

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Front seat passengers' experience of ride comfort and
NVH in modern cars

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Abstract

Due to the refinements in combustion-engine and electric cars, ride comfort has become a prominent attribute when it comes to developing cars in the future. A variety of factors, such as seat, seatbelt, sound and vibration, have been shown to influence perceived overall ride comfort in passenger cars. Numerous studies have investigated human responses to sound and vibration. However, few studies have investigated passengers' experiences of sound and vibration in real passenger cars, in different real-world driving scenarios.

The purpose of this licentiate thesis is to identify human experiences of sound and vibration in modern passenger cars. An approach has been developed to investigate how sound and vibration influence overall perceived ride comfort in combustion-engine cars (CVs) and electric cars (EVs). The first research question relates to the definition of ride comfort, from the passenger's perspective, and the methodology used to specify the factors that influence overall ride comfort. The second research question deals with specifying how ride comfort is influenced by sound and vibration.

The research includes literature reviews of human responses to sound and vibration and a user study using a mixed-method research approach that focused on subjective judgements and objective measurements of overall ride comfort.

The literature reviews found that several laboratory studies have covered the level and frequency ranges of interest for vibration and sound found in passenger cars. Other studies have employed realistic ride postures with populations of various ages, gender and anthropometric measures to investigate the influence of vibration on ride comfort. Studies of sound in passenger car have explored approaches to identify sound sources, assess sound quality and design product sound. The overall conclusion from the literature reviews was that there is a lack of studies that consider all the different parameters influencing the overall ride comfort experience of automotive vehicle passengers. Also, further studies are specifically needed to investigate the influence of sound and vibration on passengers' experience of overall ride comfort.

The user study comprised eight typical driving scenarios (initial comfort, start/stop, acceleration and deceleration, constant speed, speed bumps, long bumps and cornering, bridge joints and rough roads) with ten participants in a CV and an EV. The overall results indicated that the two cars were similar in terms of the prominent effects of ingress, room for the body, seat adjustment and seat support on initial comfort, but varied in terms of dynamic discomfort. Induced body movements dominated dynamic discomfort in the CV, while annoying sound dominated in the EV. Sound annoyance in the CV was primarily triggered by tyre noise at lower speeds and wind noise at higher speeds. In the EV it was the high frequency tonal sound from electrical components that produced the most annoyance. In both cars, vibration discomfort was linked most strongly to induced body movement. Sound annoyance was judged lower when passengers perceived pronounced induced body movement or when participants experienced vibrations coherent to the sound. Nevertheless, the overall influence of sound accumulated over time, making it difficult for passengers to relax. In contrast, the instantaneous judgement of vibration discomfort was not affected noticeably by the simultaneous sound.

The main conclusion of this licentiate thesis is that from the passenger's perspective, ride comfort encompasses static comfort and dynamic discomfort. Static comfort is associated with ingress, room for the body, seat support and seat adjustment. While dynamic discomfort is attributed to annoying sound, induced body movement, as well as discordance between sound and vibration. The influence of sound and vibration on perceived ride comfort varies depending on the type of driving scenario (e.g., road profile and speed) and on the type of cars (e.g., CV or EV). Moreover, dynamic discomfort could be controlled by controlling sound and vibration.

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Appended publications

Paper A

X. Wang, A-L. Osvalder, P. Höstmad, and I. Johansson (2020). “Human Response to Vibrations and Its Contribution to the Overall Ride Comfort in Automotive Vehicles: A Literature Review”, SAE Technical Paper, 2020.

Xiaojuan Wang planned the paper, executed the database search, reviewed the literature and wrote the paper.

Anna-Lisa Osvalder and Patrik Höstmad contributed to the planning, review and writing and provided supervision.

Ingemar Johansson contributed to the review and writing.

Paper B

X. Wang, A-L. Osvalder and P. Höstmad (2022). “Noise and Vibration Influence on Overall Ride Comfort in a Conventional Passenger Car under Different Driving Scenarios”. To be submitted for publication.

Xiaojuan Wang: conceptualization, methodology, research, data curation, validation, formal analysis, writing (preparation of original draft) and graphics.

Anna-Lisa Osvalder and Patrik Höstmad: conceptualization, methodology, writing (review and editing) and supervision.

Paper C

X. Wang, P. Höstmad and A-L. Osvalder (2022). “Influence of Sound and Vibration on Perceived Overall Ride Comfort: Comparison between an Electrical Vehicle and a Combustion Engine Vehicle”. To be submitted for publication.

Xiaojuan Wang: conceptualization, methodology, research, data curation, validation, formal analysis, writing (preparation of original draft) and graphics.

Patrik Höstmad and Anna-Lisa Osvalder: conceptualization, methodology, writing (review and editing) and supervision.

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Chapter 1 Introduction

1.1 Background

At the current level of refinement in vehicles, ride comfort has become important target when developing new vehicles and platforms. For contemporary cars, this means that consumers expect a higher level of ride comfort (Harrison, 2004; Sheng, 2012). A comfortable riding experience is critical for enhancing driver performance, reducing occupant fatigue, improving safety and long-term health (X. Wang et al., 2020). Consequently, both industry engineers and academic researchers have been increasingly interested in studies of ride comfort.

