Vibration-Induced Discomfort in Vehicles: A Comparative Evaluation Approach for Enhancing Comfort and Ride Quality

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Vibration-Induced Discomfort in Vehicles: A Comparative Evaluation Approach for Enhancing Comfort and Ride Quality

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Abstract

This article introduces a methodology for conducting comparative evaluations of vibration-induced discomfort. The aim is to outline a procedure specifically focused on assessing and comparing the discomfort caused by vibrations. The article emphasizes the metrics that can effectively quantify vibration-induced discomfort and provides insights on utilizing available information to facilitate the assessment of differences observed during the comparisons. The study also addresses the selection of appropriate target scenarios and test environments within the context of the comparative evaluation procedure. A practical case study is presented, highlighting the comparison of wheel corner concepts in the development of new vehicle architectures. Currently, the evaluation criteria and difference thresholds available allow for comparative evaluations within a limited range of vehicle vibration characteristics.

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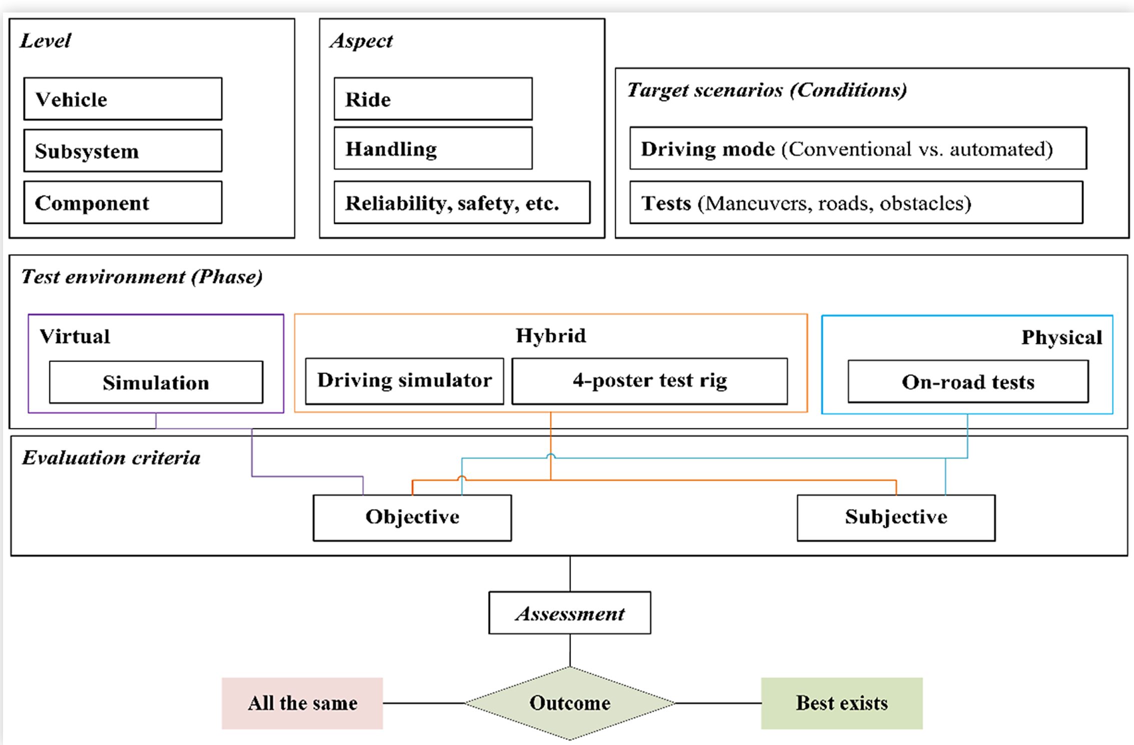
1. Introduction

Comparative evaluations are often performed in the automotive industry. These comparisons may be between vehicles, or within vehicles comparing for example suspension systems, suspension components, or tires. Figure 1 presents the various elements that a typical comparative evaluation may consist of. The *Level* defines the comparison being made, which may be at the vehicle level, e.g., comparing aspects between vehicles or component level, e.g., comparing aspects due to changes in different tires. The *Aspect* being compared may include, but is not limited to vehicle ride, handling, performance, and the like. *Target scenarios* define the conditions under which the aspects are to be evaluated. This can include the tests to be conducted, which will be defined by the maneuver (e.g., straight-line driving, double lane change) and road (e.g., ISO 8608 [1] road classes, track on proving ground), and driving mode (conventional and automated driving). The *Test environment* in which the evaluation is conducted may be simulation based (virtual domain) or on a proving ground (physical domain). A hybrid environment in the form of a driving simulator (or motion platform) and 4-poster test rig can be used. These are called hybrid as some components may be the physical ones with other being virtual. For example, considering the driving simulator, the vehicle dynamics will be based on a model, with a human driver seated in the physical vehicle interior. The test environment to use will be governed by the phase of vehicle development. Early in the development no physical components may be available and therefore a virtual or hybrid environment needs to be used. Once components become available a physical environment can be considered. *Evaluation* will depend on the aspect and may also depend on the test environment, target scenarios, and level. Many aspects may result in two categories of evaluation, i.e., objective or subjective. The *Assessment* of the evaluation results needs to reach an outcome either that all the variations being compared are similar or that a best exists.

Various comparative evaluations related to the automotive industry have been conducted. These studies covered aspects such as driving workload [2], vehicle crashworthiness and passive safety design [3], brake pad performance [4], fuel consumption [5], and emissions [6]. Of interest in this study is comparative evaluations of vehicle ride and more specifically, discomfort due to vehicle vibrations. Studies have investigated the evaluation methods of ride comfort [7, 8, 9, 10, 11] and used them to investigate control strategies and component characteristics in suspension systems [12, 13, 14] and to compare the vibration of different road vehicles [15, 16]. In many evaluations, a quantifiable value is obtained, which serves as a basis for comparison. However, the significance lies in not only the numerical value itself but also the interpretation of the differences or similarities observed. The article acknowledges that the interpretation of these variations in the values holds greater importance than the values alone. Understanding the implications and significance of the differences or similarities observed provides valuable insights into assessing the practical significance of the comparative evaluation results.

