4 Hz was evident at all body segments indicating a whole-body resonance in this frequency range. The transmissibility of the vibrations to the head was higher compared to all the body segments.

5.2.3. Individual characteristics

Despite the indications that the human body dynamics and the transmission of vibrations to the head is affected by individual characteristics, there is limited research to fully capture and explore the effect. Paddan et al. [35,234,235] were the first to mention the significant inter-subject variability of their data. However, in these studies, all participants were males and the conclusions cannot be generalised for different genders. This is also the case for most of the available studies where the participants were explicitly males. Nevertheless, Rahmatalla et al. [254] proved that female subjects showed more pelvis vertical motion, less pelvis roll, and more pelvis pitch than male subjects. Meanwhile, a higher body mass was related with less pelvis vertical motion, more torso roll, more pelvis roll, and more torso pitch. Therefore, there is a need to explore the impact of individual characteristics, including gender, age and anthropometric characteristics, on seat-to-head-transmissibilities.

First efforts on this direction were conducted by Dewangan et al. [255], who explored the effects of gender and antropometric effects on the vertical and fore-aft seat-to-head transmissibility response to vertical whole body vibration with 58 participants (21 male and 27 female). According to Dewangan et al. [255], the vertical and fore-aft STHT responses of the two genders were distinctly different. The peak magnitudes at the primary resonance frequency was similar for the two genders, but the primary resonance frequency was higher for the male subjects. The latter indicates that the softening effect was greater in male subjects regardless of sitting position. The body mass had a strong effect on the STHT responses in both genders, where lighter subjects had higher primary response. The male subjects showed significantly higher primary resonance frequency than the female subjects, even when comparable body mass, BMI and lean body mass were considered. The vertical STHT response of the two genders with same body fat mass was very similar for the sitting and excitation conditions considered in the study, particularly up to 10 Hz. Dewangan et al. [256] proved that the vibration power absorption is affected by gender for subjects of comparable anthropometric dimensions, while it was correlated with the body mass, lean body mass and body fat. However, no definite trends were found for stature related parameters such as sitting height. In the same direction, Cvetkovic [101] proved that by taking into account motion direction and body segment information, over 72% of the peak translational gains could be explained. Adding adopted sitting postures (i.e. slouched, upright passive and active) and biological sex (as a categorical predictor) did not significantly affect the model's coefficient of determination.

5.3. *Across transport modes*

According to the previous section, it is evident that there is limited research conducted in vehicle environments to assess the transmissibility of vibrations from the seat to the head. The majority of the studies has been conducted on motion platforms without any vehicle-mock up, apart from Mirakhorlo et al. [249]. One one hand, this limits the applicability of the conclusions in specific scenarios where the occupants, of any vehicle, could not anticipate the upcoming motion due to eyes closed or with internal vision. On the other hand, this allows the generalisation of the conclusions across transport modes. In the majority of the studies, participants were requested to maintain specific postures, which are applicable to both passenger and rail vehicles, meanwhile the lack of specific vehicle environment did not introduced any bias in their subjective feeling. Meanwhile, the frequency range of the stimulus used is relevant for both transport modes. Nevertheless, even if the generalisation of the results is possible between passenger and rail vehicles, this is not possible in bikes. For this, more challenges arise because the riders actively control their body together with the bike, significantly affecting the vibration transmission from the seat to the head. This complex aspect is discussed more in Section 6.

Regarding focussed research on bicycles and transmission of vibrations, Dialynas et al. [257] measured vertical and horizontal vibration transmission on 24 men with a bike mounted on a motion platform. Results show amplification of vertical vibrations with a factor of about 2 around 5 Hz as measured at the sternum. This is similar to the amplification found on car seats as shown in Figure 9 (mid left) for trunk motion. This paper also presents measured contact forces at seat, pedals and handlebars in the frequency domain in vertical and horizontal direction where also at pedals and handlebars oscillations were found around 5 Hz in particular in vertical forces but also in fore-aft and lateral forces. To the authors knowledge, there is no other research exploring this aspect.