A variety of factors have shown influence on human perception of ride comfort, including ambient, dynamic and ergonomic factors. Ambient factors refer to aspects such as air temperature, air quality and sound. Dynamic factors include vibration, impact, ride motion and acceleration. Visibility, functionality, seat architecture, seatbelt and seat-human interfaces are categorised as ergonomic factors (X. Wang et al., 2020). The effects of these different factors are not independent; indeed, there are interferences between them. For instance, Huang (2012) concluded that higher-magnitude vibrations had a masking effect on discomfort caused by lower levels of noise and vice versa.

Studies of ride comfort for seated occupants have mainly focused on the discomfort. However, Helander and Zhang (1997) demonstrated that comfort and discomfort could be independent factors. They indicated that comfort is associated with well-being and relaxation and does not change as a function of time, while discomfort is mainly related to physical constraints and poor biomechanics. As other papers have summarised, experienced vibrations and ride motion (X. Wang et al., 2020), perceived sound level and perceived sound characteristics (Sheng, 2012) were also associated with discomfort. According to Helander and Zhang (1997), experiences of discomfort are cumulative over time. Therefore, the perception of discomfort differs between shorter and longer rides. Kamra et al. (2017) defined static comfort/discomfort as the perception in a stationary car and dynamic comfort/discomfort as the perception in a moving car.

Studies of static ride comfort in passenger cars have focused on ergonomic factors, such as roominess and the seat-human interference. Pheasant and Haslegrave (2002) suggested using clearance between knee and car door/centre console as an indicator of legroom, while Mohamed and Yusuff (2007) suggested using clearance between elbow and car door/centre console as an indicator of upper body room. Mergl (2006) concluded that when sitting, the pressure under the thigh/buttock area should be distributed in a ratio of 25–29% under the buttocks, less than 14% under the mid-thighs and less than 3% under the distal end of the thighs.

X. Wang et al. (2020) concluded, in summary, that the experience of vibration in passenger cars might degrade overall ride comfort, cause motion sickness and interfere with activities during the ride. The review found that based on existing laboratory studies, seated humans were most sensitive to vertical vibration in the range of 4–6 Hz, and in the 1–4 Hz for horizontal vibration. Weighted vibration in passenger car seats was usually significant below 20 Hz in the lateral and vertical directions and below 30 Hz in the fore-and-aft direction. Studies of Lin et al. (2006) and Kaderli and Gomes (2015) concluded that vibrations transmitted to the seat pan and backrest were more significant in the vertical and lateral direction than in the fore-and-aft direction. The studies by Mansfield (2001) and Kilincsoy et al. (2016) identified the greatest level of seat vibration in the contact areas between the seat and the human body, including thighs and buttocks. Whitham and Griffin (1978) indicated that occupants attributed their experience of vibration discomfort to body movement. According to their studies, discomfort caused by vibrations in the range of 4–16 Hz was mainly experienced in the upper torso and head. At higher and lower frequencies, discomfort was mainly reported in the lower body, such as abdomen and buttocks. Hiemstra-van Mastrigt et al. (2015) found that passive thigh movement had a positive effect on easing ride discomfort.

There have been a number of studies of perceived vibration in electric cars (EVs). Karikomi et al. (2006) found that in EVs without a torque converter, torsional vibration could cause a noticeable deterioration in ride comfort. The results of He et al. (2010) indicated in some EVs, vibration was greater than in combustion-engine cars (CVs) due to the resonance between the traction motor and vehicle driveline. Q. Wang et al. (2017) found that mechanical dampers such as the clutch, flywheel and flexible joints of the CV driveline served to suppress the coupling vibration between the engine and the transmission system. In the majority of EVs, in contrast, the effects of such mechanical dampers are partially eliminated due to use of an electric motor and the need to reduce weight.

Clark et al. (2006) indicated that sound inside the cabin could lead to annoyance and discomfort. Qatu et al. (2009) demonstrated that in CVs, the major energy of interior sound was concentrated in low frequencies. They found that in CVs, the overall interior A-weighted sound pressure level at wide-open throttle was usually between 45–80 dBA. They also indicated that powertrain sound was noticeable, especially when idling or with the throttle partially or fully open, and while cruising and coasting. In another study, Qatu (2012) concluded that sound inside the cabin was dominated by tyre noise at low to medium constant speeds (i.e., 40–85 km/h) and by wind noise at higher constant speeds (i.e., above 75 km/h). The results of Zeitler and Zeller (2006) showed that sound discomfort in CVs was dominated by sound at constant speeds, and that occupants attributed sound during acceleration to the perception of sportiness.

A number of studies have investigated perceived sound inside EVs. Fang et al. (2015) founded that in EVs, the main energy of A-weighted sound was concentrated between 1000–2500 Hz. The sound generated by electrical components could be more noticeable in EVs than in CVs due to the absence of sound from an internal combustion engine (Qin et al., 2020). Berge and Haukland (2019) indicated that tyre noise became audible at lower speeds (around 20 km/h) in EVs. He et al. (2010) concluded that sound radiated by the differential is the main source at low speeds, and sound from the electric motor is the main source at high speeds.