FIGURE 1 Elements of a typical comparative evaluation.



The contribution of this article is the procedure for conducting comparative evaluations of vibration-induced discomfort. The article emphasizes identifying the metrics that effectively quantify such discomfort and utilizes available information to guide the assessment of the results obtained from these comparisons. Furthermore, the study discusses the selection of suitable target scenarios and test environments that align with the proposed comparative evaluation procedure. These considerations aim to enhance the reliability and relevance of the evaluations conducted.

Sections 2 to 4 provide an overview and summary of the evaluation criteria, a discussion of the assessment and target scenarios. Section 5 discusses possible test environments and their limitations. Section 6 presents the proposed comparative evaluation procedure for vibration-induced discomfort and applies it to a case study, in which wheel corner concepts are compared in the development of new vehicle architectures. The conclusions are presented in Section 7.

2. Evaluation Criteria

Automotive manufacturers are continuously seeking innovative approaches to enhance occupant comfort in vehicles. Unwanted motion and vibration are the primary contributors to discomfort. One crucial factor associated with ride quality is the extent to which occupants are exposed to vehicle vibrations, which can be mitigated through appropriate suspension system design. It is important to note that not all vibrations and motions are directly perceived by the occupants. Their perception is primarily limited to the motion and vibrations experienced by the vehicle body, specifically the sprung mass. Therefore, the study of ride quality involves analyzing the accelerations of the sprung mass, which serve as a key indicator of vibration. These accelerations offer insights into how the sprung mass responds to various road inputs. Generally, it is assumed that reducing vibration levels leads to reduced discomfort. Consequently, the objective of enhancing a vehicle's ride quality is centered around minimizing body accelerations.

2.1. Objective Evaluation Criteria

The objective measures of comfort used to assess ride quality and driving comfort are presented and discussed in this section. The expected response to overall vibration levels in public transport is standardized in ISO 2631-1 [17] and BS 6841 [18]. However, more objective metrics have been proposed. Table 1 provides an overview of standardized metrics from research and industry for the vertical direction that can also be used to evaluate longitudinal and lateral motion.

Objective evaluation of ride quality and comfort are mainly based on [17] metrics such as r.m.s. acceleration, MTVV, and the like, and/or on established industrial criteria, e.g., Ford Ride Comfort Metrics [26].

In addition to the above criteria, there have been attempts to develop metrics to quantify discomfort that correlate with physical stimuli. Ideally, such metrics would be calculated directly from measurement, without the need for subjective evaluation, so that discomfort caused by different vibrations could be compared or discomfort could be predicted from measurements or simulations [19]. Psychophysical studies have shown a general relationship between physical stimuli and human sensations. Perceived discomfort depends on not only physical magnitude or intensity, but also other physical properties of vibration stimuli, such as frequency and direction. For example, humans are most sensitive (causing most discomfort) to vertical whole-body vibration at about 5 Hz and less sensitive to vibration at higher frequencies [27]. Therefore, these physical properties must also be considered. The use of physiological measurements as objective measures has also been investigated. The effect of whole-body vibration on various physiological parameters has been considered [28]. The relationship between heart rate and heart rate variability, and the magnitude of vertical whole-body vibration on an automobile seat was investigated. Their findings revealed no relationship between heart rate and heart rate variability, and the magnitude of whole-body vibration. As a result, they concluded that heart rate and heart rate variability may not be as effective as other objective measures in quantifying vibration-induced discomfort. Electroencephalogram data of drivers was considered to investigate the use thereof to evaluate and improve vehicle ride comfort [29]. Their results showed this to be feasible and claimed that their method employing electroencephalogram data "… can predict vehicle performance more precisely in a shorter time …."

2.2. Subjective Evaluation Criteria

In experimental studies focused on comfort assessment, subjective measures are often utilized [30]. Test subjects are typically required to complete questionnaires at the end of the experiment, whether it involves tasks in test rigs, prototype seats, or real-life driving scenarios. These questionnaires aim to obtain qualitative ratings from the participants regarding the perceived comfort or discomfort of specific stimuli. The challenge in assessing comfort lies in its subjective nature and the limited understanding of the physiological mechanisms behind certain conditions, e.g., motion sickness. Moreover, there are often multiple interconnected factors that can influence or trigger sensations or symptoms related to comfort.

As highlighted in [31], the discrepancies and variations in the current state of the art of seating comfort studies make it challenging to compare or interpret findings. Each study tends to be highly specific and individual, further complicating the process. The absence of a universal standard for comfort is a significant issue, despite the increasing number of publications in this area. Questions arise regarding whether comfort and discomfort should be measured as a single unified

TABLE 1 Objective metrics for comfort evaluation.