Similar to bicycles, limited research exists on seat-to-head transmissibilities in rail vehicles. The only focussed research is by Nagai et al. [89], who conducted experiments on a simulator to investigate the coupled vibrations of the human body, on a Shinkansen high speed train passenger seat and a car body. The signal for exciting the hydraulic actuator is generated by random wave from 3 to 20 Hz to simulate an actual track irregularity. The time for excitation is 20 s and the r.m.s. value of the exciting wave is 0.2 ms^{-2}. Accelerations were measured from the head, shoulder, chest, waist and knee of 25 subjects under different postures. Resonant frequencies of the human body are predominantly in the 4–6 Hz range, with upper body parts (head, chest, shoulders) showing stronger resonance. Lower body parts (waist, knees) act more as vibration transmission elements rather than independent contributors to the coupled system. Heavier passengers further dampen the vibrations, lowering the peak amplitude of the resonant frequency, though the frequency itself remains relatively unaffected. However, the results of this analysis could be also extended to passenger vehicles even if the lack the low frequency area (0.1-1 Hz) which is of great importance for motion sickness.

5.4. Summary, research gaps and future work

In summary, while research has not focussed on human body dynamics for each transport mode individually, results from passenger and rail vehicles can likely be generalised, enabling rail engineers to utilise transmissibilities for accurate ride comfort and motion sickness assessments. However, further exploration of human body dynamics in cycling is needed, as only one relevant study was identified. Despite recent efforts, there remains a significant gap in adaptive seat-to-head transmissibility functions or human body models capable of capturing the full spectrum of individual characteristics, including not only gender but also body mass, proportions, and other relevant factors. This is compounded by an overrepresentation of male participants in available datasets, as highlighted by van de Kruk's [258] meta-analysis, which revealed a lack of justification for male-only studies and reinforces the notion that male data is the standard in biomechanics research.

Although multiple models exist for pre-crash conditions, models focussing on normal conditions where comfort is the priority are limited. These existing models often neglect upper limb motion by considering them part of the trunk, despite the increased importance of upper limb movement due to non-driving-related tasks (NDRTs) in AVs and trains. Crucially, most existing models also assume that the human body responds passively to perturbations, failing to account for the active postural control strategies employed by occupants. The impact of upper limb position on trunk motion across various NDRTs remains unexplored experimentally, though initial indications suggest a critical influence. Therefore, experiments are needed to quantify this effect and facilitate the development of human body models that treat the upper limbs as separate segments, which could significantly advance interior design. Another key aspect that has not been widely explored is the modelling of soft tissue interaction. The shift in resonance frequencies in the STHT might be attributed to the interaction of the seat with soft tissues, but this hasn't been fully proven. This suggests a research gap in developing more detailed models that accurately capture the interaction between the seat and the occupant's soft tissues. Future research should also prioritise developing individualised and gendered human body models capable of accurately predicting occupants' human body dynamics during travel. These models should adapt to conditions known to affect human body dynamics, such as sitting postures, NDRTs, and visual conditions. However, focussed experiments are essential to generate the necessary datasets for validating such models.

6. Postural control

6.1. General

Controlling the human body to secure balance and orientation within dynamic environments, is a challenging task especially in dynamic environments, such as in vehicle environments. This becomes even more difficult in scenarios when occupants are distracted by engagement in NDRTs, or they have limited horizon view to anticipate the