Most of these previous studies have investigated the influences of a single factor (e.g., sound or vibration) or have been conducted under a single scenario (e.g., constant speed). However, in real-world rides there are a variety of simultaneous inputs from the car that differ under different driving scenarios or in different cars. The literature review (X. Wang et al., 2020) summarized that human responses to sound and vibration vary depending on their frequency and amplitude and that influences from sound and vibration interfere with each other. Moreover, few studies have examined the influence of sound and vibration on perceived ride comfort in EVs. The differences in overall ride comfort between CVs and EVs have not been clearly identified yet.

1.2 Aim and research questions

The purpose of the five-year research project is to provide the automotive industry with targets and guidelines for future mobilities of high comfort level. The overall hypothesis behind this work is that single factors (e.g., sound or vibration) have different influences on occupants' perception depending on the driving scenario (e.g., road profile and speed) and this fact can be used to reduce experienced discomfort.

The first research question relates to the definition of ride comfort from the passenger's perspective and the methodology used to specify factors that have significant effects on overall ride comfort. Passenger car occupants are exposed to various factors and interact with the car's components during the ride. Occupants can perceive these inputs and respond to them. Studying occupants' subjective assessments of their experiences in various scenarios deepens our understanding of the factors that influence perceived ride comfort.

The second research question deals with specifying how ride comfort is influenced by sound and vibration. Sound and vibration change as the driving scenario varies. The occupants' experienced ride

comfort is, therefore, different. An approach that establishes the correlation between subjective assessments and objective measurements of sound and vibration is needed in order to specify how occupants' experiences change depending on variations in sound and vibration.

The purpose of this licentiate thesis is to analyse the compiled work addressing the earlier stages of research development, which is to first identify and explain the causes of experienced ride comfort and discomfort. This thesis includes three papers. The specific aim of paper A is to analyse previous studies in order to investigate the definition of ride comfort and the influence of vibration on discomfort. Papers B and C investigate the influence of sound and vibration under various driving scenarios in a combustion engine car and an electric car. The correlation between subjective assessments of ride comfort and objective measurements of sound and vibration is discussed to arrive at a better understanding of perceived ride comfort.

1.3 Outline

The thesis is divided into three parts. It starts with a general introduction, followed by the literature reviews and a discussion of methodology (Chapters 1, 2 and 3). The second part deals with front-seat passengers' experience of ride comfort in a combustion car (Chapter 4) and an electric car (Chapter 5). The third part formulates answers to the first two research questions and develops a methodology that can be used to assess ride comfort (Chapter 6, 7 and 8). In addition, this section describes suggested directions for future research (Chapter 9).

Chapter 2 features literature reviews of the influence of sound, vibration and seat on ride comfort. This chapter includes the findings from Paper A. The reviews encompass both laboratory studies of sound and vibration and tests on real vehicles. Chapter 3 describes the literature study method, subjective assessments and objective measurements methods used in the user study.

Chapters 4 and 5 discuss how different factors influence static ride comfort and dynamic discomfort in a CV and an EV. Their major focus is on the influences of sound and vibration. These chapters correspond to Papers B and C. Subjective assessments and objective measurements of sound and vibration were collected in both cars to determine how these factors influence perceived ride comfort. The results indicated the importance of sound and vibration to overall ride comfort. Moreover, the influences of sound and vibration varied in different driving scenarios and in different cars.

The studies show that it is possible to correlate the occupants' perception with measured sound and vibration. Chapter 6 analysed the results obtained in literature studies and the user study, as well as the changes in occupants' experience while sound and vibration varied in different scenarios and in different types of cars. The characteristics of perceived sound and vibration is argued due to their significant influence on dynamic ride comfort. In Chapter 7, the answers to the first two research questions are formulated. The methodology that could be applied in assessing ride comfort is discussed. Chapter 8 presents the conclusion that it is possible to control experienced ride comfort by controlling the sound and vibration transmitted to occupants. The methodology employed in the studies could be used in future research on ride comfort.

Chapter 2 Overview of the fields involved

This is an interdisciplinary study that involves sound, vibration and human factors. Thus, the thesis includes literature reviews of the fields of human response to sound and vibration in both laboratory and real-world vehicle settings, as well as the influence of seat characteristics on ride comfort.

2.1 The influence of vibration on ride comfort

Vibration can degrade overall comfort, cause motion sickness, interfere with activities during the ride and, over the long term, lead to impaired health (X. Wang et al., 2020). Thus, vibration has been highlighted as important factor contributing to perceived ride comfort. Passenger car occupants experience both whole-body vibrations (WBV) and local vibrations. WBV refers to vibration transmitted to the human body through a supporting surface. Local vibration, in contrast, is transmitted to parts of the human body through contact areas (Griffin and Erdreich, 1991).

Von Gierke and RR (1961) found that seated humans were more sensitive to WBV than to local vibration below 20 Hz. They found that above 20 Hz, vibration was intuitively attenuated by the soft tissues of the human body. By the results of Griffin and Erdreich (1991), above 20 Hz, motion in various body parts was mainly localized around contact areas with the vibrating surface. Thus, vibration discomfort at higher frequencies was mainly attributed to resonance and the biodynamic response of the various human body parts (Von Gierke and RR, 1961). Between 100 Hz (Griffin and Erdreich, 1991) and 300 Hz (Giacomin and Woo, 2005; Morioka and Griffin, 2009), vibration transmitted to the steering wheel in passenger cars has also been investigated due to its relationship with hand discomfort.