Metric		Formula	Threshold value/Application
1	Root mean square (r.m.s.) acceleration	$a_{z,w} = \sqrt{\frac{1}{T}\int_0^T a_{z,w}^2(t)dt}$ where T is the duration of measurement; $a_{z,w}(t)$ is the weighted acceleration as a function of time for the vertical direction.	The frequency-weighted r.m.s. acceleration is based on calculations of the r.m.s. values of vertical acceleration typically measured at the driver or passenger seat [17].
2	Maximum transient vibration value (MTVV)	$\text{MTVV} = \max(a_{z,w}(t_0))$ where $a_{z,w}(t_0)$ is the weighted acceleration as a function of time for the vertical direction.	An example of an additional evaluation used to correct the calculation is the running r.m.s. method, which integrates the acceleration in a short period t over the measurement period T. The MTVV gives the magnitude [17].
3	Vibration dose value (VDV)	$\text{VDV} = \sqrt[4]{\int_0^T a_z^4(t)dt}$	VDV is a simple and robust method that is not affected by averaging [19].
4	Comfort index (CI) [m/s²]	1. Not uncomfortable, CI < 0.315 2. Little uncomfortable, 0.315 ≤ CI < 0.63 3. Fairly uncomfortable, 0.5 < CI < 1 4. Uncomfortable, 0.8 < CI < 1.6 5. Very uncomfortable, 1.25 < CI < 2.5 6. Extremely uncomfortable, CI > 2	Many other factors influence ride comfort. The likely reaction of comfort to the vibration magnitude for urban public transports can be indicated by CI refers to the approximate indication of discomfort on a six-grade scale [20].
5	Root mean quad (r.m.q.)	$\text{r.m.q.} = \sqrt[4]{\frac{1}{T}\int_0^T a_z^4(t)dt}$	r.m.q. yields a time-averaged value more suitable than r.m.s. When the motion is non-stationary and characterized by concentrated shocks, experimental results show better correlation with human experience when applying the r.m.q. method to transient events than with r.m.s. [17].
6	ISO 2631 index	$\text{ISO} = \sqrt{\begin{matrix} k_x \cdot \text{r.m.s.}(a_x)^2 \\ +k_y \cdot \text{r.m.s.}(a_y)^2 \\ +k_z \cdot \text{r.m.s.}(a_z)^2 \end{matrix}}$ where k_x, k_y, and k_z are multiplying factors used to correlate the objective metrics to the subjective evaluations for the longitudinal, lateral, and vertical directions correspondingly.	The weighted r.m.s. accelerations can be added to a total acceleration level using the ISO index. ISO 2631 provides the guideline for calculating a global discomfort index that considers the r.m.s. acceleration in the three spatial directions. Multiplication factors are included to account for the different effects on different parts of the body [17].
7	Vibration total value (VTV)	$\text{VTV} = \sqrt{\sum_{j=1}^{6} k_j \cdot \text{r.m.s.}^2(a_{w,j})}$ where $a_{w,j}$ is the frequency-weighted accelerations (j = 1 – x direction, j = 2 – y direction, j = 3 – z direction, j = 4 – angular acceleration around x axis, j = 5 – angular acceleration around y axis, j = 6 – angular acceleration around z axis, k_j is the frequency weighting factors defined according to ISO 2631.	VTV is used to evaluate vibration in all 6 DoFs. For the assessment of ride quality based on whole-body accelerations, the approximate values of ISO 2631-1 can be used [17].
8	NASA model	$D_{vertical} = \begin{cases} 0.241 + 44.672 a_{w,z}, a_{w,z} > 0.1 \\ 68.772 a_{w,z}, a_{w,z} < 0.1 \end{cases}$ $D_{lat} = \begin{cases} 0.393 + 47.494 a_{w,y}, a_{w,y} > 0.1 \\ 87.794 a_{w,y}, a_{w,y} < 0.1 \end{cases}$ $D_{long} = -0.02 + 42.24 aw_{,}x$	The NASA model applies the human comfort sensitivity weighting factors for vibration to the spectral data in the five axes of measurement. After applying the filters to the experimental data, the weighted acceleration spectra in each axis are converted to discomfort units using empirical relationships [21].
9	Peak-to-peak index (p-p)	$p - p = \max(a_w(t)) - \min(a_w(t))$	p-p is used to assess the acceleration magnitude [22].

(Continued)

TABLE 1 (Continued) Objective metrics for comfort evaluation.

Metric		Formula	Threshold value/Application
10	Janeway's comfort criterion	Frequency range: 1. 1–6 Hz: peak jerk < 12.6 m/s^3 2. 6–20 Hz: peak acceleration < 0.33 m/s^2 3. 20–60 Hz: peak velocity < 2.7 mm/s	The Janeway's comfort criterion defines the permissible amplitude of the vertical vibration as a function of frequency and is divided into three parts [23]. This criterion does not consider the resonance effects of vibration associated with pitch and roll. The jerk is the derivative of longitudinal acceleration during braking and can worsen ride comfort if severe pulsations occur in the ABS mode [24]. All data used to establish comfort boundaries were obtained with test subjects standing or sitting on a hard seat.
11	Virtual ride (VR)	$VR = \frac{5}{3\max(a_z) + 2\text{r.m.s.}(a_z)}$	VR has been proposed to assess ride quality. To evaluate the ability to filter medium and high frequencies due to pavement unevenness in the range of 4 Hz to 30 Hz, the calculation of the virtual ride is based on the measured vertical acceleration at the driver position (CG vertical acceleration + pitch vertical component) [25].

scale or as separate entities, among other considerations. Another aspect that adds complexity to the evaluation of comfort and discomfort is the variation in the understanding of these terms among different experimenters and subjects.

A well-known and widely used questionnaire targeting motion sickness and its individual differences is the Motion Sickness Susceptibility Questionnaire (MSSQ) for subjective evaluation. This questionnaire aims to predict individual susceptibility to motion sickness from various stimuli, and later an improved MSSQ was proposed [32]. The redesigned MSSQ provides new (and only) adult reference norms and was validated with data of motion and non-motion-induced nausea stimuli. Following its predecessor study, the MSSQ has been shortened even more (MSSQ-Short) [33]. Another common supporting questionnaire usually related to drowsiness and fatigue is the Karolinska Sleepiness Scale (KSS) [34]. This questionnaire includes questions to measure the subjective sleepiness level at a given time. The KSS could be useful in certain studies where changes in subjects' sleepiness, alertness, and performance need to be assessed under the influence of vibration or prolonged exposure while driving. A limitation of subjective evaluation is that when the change in vibration is less than the difference threshold it would not be perceived. Objective criteria will enable these changes to be quantified and to be combined to result in perceptible changes.

Overall, while subjective measures remain an essential aspect of comfort assessment, the integration of virtual testing and objective physiological measurements can provide valuable insights and predictions during the design process, leading to improved comfort outcomes with reduced costs and time investment. The subjective assessment is not considered in the article scope.

3. Assessment

Once the evaluation of vibration-induced discomfort has been done using one of the objective metrics above, the results of the evaluation need to be assessed. Likely reactions to magnitudes of frequency-weighted r.m.s. acceleration [18] and overall vibration total values [17] are listed in row 4 of Table 1. As far as the authors are aware there are no guidelines for the other metrics. Based on the assumption that lower levels of vibration magnitude are most likely associated with less discomfort, the other metrics may be interpreted as smaller values suggest less discomfort.