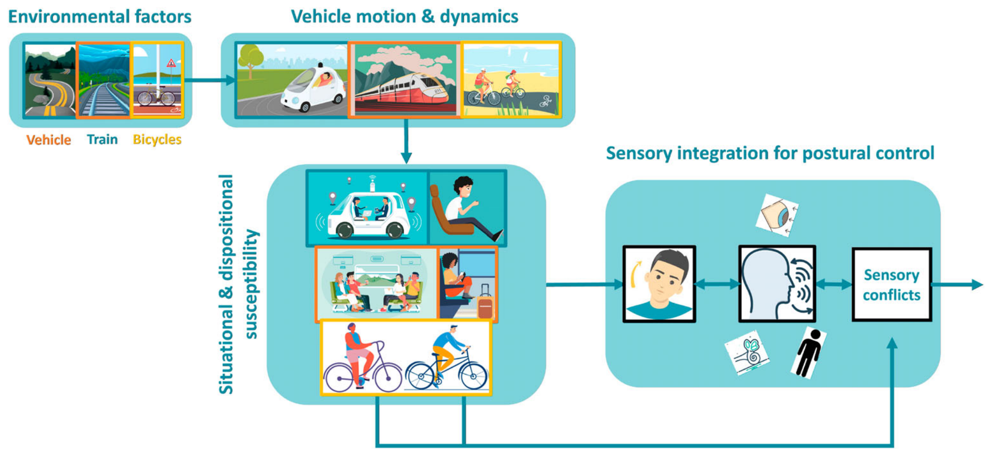

Figure 12. Factors that influence occupants' postural control and motion sickness.

upcoming motion. Hence, the need to understand the process of postural control, while being driven, has risen.

According to Figure 12, the environment (route, road surface, track, traffic etc.) define the vehicle (passenger vehicle, rail vehicle and bicycle) motion and dynamics. The vehicle dynamics are isolated by the different vehicle subsystems (tires, wheels, suspensions, chassis, and seat), and are transferred to the human body inducing whole-body vibrations from the contact points (body-seat surface and back, the feet-floor, feet-pedal unit, hands-steering wheel/handle bar). The transmission and perception of the vibrations is significantly affected by a multitude of factors such as situational (e.g. participation in NDRT, occupants' health and physiological status) and dispositional factors (e.g. posture, gender, experience, age, anthropometric characteristics). These factors also affect MS occurrence (Figure 3). The central nervous system (CNS) integrates sensory information from visual, vestibular, and somatosensory systems to produce coordinated motor responses that ensure postural stability and orientation awareness. In this paper, we refer to this process as postural control. Postural control relies on sensory integration (visual, vestibular and somatosensory), internal models of body and sensory dynamics [259], and adaptive mechanisms, essential for responding to perturbations to produce coordinated motor responses to perturbations that ensure stability and orientation awareness [260]. Although many theories exist regarding the CNS's inference and beliefs for the activation of these adjustments the true end-to-end process is not yet proven and only plausible explanations exist [261,262]. Existing validated motion perception models [39,41,263] utilise the sensory conflict theory [148] in which the CNS is assumed to anticipate and interpret motion through an internal model while updating this prediction through sensory feedback and minimising the sensory conflict.

In the presence of perturbations, the postural adjustments initiated by the CNS can be categorised as anticipatory (APAs) and compensatory postural adjustments (CPAs) [264]. A likely explanation for how beliefs are acquired and realised, leading to the activation of both adjustments, involves a complex mechanism centred on the neural store, which contains internal models of bodily and sensory dynamics [265,266]. APAs reflect feed forward control, i.e. muscle activity is produced in preparation based on predictions of an upcoming postural perturbation. The internal models enable the CNS to estimate and predict motion patterns, issuing preemptive motor commands when anticipatory control is possible. Anticipatory adjustments occur before a predictable motion disturbance (∼ 150–250 ms [267]). On the other hand, CPAs are a feedback-based control, wherein changes in muscle activity follow the perturbation based on sensory feedback following the perturbation. These adjustments occur in two phases: an initial reflexive response, followed by voluntary reactions which help restore balance [267]. Compensatory postural adjustments are made by comparing actual sensory feedback with the estimated motion and any desired voluntary actions [268].

APAs, which are generated based on available visual and proprioceptive feedback, are crucial to minimise the impact of upcoming perturbations and lead actions to maintain postural stability by preparing the human body for upcoming perturbations. CPAs complete the process by fully restoring the body to balance after the perturbation. Efficient APAs reduce the need for CPAs, decreasing muscle fatigue and postural instability. Their efficiency is based on previous experience, while research has proven that individuals could learn how to anticipate motions in specific tasks, e.g. catching a ball, etc. [269]. However, there is limited research on postural control within the vehicle environment, a knowledge critical to design comfortable and safe road and rail vehicles.