Human response to vibration depends on the characteristics of both the vibration and the subject. As Figure 1 shows, the characteristics of the vibration include frequency, magnitude, direction and duration. While subject's characteristics encompass intra-subject variables such as posture and orientation, and inter-subject variables including age, gender and anthropometry (Griffin and Erdreich, 1991).

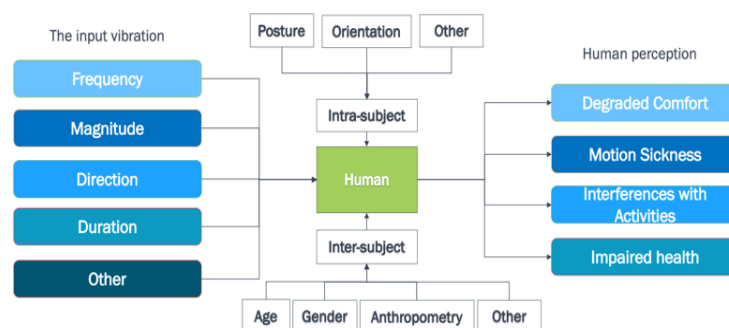


Figure 1. Factors that affect human perception of vibration (Griffin and Erdreich, 1991).

Human sensitivity to vibration discomfort varies with frequency, as Figure 2 shows. Higher frequencies require a greater level of vibration to produce the same level of vibration discomfort. The effect of frequency on human perception of degraded comfort is also affected by the vibration magnitude and direction (Morioka and Griffin, 2006), the subject's body posture (Nawayseh and Griffin, 2012) and body orientation (Huang and Griffin, 2009), as well as the subject's age, gender and anthropometry (Toward and Griffin, 2011).

Humans are more sensitive to vertical vibrations at low frequencies than at high frequencies (Morioka and Griffin, 2006). Zhou and Griffin (2014) concluded that the greatest sensitivity occurred at around 5 Hz. They attributed peak values in human sensitivity partially to the resonance behaviour of the human body. Studies by Arnold and Griffin (2018) found that the body parts that mostly affected by low-level vertical vibrations below 10 Hz were the lower abdomen, lower thighs and the ischial tuberosities. At

higher vibration levels, the spine (Holmlund et al., 2000), head and neck (Matsumoto and Griffin, 2002), shoulders and chest (Arnold and Griffin, 2018) were most prone to discomfort due to vertical vibration.

Morioka and Griffin (2006) found the highest sensitivity to longitudinal vibration and lateral vibration occurred at around 2–3 Hz and 1–2 Hz, respectively. They indicated that human sensitivity to horizontal vibrations decreased with increasing frequency because of variations in the affected body parts. Arnold and Griffin (2018) reported that discomfort in the upper torso lessened as the vibration frequency increased when subjects were exposed to longitudinal vibration. The greatest sensitivity to lateral vibration was mainly associated with vibration transmitted to shoulders, chest, lower abdomen, ischial tuberosities and lower thighs.

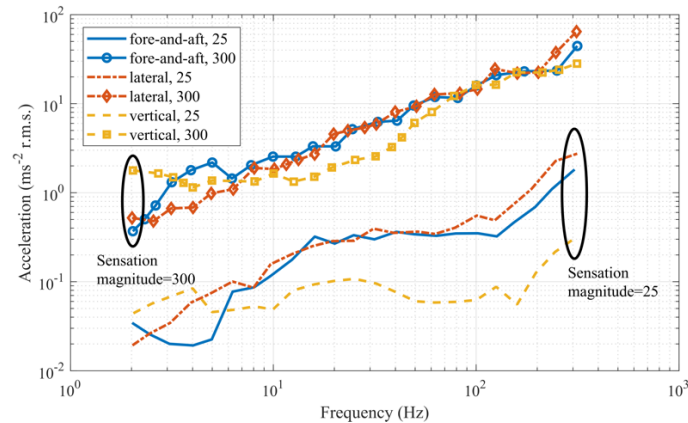


Figure 2. Equivalent comfort contours for sensation magnitudes of 25 and 300. Figure adapted from Fig. 7. In (Morioka and Griffin, 2006).

Morioka and Griffin (2006) concluded that in the frequency range between 10–20 Hz, human sensitivity to vertical vibrations grows more slowly as the vibration level increases. They indicated that the frequency of greatest discomfort also decreased with increasing vibration level. Arnold and Griffin (2018) attributed the change in human sensitivity to vertical vibration at various vibration levels partially to differences in the affected human body parts. As the vibration level increased, discomfort became more significantly associated with the shoulders and chest, while discomfort in the ischial tuberosities and lower thighs was considerably reduced.

Human sensitivity to horizontal vibrations depends also noticeably on the magnitude of the vibration. Morioka and Griffin (2006) showed that the equivalent comfort contour at a low vibration level followed a pattern similar to that of the threshold of perception. At high vibration levels, human sensitivity decreased significantly as frequency increased. They also found that the frequency of greatest sensitivity to horizontal vibration increased as the vibration level increased. Arnold and Griffin (2018) found that the contact areas between human body and the seat pan were always the body parts most affected by horizontal vibration due to the limited transfer of vibration to the upper torso; this resulted in small changes in sensation as magnitude increased.