Difference thresholds (DT) could further aid in the assessment of vibration-induced discomfort. DT, also known as just noticeable difference, is defined in [35] for vehicle vibration on a seat as "...the minimum change in the magnitude of the whole-body vibration required for the seat occupant to perceive the change in magnitude." DT could therefore be used to predict whether the occupant would perceive a difference between vehicle vibrations due to different vehicles or changes to subsystems/components of the same vehicle. DTs can therefore be useful during the assessment of the comparative evaluation of discomfort to determine whether resulting differences will be perceptible by the human. Studies have estimated DT for whole-body vertical vibrations of participants on a rigid surface subjected to sinusoidal vibrations [36, 37, 38] and to account for the effects of seating posture on an automobile seat exposed to sinusoidal [39] and random vibrations [35, 40]. For multiaxial vibrations in a vehicle, DT was estimated for participants in a vehicle on a 4-poster test rig [41]. The relative DT from the literature are summarized by stimulus type, i.e., sinusoidal (Table 2) and

TABLE 2 Summary of median relative difference thresholds [%] to sinusoidal stimuli.

		Frequency [Hz]							
		1.3	**2.5**	**5**	**6**	**10**	**20**	**40**	**80**
Magnitude [m/s², r.m.s.]	**1.20**				7.3[2]				
	0.80		9.48	12.88		14.30	13.11	16.38	14.35
	0.50	6.4[2]		10.32[1]	7.9[2]		8.13[1]		
	0.20	11.0[2]	14.37	14.04	8.4[2]	15.45	12.41	15.74	17.61
	0.10			12.26[1]			10.99[1]		
	0.05		14.01	12.64		13.19	12.24	13.84	17.36

Median RDT from [38]; [1] [36]; [2] [39].

TABLE 3 Summary of median relative difference thresholds [%] to random stimuli.

			Spectral shape		
Stimuli direction	**Magnitude**		**Tarmac[1]**	**Pave[1]**	**Ride road[2]**
Vertical	[m/s², r.m.s.]*	0.80	11.85		
		0.40	13.85	14.1	
		0.20	12.85		
Multi	Vertical component ride value [m/s², r.m.s.]**	1.01			8.58
		0.58			10.13
	Combined point ride value [m/s², r.s.s.]***	1.22			9.24
		0.65			10.99

Median RDT for stimuli spectrum in [1] [35]; [2] [41].
* Weighted r.m.s.
** Median r.m.s. of vertical component ride value.
*** Median r.s.s. of combined point ride value.

random (Table 3). It should be noted that frequency-weightings [18] were applied before estimating DT in [35, 42].

4. Target Scenarios

4.1. Driving Mode

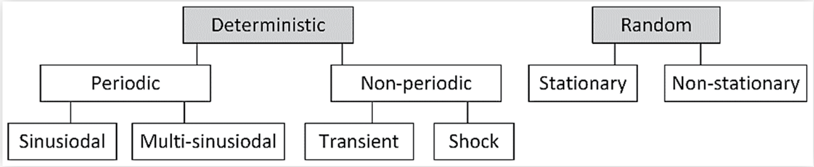
Automated driving (AD) is a promising but challenging area of innovation in the automotive industry. AD technology is closely linked to societal and economic challenges such as minimizing traffic accidents, fuel consumption, traffic congestion, parking needs, and providing mobility for an aging population, as well as addressing customer needs for more personalized services [42]. When choosing between conventional and AD vehicles, three main factors are considered [43]. These factors include motion comfort, perceived safety, and user acceptance.

In conventional vehicles, the act of driving makes the driver virtually impervious to motion sickness and vibration-related discomfort, while passive passengers usually suffer the most, especially if they do not receive visual information about their own motion [44]. A similar problem occurs when the vehicle can drive autonomously without active human involvement. Since humans no longer need to be actively involved in driving, travel time can be used for work or leisure; however, this requires a high level of comfort to avoid vibration-related discomfort and motion sickness [45]. Incongruence between visual and vestibular stimuli, especially during abrupt automatic driving maneuvers, can also lead to acceleration discomfort and excessive body motion. Moreover, long-duration exposures to high-frequency vibrations may lead to reduced task performance ability and adverse health effects such as lower back pain [46].

Considering the above aspects, the AD style must therefore be carefully designed and evaluated. This requires the revision of ride quality and driving comfort criteria currently used in the industry and research community, with a special focus on AD. Recent studies focusing on AD comfort are an experimental assessment for ride comfort between active driving participants and inattentive occupants performed secondary tasks [47]; the multiple logistic regression model to evaluate ride comfort of automated vehicles under typical braking maneuvers [48]; motion comfort assessment during automated lane changes using moving-base driving simulator [49]; perceived comfortable thresholds for longitudinal and lateral accelerations while AD [50]; pressing-based and smartphone-based methods to evaluate AD comfort [51].

Investigating the applicability of the evaluation criteria to AD is outside the scope of this study.

FIGURE 2 Categories of road inputs.



4.2. Tests

To evaluate comfort, different driving maneuvers with different speeds, roadway irregularities, and roadway profiles corresponding to various pavement situations (e.g., cobblestone medium, large, asphalt, etc.) may be considered. The target scenarios proposed in this section are based on the excitation of the vehicle by the road input. The road excitations can be generally categorized as shown in Figure 2.

Ride comfort tests can be conducted on dedicated test sites (or proving grounds) and in a virtual environment that replicates road profiles and driving conditions. The test site may have special comfort roads with damaged road surfaces (with potholes and corrugations). The artificial pavement element shown in Figure 3 to reduce vehicle speed would be categorized as a non-periodic road input. The geometry of these pavement elements and their shape can vary. Figures 3 and 4 show four common speed-reducing bumps used in the comfort tests and their qualitative geometry and shape. Periodic road inputs can easily be defined in simulations and test environments such as motion platforms and 4-poster test rigs. Periodic road profiles can even be found on some proving grounds. Random road profiles can be generated from ISO 8608 road classes [1] that can be used in simulation, motion platforms, and 4-poster test rigs. Example test specifications commonly used by industrial companies are presented in Table 4.