6.2. Across transport modes

6.2.1. Passenger vehicles

For passenger vehicles, there is significant literature exploring the process of postural control during evasive maneuvers, pre-crash/impact conditions [270–273]. However, there is limited work exploring how occupants' activate their muscles in safe conditions where comfort is the priority. Happee et al. [38] integrated sensory integration into a biomechanical models capturing neck postural stabilisation while being driven. Similarly, Messiou et al. [274] modelled head-neck postural control by our CNS using model predictive control, incorporating a prediction of future behaviour (internal body and sensory model) and optimising control inputs using a cost function (minimization function representing sensory conflict) over a finite time horizon (prediction) and under constraints (biomechanical and space). In this model, the MPC's cost function represents a plausible objective of the CNS which is to minimise sensory conflict and muscle effort within biomechanical constraints, ensuring stability. However, this model was validated only in eyes closed conditions where the anticipatory postural adjustments are not present.

Albeit no research has mathematically identified seated occupants' optimal postural control [275], there are empirical indications about postural control strategies that mitigate motion sickness. Drivers actively control their body based on the upcoming motion, whereas vehicle passengers mostly react passively to the impeding vehicle motion [276]. When navigating curves, drivers tilt their heads, as APAs, toward the direction of the gravito-inertial force (GIF), which is a vector formed by the summation of the gravity force pulling us down and inertial forces resulting from accelerations [277]. By adopting these APAs and aligning their head reference frame with GIF, the sensory conflict between sensed and experienced motion is minimised, making drivers almost unsusceptible to MS. Passengers, even with driving experience, passively tilt their heads in opposite direction due to centrifugal accelerations, making them more susceptible to MS than drivers. Similarly with curves, passengers often lean forward passively during braking, causing misalignment of their body axis with GIF and increasing MS (Figure 1, right). However, passengers are not experienced to such postural adjustments. Motivated by this, Croucher et al. [278] developed a serious game (MATE-AV) to train AV occupants to adopt comfort-oriented postural control strategies (e.g. leaning into the curves) and self-enhance their motion comfort while being driven in the virtual environment. A mixed-design experiment with human participants proving the participants effort to adapt to the comfort-oriented postural control they were being trained for through MATE-AV.

6.2.2. Two wheelers

A cyclist's posture is primarily determined by the three contact points: handlebar, saddle, and pedals. However, this posture can vary significantly depending on the riding situation. The most common situation related to comfort is the standing position, often adopted on rough road irregularities where the cyclist utilises their arms and legs as natural suspension elements. Another common reason for standing is the sway pedal stroke, typically used when climbing uphill to achieve a short-term increase in power at a lower cadence. Additional posture adjustments may aim to reduce aerodynamic drag, such as adopting a stretched, aerodynamic position on the bike, or simply to avoid discomfort caused by maintaining the same position for extended periods. This is one reason why drop handlebars are popular, not only in road racing but also for long-distance cycling. Finally, posture adjustments are also made during cornering, where the cyclist shifts their centre of gravity laterally to adapt the effective roll angle. This technique is commonly referred to as *hang-in* or *hang-out*.

6.2.3. Rail vehicles

Regarding occupants' postural control while being driven in trains, there is no literature, to the authors knowledge exploring this topic.

6.3. Summary, research gaps and future work

In summary, the authors identified a significant gap in the literature in fundamentally understanding how occupants' activate their muscles for postural stabilisation in safe conditions under different conditions (e.g. with or without external vision, different postures, engagement in NDRTs, and others). Specifically, there is a lack of knowledge on how the central nervous system (CNS) integrates sensory information from visual, vestibular, and somatosensory systems to produce coordinated motor responses for postural control. This will allow us to map anticipatory (APAs) and compensatory (CPAs) postural adjustments while being driven, and fully understand occupants' postural control. This lack of information about postural control within the vehicle environment has also led to limited available active human body models, which could capture the intrinsic behaviour of our CNS for postural control. Such models are critical for the efficient design of effective methods to decrease whole-body vibrations and motion sickness.