Arnold and Griffin (2018) studied the differences in human sensitivity to the vibration in different directions. Below 2 Hz, there was little variation in human sensitivity to vibrations among the three directional axes. Above 4 Hz, human sensitivity to vertical vibration was generally greater than sensitivity to horizontal vibration. As frequency increased, human sensitivity to horizontal vibrations was greater than that to vertical vibration. This was partially attributed to differences in the body parts that were predominantly affected. When exposed to horizontal vibrations, the shear movement between subjects and the seat pan is the major cause for degraded comfort. This type of vibration is not transferred to the upper torso to a significant degree, and thus the location of discomfort does not change notably as the vibration increases in magnitude. In contrast, when exposed to vertical vibrations, the

most affected body parts are not the contact areas but rather the upper torso, which is the major reason for human's higher sensitivity to the vertical vibration magnitude.

The subject's posture and orientation have significant effects on the perception of vibration discomfort. Morioka and Griffin (2006) concluded that the frequency of greatest sensitivity varied significantly as posture changes. Biodynamic responses also differ depending on the subject's orientation, e.g., sitting upright (Toward and Griffin, 2011), lying down (Toward and Griffin, 2009) or driving (Rakheja et al., 2002).

Rakheja et al. (2002) found that drivers exhibited two discernible resonances in vertical apparent mass (APMS) between 5–8 Hz and 8–12 Hz, while passengers' vertical APMS showed a single resonance at 6–9 Hz. The primary resonance frequency and the corresponding magnitude were lower for drivers than for passengers. The additional distinct resonance in a driving posture might be attributed to the greater relative motion in the hand and arm for subjects who are sitting with their hands on the steering-wheel.

Human response to vibration also depends on backrest inclination. Basri and Griffin (2012) found that increasing the backrest inclination decreased human sensitivity to vertical vibrations, especially at resonance frequency. When the backrest was set to an angle greater than 60°, human sensitivity was lower than it was with no backrest. The authors explained this finding in part by the fact that as the backrest inclination increased, the most affected body parts changed from the buttocks and thighs to the back and shoulder.

Unlike the findings for seated subjects, Huang and Griffin (2009) found that for recumbent subjects, sensitivity to vibration in the back was relatively low compared to sensitivity in other body parts. This finding was mainly associated with the biodynamic responses of soft tissues, especially the abdomen. Matsumoto and Griffin (1998) studied the biodynamic responses of standing subjects and found that the principal frequency of vertical APMS was similar for standing subjects and seated subjects, which implied that the dynamic mechanisms of the upper body were similar in both orientations.

Toward and Griffin (2011) found that inter-subject variables such as age, gender and anthropometry had a significant influence on the perception of vibration discomfort. Additionally, the effect of these inter-subject variables on human sensitivity was affected by vibration magnitude. They found that the resonance frequency and the corresponding peak magnitude of vertical APMS increased with age. Osvalder et al. (2019) found that the seniors were more forward-leaning than other subjects when sitting in a passenger car.

Toward and Griffin (2011) indicated that vibration magnitude had a greater influence on males than on females. This may have been, in part, because males had greater body weight supported by the reclined backrest. Even if the differences in anthropometry was eliminated, differences between genders are still noticeable. From their study, males had a higher normalized APMS at the resonance frequency of vertical APMS, regardless of whether or not they had a backrest.

Toward and Griffin (2011) found that vertical APMS was considerably affected by body weight at resonance frequency. Nevertheless, the normalized AMPS at resonance frequency was not significantly affected by body weight except at the highest body weights. However, they did not indicate a specific threshold body weight beyond which this variable had a significant effect on normalized AMPS. They also found that the resonance frequency in vertical APMS decreased as BMI increased, especially when subjects were sitting with a backrest. They partially explained this finding as reflecting the fact that subjects with higher BMIs were more weakly coupled to the backrest, and thus, the stiffness of the body was reduced.

2.2 Vibrations in real automotive vehicles

Vibration levels on the seat, floor and steering wheel are influenced by road profile, driving speed and type of vehicle. Adam and Jalil (2017) found that vibration on the floor was generally greater than

vibration in the seat of the same car. When driving at high speed or on rough roads, vibration transmitted to the seat, backrest and steering wheel was greater in the vertical (Kaderli and Gomes, 2015) and lateral (Lin et al., 2006) directions than in the longitudinal direction.

The highest vibration in the seat was identified at the contact areas between the seat and the human body, including locations beneath the knee (Mansfield, 2001), at the back of the thighs (Wu et al., 1999) and on the buttocks (Kilincsoy et al., 2016). Significant vibration transmission to the vehicle seat was mostly concentrated below 20 Hz in the lateral and vertical direction (Griffin and Erdreich, 1991) and below 30 Hz in the longitudinal direction (Nawayseh, 2015).

Rakheja et al. (2002) indicated that in passenger cars, backrest inclination and seat height can alter the angle between the upper and lower body and change the passenger's knee height. They also found that the driver's choice of steering-wheel grip posture led to other positional differences.