Vehicle speed affects how a particular road excites the vehicle. It is suggested that the speed be chosen to be representative of typical driving on the specific road and to allow the use of available relative DT. Consideration of sinusoidal road inputs during virtual and physical testing would allow the use of the relative DT estimated with sinusoidal stimuli. Similarly, consideration of roads and vehicle speeds that result in random stationary vibrations to the occupant that are similar to the stimuli used in the studies, in which the DT were estimated, would allow for increased applicability.

5. Test Environment

Ride comfort assessment can be conducted at various stages of vehicle development. In the early stages, virtual testing can be employed using simulations or driving simulators. Simulation-based evaluations typically utilize objective metrics to assess ride comfort. Additionally, driving simulators offer the advantage of involving human subjects, enabling subjective evaluations alongside objective assessments. As the development progresses, further evaluations can be performed using a vehicle test bench, such as a 4-poster test rig, to simulate real-world conditions in a controlled environment. This enables more comprehensive testing of ride comfort attributes. In the final stage of evaluation, on-road testing is

FIGURE 3 Artificial pavement element for reducing vehicle speed: (a) speed bump; (b) speed hump; (c) cushion speed bump long wavelength; (d) cushion speed bump short wavelength.

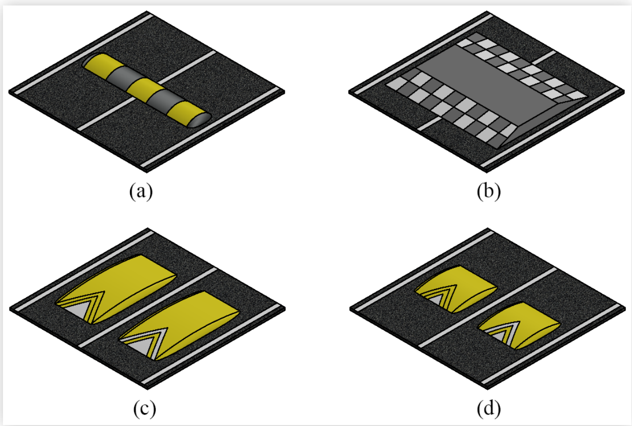


FIGURE 4 Global and lateral views of speed bumps: circular (top); trapezoidal (middle); sinusoidal (bottom).

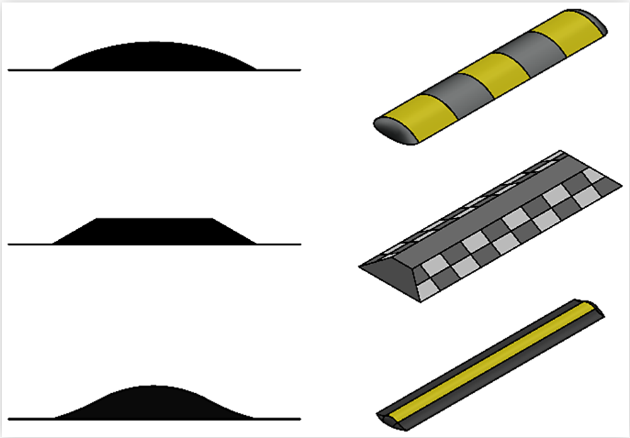


TABLE 4 Ride comfort test specification.

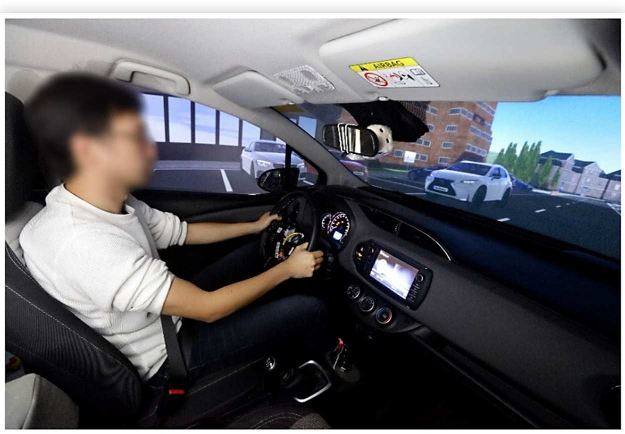
Excitation type	Description	Constant speed specification [km/h]
Random	Driving with constant speed and constant steering wheel angle in a bend on a Belgian block	65; 50
	Driving with constant speed over a special section on comfort road with different bends and gradients	60; 50
	Driving with constant speed over a special section on comfort road in severe surface condition	45; 35
	Driving with constant speed over a gravel section	45; 35
Deterministic, non-periodic	Driving with constant speed over a special section on comfort road with some transversal edges and potholes	70; 50
Deterministic, non-periodic	Driving with constant speed over a special section on a road with different speed bumps	25
Deterministic, periodic, multi-sinusoidal	Driving with constant speed over a special surface with changing sinus stimulations	40

conducted to validate the performance and ride comfort of the vehicle under real-world driving conditions. The case study presented in Section 6 will make use of a simulation test environment. As the case study project progress hybrid and physical environments will also be used. These environments are discussed in the following sections.

5.1. Motion-Based Driving Simulator

Typically, the 6-DoF motion system is used to generate accelerations up to 1 g in all directions and can effectively cover the frequency range of 0.1 Hz–10 Hz with a limited amplitude. The stroke lengths and consequently the used working space are the physical limitations of the reproduced signals in the context of ride comfort studies. An example of the simulator, the TU Delft Advanced Vehicle Simulator [52], is shown in Figure 5. Its dynamic threshold values for platform motion latency range are from 10 to 20 ms, depending on motion direction. In addition, the curved rigid projection screen is used, covering horizontal and vertical fields of view for 210° and 45°, correspondingly. The generated images are projected by three Barco F50 WQXGA – VizSim Bright projectors. The simulator is operated in hard real-time using the dSPACE Scalexio system. HIL CarMaker software is extended for vehicle simulation by validated vehicle models and subsystems. The motion-based driving simulator allows testing to be done without or with visual inputs.

FIGURE 5 Driving simulator (TU Delft Advance Vehicle Simulator).