Similarly, albeit there are empirical indications about postural control strategies that mitigate motion sickness, there is no actual evaluation of optimal control strategies to enhance comfort and mitigate sickness. Efficient human body models, that can predict the fundamental behaviour of our CNS towards postural control, could allow the evaluation of such strategies. This information could be greatly useful for dissemination in the public, incorporating in training frameworks such as MATE-AV [278], and exploiting in the design of other methods to enhance comfort or mitigate MS (e.g. anticipatory cues). Furthermore, the role of internal models in predicting and responding to motion disturbances requires further investigation.

In addition to empirical postural adjustments existing in the literature about bicycles, the postural control of cyclists is more challenging than occupants in passenger vehicles and still with limited understanding. Cyclists control their body while they also control and stabilise the vehicle [279] which makes it an even more challenging process than the one described for seated occupants in passenger vehicles. Therefore, significant work is required to understand and model the cyclists steering process, as Cole et al. did with the vehicle drivers' [280,281], and relate it with their body control which affects the bike dynamics. Such human body models could pave the path for performance optimisation in racing and also for comfort. Future research should also explore the interaction between cognitive load and postural control in cyclists, as the demands of cycling can be mentally taxing.

Another gap identified is with regards to postural control in rail vehicles, where there more challenges given that occupants already engage in NDRTs adopting non-comfort oriented postures and they have limited view or information with regards to the upcoming motion. Therefore, there is the need to explore this area more similarly. However, in trains, knowledge can be extracted from the research on vehicles as also explained in Section 5. The two interior environments are similar, and the envisaged designs of AVs will further bridge the existing differences by converting the interior to a living or working space as in trains, and limiting the visual cues due to limited horizon view or no external view. Therefore, research on this topic can benefit both transport modes to fundamentally understand occupants' postural control and eventually improve their comfort. Further research should also investigate the long-term effects of prolonged non-comfort oriented postures on postural control and overall well-being in rail and automated vehicle environments.

7. Conclusions

To sum up, in this paper, we focussed on physical comfort by delving into the modulating factors of motion (dis)comfort (i.e. combined symptoms of ride comfort and motion sickness): environment, posture, human-body dynamics, and postural control. Below we summarise our literature review.

Ride comfort assessment relies on both objective and subjective metrics. In terms of objective measures, frequency weighting filters for road and rail vehicles are based on similar experimental data obtained from single-axis sinusoidal motion in laboratory conditions. Guidelines are well established for evaluating whole-body vibrations and comfort in road and rail vehicles, whereas a metric is proposed for bicycles in the literature which is not included in international standards. Subjective comfort assessment methods vary across studies, with some introducing new techniques. However, relying on established methods could improve comparability across research and yield more meaningful conclusions. Ride comfort on bikes is particularly relevant for professionals such as delivery cyclists, couriers, and police officers, whereas occasional cyclists and commuters may not face significant health risks but could experience enough discomfort to reduce the enjoyment of riding. Additionally, studies highlight concerns about the transport of children and infants, though current research is based on standards developed for adults, making it unclear how applicable these findings are to younger passengers. However, the increasing use of bikes for not only recreational and commuting, but also occupational reasons, raises the need to standardise the comfort and health assessment of cyclists and bike passengers (e.g. babies or children). The proper assessment methods will allow the efficient design of future bikes which will mitigate any comfort and health concerns.