The results of Van Veen et al. (2015) showed that macro-movements (frequent and distinct changes of posture) could enhance perceived comfort due to the pleasant stimulation of tactile sensation. Beach et al. (2005) suggested that macro-movements to reduce discomfort, especially when seated for long periods of time. They also noted that posture variation was more frequent in a stationary car than in a moving one.

Kyung and Nussbaum (2009) found that driving postures also differ according to age, gender and anthropometry. The angles of the right elbow, left hip, right hip (Kyung and Nussbaum, 2009), and spine (Bohman et al., 2019; Osvalder et al., 2019) differed significantly between younger and elderly groups in a passenger car. Kyung and Nussbaum (2009) concluded that gender had a considerable effect on the angle of the left elbow while driving and that body height influences the angles of the left ankle, left hip and neck.

2.3 Influence of sound on ride comfort

Sound has been associated with human comfort and well-being (Fastl and Zwicker, 2007). Sound has been highlighted in the studies of ride comfort in modern passenger cars due to the noticeable reduction in overall sound pressure levels and the increasing demand for sound quality (Sheng, 2012).

Accumulated experimental results have agreed that people associate the equivalent A-weighted sound pressure level with sound annoyance (Berglund et al., 1976; Berglund et al., 1990; Beutel et al., 2016), especially when a sound first starts (Dickson and Bolin, 2014). Nonetheless, many studies (Fastl and Zwicker, 2007; Moore, 2012) have pointed out that the commonly applied A-weighting does not properly represent the human response to complex sounds. Previous studies have concluded that humans' perception of sound is influenced by the time variation of sound (Ishiyama and Hashimoto, 2000), the energy of its low frequency components (Nilsson, 2007) and the sound characteristics (Fastl and Zwicker, 2007).

Figure 3 illustrates the human response to sounds, including the process of human auditory and cognition systems (Fastl and Zwicker, 2007; Moore, 2012). Fastl (2006) noted that assessments of sound were usually based on measurements of physical variables such as frequency, sound pressure level, measured loudness and sharpness. However, the ultimate evaluation and impression of a sound was "filtered" by the human auditory and cognitive systems. Subjects judge a sound according to their sensation. Therefore, the measurements of physical magnitudes should be mapped with psychoacoustic magnitudes: for instance, auditory loudness, sharpness, fluctuation strength and roughness. Based on these psychoacoustic variables, the power, tone colour and temporal structure of sounds can be correlated to listeners' perception, including the annoyance, speech intelligibility, sleep disturbance and impairment to cognitive performance (Fastl, 2006). Human responses to sound have shown to be dependent on inter-subject variations such as age, gender (Stelrnachowicz et al., 1989) and individual psychological factors such as expectations and experiences (Skagerstrand et al., 2017).

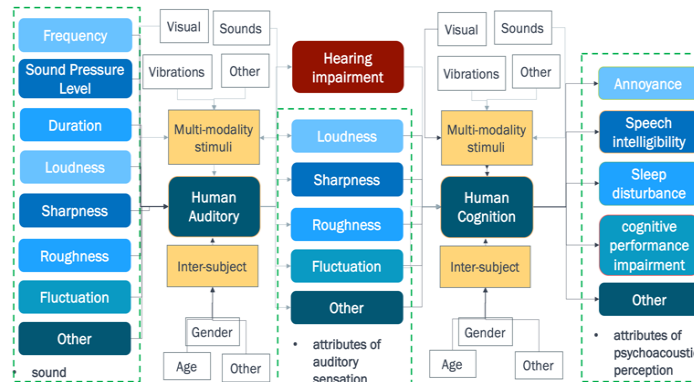


Figure 3. The factors that affect human perception of degraded comfort due to sound.

Sound annoyance has been related to disliking the source, distraction (Guski et al., 1999), unpleasantness, exhaustion (Öhrström et al., 2006), sleep disturbance and other stress-related symptoms (Bakker et al., 2012). Jeon et al. (2010) suggested that perceived sound discomfort was strongly related to annoyance, which in turn depended on properties such as sound level, frequency spectrum (Ouis, 2001), loudness, sharpness, fluctuation strength (Hall et al., 2013) and the context of the sound (Genell et al., 2006), together with the listener's attitude toward the sound (Ouis, 2001) and the general condition of the subject (Genell et al., 2006).

Takahashi et al. (2002) argued that low-frequency sounds could evoke noticeable annoyance and discomfort. Subedi et al. (2005) found that as the sound pressure level increased, the growth rate of annoyance was higher at lower frequencies than at higher frequencies. This could be because low-frequency sound caused additional vibrations in parts of the human body such as the chest (Pelmeur and Benton, 2003) and abdomen (Takahashi et al., 2002), which aggravated the perception of annoyance (Takahashi et al., 2002).

The balance between high-frequency and low-frequency sound showed also effects on the perception of annoyance. Genell et al. (2006) concluded that listeners were more annoyed by sounds that lacked higher frequencies than by sounds with balanced frequency content.

Alayrac et al. (2011) indicated that the judgments of pure tones were weaker than those of broadband noise. Subedi et al. (2005) showed that the differences (most of the time as an increase) between annoyance caused by combined tone components and by pure tones depended on the differences in level and separation of frequencies within the complex tones. Sounds of energy dominated by low frequencies were evaluated as more annoying for broadband noise (Persson Waye and Rylander, 2001) and less annoying for pure tones (Subedi et al., 2005).