5.2. 4-Poster Test Rig

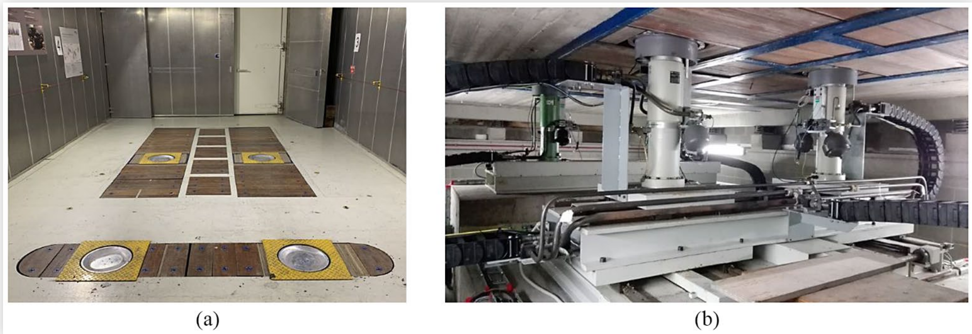
As described above, the driving simulator has some limitations due to the limited workspace envelope; therefore, a 4-poster test rig may be preferred. One advantage of the 4-poster test rig is that a vehicle of specific interest can be used for comfort evaluation. However, the tests are limited to vertical, roll, and pitch. The stimuli used in the laboratory tests are based on vehicle vibrations on the road(s) of interest measured during on-road tests or can be profiles generated from ISO 8608 road classes [1] and simple harmonic wave forms. The semi-anechoic chamber in which the 4-poster test rig is located creates an environment with limited aural and visual inputs. Aural inputs which reach the test participants are generated by the actuators, and these signals can be reduced using earplugs or headphones.

For example, Figure 6 shows the 4-poster test rig at Tenneco Automotive Europe BVBA, which consists of four actuators acting in a vertical direction. The actuators generate a force of 40 kN on the front wheels and 25 kN on the rear wheels. The rig is controlled by an Instron 8800ml controller using Instron RS Studio ml as part of the Instron RS LabSite Modulogic 2.0 software suite.

5.3. On-Road Tests

On-road tests are usually conducted on proving grounds in order to provide a higher degree of repeatability. The ride

FIGURE 6 (a) Semi-anechoic chamber in which vehicle is placed on the 4-poster test rig; (b) room below the floor of the semi-anechoic chamber housing the actuators.



(a) (b)

roads on the proving ground considered in this study contain three sections, each corresponding to a (relative) comfort index that can be further analyzed:

- Symmetric and asymmetric impact strips (deterministic road input);
- Asphalt road in poor condition with large primary ride inputs, body control, and head toss (random road input);
- Asphalt road with choppy secondary ride inputs, shake, and harshness (random road input).

In addition, an outer durability road is used, which is a smooth road (almost no primary ride inputs) and consists partly of a smooth asphalt surface and an older, coarser asphalt surface. It can be classified as a secondary road of good quality to evaluate mainly harshness and shake.

6. Proposed Procedure

Section 1 discussed a typical comparative evaluation procedure. Sections 2–5 provided an overview of ride comfort evaluation criteria, assessment, target scenarios, and test environment. This section presents the proposed comparative evaluation procedure for vibration-induced discomfort. Figure 7 presents the outline of the comparative evaluation procedure for vibration-induced discomfort as applied to the comparative evaluation of wheel corner concepts.

The procedure is applied to the OWHEEL project, in which wheel corner concepts are compared in the development of new vehicle architectures. The development of vehicle corners promises improved performance in terms of comfort, efficiency, safety, and stability. The new design of corners includes the selection of in-wheel motors, the design of new active suspension components, as well as actuators for wheel positioning. In this investigation, the passive wheel corner is analyzed.

The wheel corner concept is evaluated at the full vehicle level in a simulation environment, rather than using simplified versions (e.g., quarter-car or pitch-bounce models), as it has been shown that the simplified versions do not accurately predict ride comfort [53]. As physical components become available, comparative evaluations can be performed in hybrid and physical environments to validate simulation-based evaluations. Using virtual evaluations, objective criteria were used for comfort evaluation. The assessment of the evaluation results considers the likely reaction (as guided by [17, 18]) and whether perception and DT are exceeded. The latter is of importance to the comparative evaluation.