Motion sickness assessment also involves objective and transport-specific considerations. Current methods primarily derive from human sickness experiments with vertical vibrations, where recent experimental data suggests that horizontal and vertical motion result in similar susceptibility levels. To improve assessment accuracy, researchers have proposed modifying the ISO motion sickness frequency weighting function to a new factor, which accounts for both vertical and horizontal loading. Across transport modes, studies indicate that females are generally more susceptible to motion sickness than males, and road and rail vehicles exhibit similar frequency susceptibility patterns below 1 Hz. Although motion sickness is reported in rail vehicles, statistical evidence suggests it occurs less frequently compared to road transport. Regarding different rail vehicles, more passengers on tilting trains experienced nausea compared to conventional trains. While motion sickness research has largely focussed on conventional transport, potential issues could arise for passive passengers, such as children in cargo bikes or tandem bike riders, yet no studies have investigated motion sickness in these conditions.

Environmental factors also influence ride comfort and motion sickness. Compared to road profiles, track roughness standards are more stringent in terms of geometric requirements. These stricter limits may indicate a higher risk of induced vibrations from the track to the vehicle, leading to greater discomfort. However, trains are primarily designed to ensure continuous vehicle-track contact rather than to minimise vibrations. Based on this literature review, comfort should be taken into consideration in rail vehicles to ensure the wide use of rail vehicles.

Posture plays a significant role in comfort and motion sickness, particularly with the evolving design of automated vehicles (AVs). In conventional vehicles, occupants typically adopt standardised postures due to space constraints, whereas AVs are expected to introduce greater flexibility, allowing passengers to engage in non-driving-related tasks (NDRTs). AV interiors will more closely resemble those of trains, where multiple seating postures are possible due to increased space. Research on posture in cycling has primarily focussed on performance and efficiency, with some efforts to optimise bike design for a balance between comfort and effectiveness. In contrast, extensive studies on posture in trains have been conducted due to the flexible seating arrangements they offer. However, the impact of these postures on ride comfort and motion sickness have not been tested.

The transmission of vibrations from the seat to the occupant's body and head has been widely studied, with the aim of modelling human body dynamics under different perturbations. Most research in this area has been conducted with seated human participants using motion platforms or simulators. While these studies provide insights applicable to passenger and rail vehicles, extending them to bicycles is more complex because cyclists actively control their posture to maneuver the bike. Limited research exists on human responses to multi-axis vibrations, particularly in relation to different postures and engagement in NDRTs. Individual characteristics also significantly influence seat-to-head vibration transmission, but most available studies suffer from gender bias, with male participants being overrepresented. The lack of gender-balanced datasets hinders the development of adaptive seat-to-head transmissibility functions or human body models that account for variations in body mass and other individual differences. Additionally, most studies assume that the human body functions as a passive system that reacts to perturbations without actively adapting based on feedback.

There is little research on how occupants control their posture before and after perturbations, leaving an important gap in understanding human responses to dynamic vehicle motion. In addition to empirical studies about comfort oriented postures, the optimal postural control for comfort has not been studied in any of the transport modes. Meanwhile, the postural control of cyclists is more challenging than occupants in passenger and rail vehicles. Cyclists control their body while they also control the vehicle which makes it an even more challenging process than the one described for seated occupants in passenger vehicles. Therefore, significant work is required to understand and model the cyclists steering and balancing process, and relate it with body postural control. The literature on postural control is limited also within rail vehicles, where more challenges rise given that occupants already engage in NDRTs adopting non-comfort oriented postures. However, combined efforts with research on passenger vehicles could be conducted.

In conclusion, this literature review reveals that while significant progress has been made in understanding comfort in conventional road and rail vehicles, critical research gaps remain that hinder our ability to ensure comfort and mitigate motion sickness, especially in emerging transportation modes and for vulnerable populations. Addressing these gaps, particularly through the development of comprehensive human body models and a deeper understanding of postural control, is essential for designing future transportation systems that prioritise occupant well-being.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

For Dr Malte Rothhämel, this research was funded by the Swedish National Strategic Research Area TRENoP: Transport Research Environment with Novel Perspectives. The remaining researchers did not receive direct project funding for this research.

Declaration of generative AI

During the preparation of this work, the authors utilised ChatGPT-4o to only enhance English grammar and flow. The tool was not used to extract conclusions or help in the literature review. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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