Sound annoyance increases as a function of sound pressure level (Skagerstrand, 2017) and rises particularly quickly under exposure to low-frequency sound (Leventhall, 2004). Ishiyama and Hashimoto (2000) found that sound annoyance grew more quickly as sound pressure level increased when exposed to sound above 60 dB(A). The results from Skagerstrand et al. (2017) suggested that there was a correlation between “comfortably loud/not annoying”, “slightly annoying” and “very annoying” and sounds with a SPL between 48–55 dB, 56–65 dB, and above 79 dB, respectively.

A study by Skagerstrand et al. (2017) found that sound annoyance increases as a function of loudness. Both the mean (Glasberg and Moore, 2002) and the maximum loudness value (Zorilă et al., 2016) have been suggested as indicators of annoyance caused by temporal varying sound.

The most crucial factor in sound annoyance, apart from loudness, was found to be sharpness (Fastl and Zwicker, 2007). A study by Ishiyama and Hashimoto (2000) observed that when loudness remained constant, annoyance increased as sharpness increased. Sounds with frequencies above 1000 Hz were

rated as more annoying than sounds with frequencies below 1000 Hz. The effect of sharpness on annoyance also became more notable as sound pressure level increased.

Jeon et al. (2011) concluded that tonal sounds were rated as more annoying than untuned sounds. Landström et al. (1995) found that the annoyance increased as tonal components increased and decreased as tonal components were reduced. In addition, the effects of tonal components on annoyance were influenced by the sound pressure level. The study by Dickson and Bolin (2014) found that a reduction in tonal components had a more significant effect on instantaneous annoyance than did amplification of tonal components.

The results of Moorhouse et al. (2008) showed that fluctuation strength and roughness led to changes in annoyance even when loudness remained constant. Di et al. (2011) indicated that an additional frequency modulated sound had a notable effect on the perception of annoyance. In their study, annoyance decreased as the modulation frequency increased while the central frequency remained the same. Moreover, sound annoyance increased as the modulation sound pressure level increased (except for sounds below 30 dB).

Human perception of sounds encompasses not only the sensory domain but also cognitive and emotional aspects (Zeitler et al., 2004). This study concluded that the meaning of a sound influences the evaluation of it. In a study by Wolfgang et al. (2004), sounds with an unidentifiable meaning were rated as more annoying. Yang and Kang (2005) found that sounds identified as coming from a pleasant source were judged as less annoying even though they had a higher sound pressure level. Adding nature sounds may lower perceived sound annoyance (Jeon et al., 2010) and perceived loudness (Bolin et al., 2010). Among the added nature sounds – including waterfalls, rain, streams, waves on a lake, birds, insects, church bells and wind – the additional of water sounds showed the strongest reduction in annoyance if the sound pressure level of the water sounds was similar to or not less than 3 dB below the SPL of urban noises (Jeon et al., 2010).

Expectations about a sound have also been shown to effect on assessments of loudness and annoyance (Skagerstrand et al., 2017). Participants whose activities are dependent on the sound were less annoyed by that sound (Miedema and Vos, 1999). For example, subjects rated the sound of moving vehicle over a rough road less annoying when they were vehicle occupants than when they perceived the sound in an apartment (Genell et al., 2006).

Janssen et al. (2014) investigated the influence of demographic variables such as gender on perceived sound annoyance. They found that demographic variables had little influence on annoyance caused by a steady sound. Similarly, another study (Laszlo et al., 2012) found no significant differences in annoyance between women and men.

The results of Yang and Kang (2005) indicated that there were some differences between teenagers and senior groups with higher discomfort and annoyance being reported by the teenage participants. Senior subjects reported less annoyance from nature and human activity sounds. Moorhouse et al. (2008) concluded that the annoyance caused by a fluctuating low-frequency sound increased with the subject's age.

2.4 Sound in real automotive vehicles

Qatu (2012) categorized vehicle interior noise according to various root causes: powertrain/driveline noise, tyre noise, wind noise, brake and chassis noise, squeak and rattle, and electromechanical sounds. Zeitler and Zeller (2006) concluded that experienced sound discomfort in a vehicle was dominated by sound at constant speed and wind noise. In addition, engine sound contributes significantly to perceived noise during acceleration and has been associated with the sportiness of the vehicle. Without the masking effect of the combustion engine, noises caused by components such as tyres, the gearbox and the HVAC system become more audible and may induce annoyance (Sarrazin et al., 2012).

1) Tyre noise

Sandberg and Ejsmont (2002) found that at speeds between 30–100 km/h, tyre noise dominated the interior sound in passenger cars, especially under cruising or partial throttle conditions. And a study by Sandberg (2001) indicated that tyre noise increased as a function of speed. The study indicated that in electric vehicles, powertrain noise was lessened and thus tyre noise became an increasingly significant contributor to total noise, even at lower speeds.