6.1. The Procedure Application

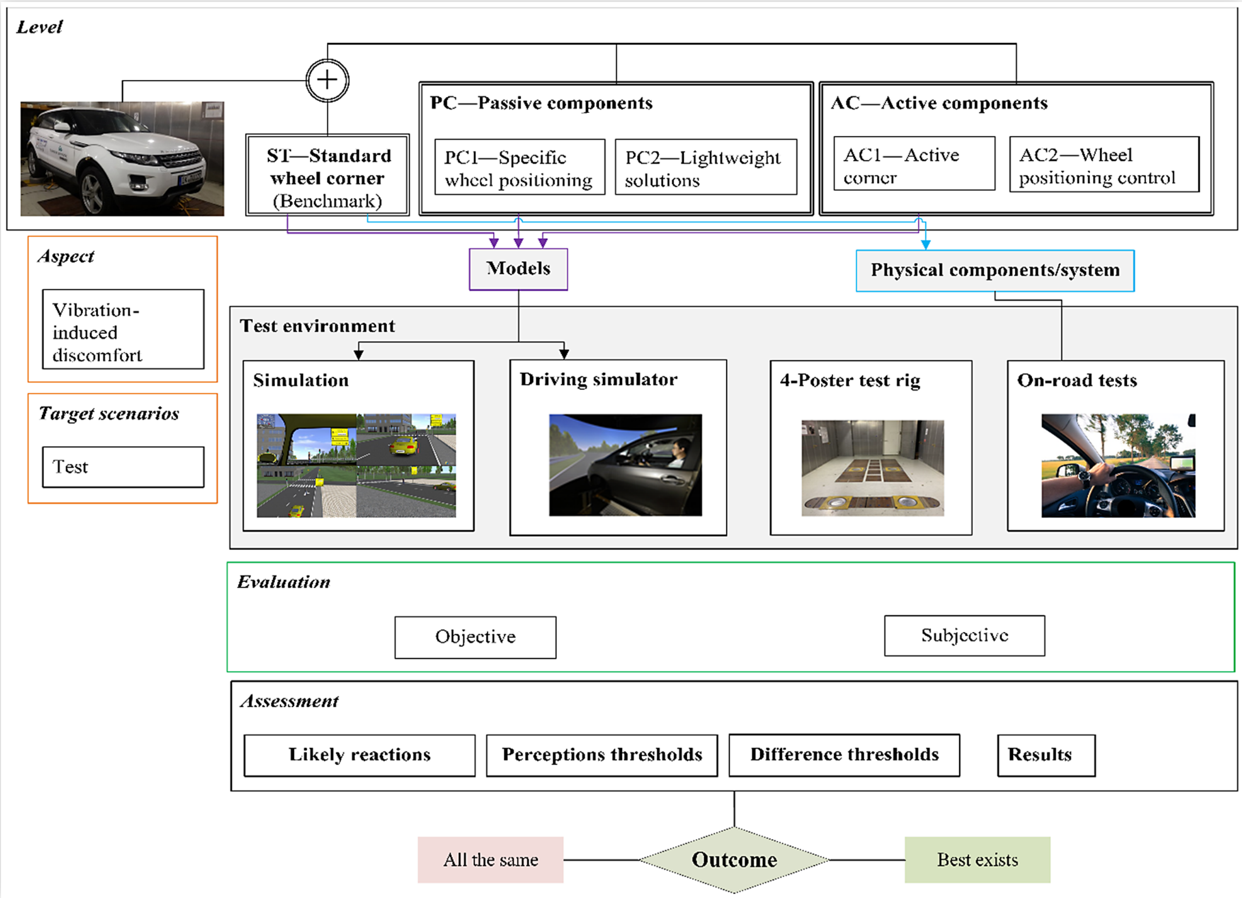
During the initial stage of the OWHEEL project, a new passive corner design with the in-wheel motor was developed for the front and rear axles (Figure 8), and the impact of increased unsprung mass on vehicle comfort has been investigated in a simulation environment using objective metrics and DT.

The tests were performed on an IPG CarMaker-based simulation platform using a high-fidelity vehicle model. The baseline model has been parametrized based on mass-inertia parameters obtained from the vehicle inertia measuring facility, vehicle data is presented in [54]. To simulate tire dynamics, the Delft-Tyre 6.2 was used in combination with a detailed tire property file identified from bench testing (pure and combined slip, transient dynamics). Suspension kinematics and compliance obtained by measurement on a kinematics and compliance test rig for wheel suspension characterization, and finally, validated by field tests on the proving ground, experimental data is available online from [55].

The kinematics and compliance of the vehicle with designed corners were obtained using simulations performed in the multibody dynamics modeling software MSC.ADAMS including 3D CAD models. Based on this, the new kinematics and compliance files were obtained for vehicle modeling in IPG CarMaker focusing on real-time feasible model, which can be later used in the driving simulator. Additionally, the unsprung mass and inertia were modified in accordance with the new corner design.

Sinusoidal road profiles were used in the simulation, with frequencies of 2.5, 5, 10, and 20 Hz and a vehicle velocity of 20 km/h. The frequencies for wheel excitation were selected

FIGURE 7 Comparative evaluation procedure of vibration-induced discomfort.



based on previous studies that estimated relative DT (as discussed in Section 3). The sinusoid amplitude was varied to achieve sprung mass acceleration 0.05 m/s^2, 0.2 m/s^2, and 0.8 m/s^2 r.m.s. at the frequencies considered. The length of the sinusoidal road used in the simulations was 180 m, r.m.s. was calculated after transient processes settled. Following this, modifications were made to the vehicle's mathematical model to evaluate the performance of new corner designs. The simulation was repeated under the same road and driving conditions as in the first case (same wavelength and amplitude); the results are presented in Table 5. Additional simulations were performed using road profile classes C and D specified in ISO 8608 [1]. The road roughness is described as a stochastic process, which is subject to the Gauss distribution. Road roughness input was generated in MATLAB/Simulink and used in IPG CarMaker. The length of the road used in the simulations was also 180 meters. Vehicle speed over the class C and D road profiles was adjusted to have the weighted vertical vibration close to the magnitudes of stimuli used in determining the DTs in [35], and vibrations were measured

FIGURE 8 Vehicle corners with in-wheel motors on (a) front suspension and (b) rear suspension.

TABLE 5 Percentage relative difference in vertical acceleration of the sprung mass in the conventional corner (i.e., ST—standard wheel corner) and the in-wheel corner (PC1—passive wheel positioning) to sinusoidal stimuli. The simulation results are compared to the median relative difference thresholds from the literature [36].

Excitation		Vertical vibration [m/s², r.m.s.]		$\left\lvert\frac{PC1-ST}{ST}\right\rvert \times 100$	Median relative difference threshold [%]
Magnitude [m/s², r.m.s.]	Frequency [Hz]	ST—standard wheel corner	PC1—passive wheel positioning		
0.80	2.5	0.8012	0.6676	16.67	9.48
	5	0.8037	1.0419	29.64	12.88
	10	0.8059	1.0664	32.32	14.30
	20	0.8354	0.7111	14.88	13.11
0.20	2.5	0.2043	0.2107	3.13	14.37
	5	0.2067	0.2311	11.80	14.04
	10	0.2015	0.2425	20.35	15.45
	20	0.2042	0.1212	40.65	12.41
0.05	2.5	0.0501	0.0516	2.99	14.01
	5	0.0506	0.0573	13.24	12.64
	10	0.0506	0.0603	19.17	13.19
	20	0.0503	0.0315	37.38	12.24

on the driver seat. This was done for the vehicle with the standard wheel corners. Once the speed was determined it was used for simulation of the vehicle with the standard (ST) and in-wheel motor corner (PC1). The results for the simulations over the class C and D road profiles are presented in Table 6. It can be seen from Table 6 that the achieved difference is less than the median DT and most likely will not be perceivable by the occupants.

Considering the vertical vibrations of the vehicle subject to the harmonic excitation between the conventional (ST) and in-wheel corner (PC1) in Table 5, higher magnitudes are observed for the in-wheel corner except at 2.5 Hz with a magnitude of 0.8 m/s^2, r.m.s. and 20 Hz. Furthermore, the results in Table 5 indicate that the difference in acceleration between the two corner designs is higher than the median DT. This implies that the changes in the vertical acceleration of the sprung mass would most likely be perceivable by the occupants. Based on the results over the harmonic road profiles, the increased unsprung mass negatively impacts ride comfort; however, it is possible to eliminate this impact by using lightweight solutions and active suspension components. When considering the vertical vibrations over the random class C and D roads, it is again observed that the in-wheel corner (PC1) results in higher acceleration. However, the difference in accelerations between conventional (ST) and in-wheel corner (PC1) is well below the median relative difference threshold reported in [35]. Therefore, the difference in comfort between the two wheel corners will not be perceivable by most occupants. It should be noted that the psychometric testing method used in the studies [35, 36] results in a relative difference threshold that estimates the required change in vibration with a 79.4% probability that the larger of the two stimuli will be identified. Furthermore, if the median relative difference is used it should be interpreted as the change in vibration at which 50% of people would have a 79.4% probability of identifying the larger of the two stimuli.

After the simulation study, the corner concepts can be evaluated on the driving simulator with subjective feedback from occupants; this will provide additional confirmation on the best corner concept. With the best concept known, a physical vehicle corner needs to be developed and installed on the vehicle platform. The physical corner can then be evaluated using the 4-poster test rig and on-road tests. Subjective assessment will be performed using a 4-poster test rig, a moving-based driving simulator, and an instrumented vehicle.

TABLE 6 Percentage relative difference in weighted vertical acceleration of the sprung mass between the reference vehicle (ST) and one with new corner design (PC1) to driving on C and D class roads [1]. The simulation results are compared to the median relative difference thresholds from the literature [35].

Excitation		Vertical vibration [m/s², r.m.s.]		$\left\lvert\frac{PC1-ST}{ST}\right\rvert \times 100$	Median relative difference threshold [%]
Stimuli direction	Magnitude* [m/s², r.m.s.]	ST—standard wheel corner	PC1—passive wheel positioning		
Vertical	0.80	0.7589	0.7671	1.08	11.85
	0.40	0.3752	0.3921	4.50	13.85
	0.20	0.1845	0.1947	5.53	12.85

* This is the magnitude for tarmac road in [35].

TABLE 7 Additional test procedures.

	Standard	Test maneuver
Vehicle handling	ISO 4138:2004	Constant radius cornering (open-loop)
	ISO 7401:2003	Step input (open-loop)
		Frequency sweep response
Vehicle safety and stability	ISO 3888-1:1999	Double lane change (closed- loop)
	ISO 19365:2016 & FMVSS 126	Sine with dwell (open-loop)
	ISO 17288-2:20	Steering-pulse (open-loop)
	ISO 7975:2006	Braking in a turn (open-loop)
Steering feel	ISO 13674-1:2010	Weave test for on-center handling
	ISO 13674-2:2006	Transition test

6.2. Other Aspects of Importance

Besides driving comfort evaluation, the corner concepts also need to be evaluated with respect to vehicle safety and stability. This will be ensured by performing vehicle handling, safety, stability, and steering feel (for the case of semi-automated vehicles) tests. In this regard, maneuvers commonly used to evaluate vehicle handling, safety, stability, and steering feel (in the case of a semi-automated vehicle) should be performed. Such tests are presented in Table 7. Energy efficiency is another important aspect that needs to be taken into account. The energy consumption of actuators can be calculated as requested energy to overcome inertia and road resistance, plus additional energy to compensate for internal power loss. The reliability of redesigned components implementing lightweight materials will be ensured by factors of safety, NVH behavior, stiffness of components, and weight reduction. The quality of ride comfort should be analyzed in the context of these other important aspects. The evaluation with respect to these aspects is outside the scope of this article.

7. Conclusions

The article presents a methodology for conducting a comparative analysis of discomfort caused by vibrations. While previous studies have predominantly utilized objective metrics in a simulation environment, we propose an extension that incorporates different thresholds to gain insights into the perceptible differences that people might feel. The main focus is on identifying metrics that can effectively measure and quantify the level of discomfort induced by vibrations, as well as providing guidance on how to interpret and assess the results obtained from such comparisons. A comprehensive review of comfort evaluation criteria was conducted, encompassing various ride comfort scenarios and test environments. The r.m.s. of vertical acceleration was consolidated to evaluate different wheel corner concepts, considering their potential as sustainable solutions for urban and intercity mobility. By utilizing the available evaluation criteria and DT, it becomes possible to conduct comparative assessments of vibration-induced discomfort, albeit within a limited range of vehicle vibration characteristics. However, further research is necessary to expand the existing knowledge and facilitate comparative evaluations across a broader spectrum of vehicle vibrations.

In the initial simulation-based evaluations of wheel corner concepts, it was observed that the introduction of an in-wheel motor resulted in increased unsprung mass, which had a slightly negative effect on comfort. However, the impact was not significant and could potentially be mitigated by implementing lightweight solutions and incorporating active suspension components with wheel positioning.

To further investigate and validate these findings, future research will encompass experimental tests using a combination of different methods. This includes conducting evaluations using a driving simulator, which allows for human involvement and subjective assessment. Additionally, a 4-poster test rig will be utilized to simulate real-world conditions in a controlled laboratory environment, enabling comprehensive analysis of ride comfort. Finally, on-road tests will be conducted to validate the performance and comfort of the wheel corner concepts under actual driving conditions.

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Definitions/Abbreviations

AD - Automated driving

CI - Comfort index

DoF - Degree of freedom

DT - Difference threshold

KSS - Karolinska Sleepiness Scale
MSSQ - Motion Sickness Susceptibility Questionnaire
MTVV - Maximum transient vibration value
NVH - Noise, vibration, and harshness
p-p - Peak-to-peak index
r.m.q. - Root mean quad
r.m.s. - Root mean square
r.s.s. - Root sum squared
VDV - Vibration dose value
VR - Virtual ride
VTV - Vibration total value

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