Hoffmann (2016) identified two main sources of tyre noise: tyre vibration and air pumping. The study indicated that tyre vibration was caused by variation in the geometry of the contact areas between the tyre and the road. Vieira (2020) showed that the noise caused by tyre vibration covered a wide frequency range, 100–1200 Hz. The low-order modes of tyre noise caused by time-varying contact shape dominated the radiated sound in the range of 1000 Hz (Kropp et al., 2012). Interference between air and the tyre surface pipes, as well as tyre tread, also produced noise that ranged from 600 to 2500 Hz (Vieira, 2020). Feng et al. (2009) observed a pattern of sharp peaks in the 190–250 Hz frequency range in the noise generated by tyre cavity resonance. The peak frequency of cavity noise showed dependency on tyre load and vehicle speed in the study of Qatu et al. (2009). Feng et al. (2009) explained this dependency by the fact that the load on the tyre broke the symmetry of the tyre under rolling conditions.

2) Wind noise

Talay and Altinisik (2019) concluded that as driving speed increased, the structure-borne noise became less significant compared to airborne wind sound generated by airflow around the vehicle. Qatu et al. (2009) found that wind noise usually dominated interior noise above 90 km/h. Talay and Altinisik (2019) indicated that sound pressure level of perceived wind noise at the driver's left ear increased as frequency increased up to around 1000 Hz and then dropped significantly as a function of frequency. The results of Ying-jie et al. (2019) showed that wind noise transmitted from the front side window was greater than that transmitted from the rear side window at most frequencies. The peak noise level contributed from the front side window occurred at around 260 Hz, while the peak noise level from the rear side window occurred at around 200 Hz.

3) Powertrain/driveline sound

Qatu et al. (2009) indicated that powertrain sound was noticeable under all driving conditions in combustion-engine cars. Their study demonstrated that powertrain noise could be more significant than tyre noise at speeds below 40–50 km/h. In some scenarios, such as idling, cruising and coasting, occupants expected to hear powertrain sounds. Most interior powertrain noise was between 50–80 dB(A) for passenger cars and 50–85 dB(A) for midsize SUVs.

Lennström and Nykänen (2015) concluded that driveline sound in electric cars differed significantly from that of combustion cars. Low-frequency firing orders, mechanical noise and engine noise in combustion cars have been replaced by high-frequency tones that generated by electromagnetic forces and gear meshing. They indicated that driveline sound in electric cars was usually of a lower level but perceived as more annoying than the powertrain sound of combustion cars.

4) Other sounds

There are a variety of other sounds that can be perceived in passenger cars, such as HVAC noise. The influence of HVAC noise on ride comfort and perceived quality also depends on changes in the vehicle's interior thermal comfort due to the interaction of perceptions of thermal and acoustic comfort (Roussarie et al., 2005). Loudness, sharpness, prominence, spectral composition and tone-to-noise ratio have been found to be important psychoacoustic models to characterize the perception and quality of HVAC noise (Leite et al., 2009).

Qin et al. (2020) found that structure-borne sound related to the combustion-engine firing cycle at 20–200 Hz was the dominant cause of sound annoyance during start/stop. In electric cars, the sound of start/stop has usually been distinctly designed to carry notification information (Frank et al., 2014).

2.5 Interferences between different factors

The human perception of discomfort is also affected by simultaneous stimuli (X. Wang et al., 2020). For instance, the subjective evaluation of simultaneous noise and vibration has been found to be interdependent (Huang, 2012; Leatherwood, 1979; Manninen, 1983). Vibration can reduce the discomfort caused by lower levels of sound (Huang, 2012) and vice versa (Manninen, 1983). The study of Huang (2012) showed that the masking effect of vibration on sound decreased with as exposure duration increased, while the masking effect of sound on vibration did not appear to depend on the duration of exposure .

Vibration and seat exhibited combined influence on experienced ride comfort. Kamra et al. (2017) demonstrated that the seat stiffness providing comfort under static conditions might cause discomfort under dynamic conditions. Therefore, it is difficult to achieve an optimal balance between static and dynamic seat comfort (Kamra et al., 2017). Mansfield et al. (2014) suggested that the experience of seat comfort might vary under different vibration conditions due to the different response of the seat cushion and backrest (Mansfield et al., 2014). Several studies have shown that the transmission of vibration to the human body in a passenger car is influenced by the seat (Corbridge et al., 1989).

Chapter 3 Methodology

This chapter introduces the methods used to conduct the literature search and the user study. Scientific journals in relevant areas of sound and vibration, ergonomics, vehicle NVH, biomechanics, and industrial health for vibration and comfort were searched. Then, a user study was conducted to investigate the experiences of occupants and their corresponding causes, including both subjective assessment and objective measurements, with a focus on the influence of sound and vibration.

The user study included ten participants experiencing eight typical driving scenarios in both a CV and an EV. Subjective data was collected using questionnaires after each scenario and by a semi-structured interview after all scenarios in each car. Objective data on sound and vibration were measured using microphones and accelerometers and analysed for each scenario. The test cars, test tracks, test scenarios and demographic data of the participants are described in greater detail in Paper B and Paper C.

3.1 Subjective data collection

The five-point scale used in the user study consists of a semantic scale and a self-assessment manikin (SAM) scale. Semantic scaling has been widely used to rate stimuli according to the differing extent to which they are perceived during exposure (Carroll et al., 1959). This method has advantages for analysing whether the stimuli are suitable to convey an intended message (Fastl, 2006). Both unipolar (e.g., “not annoyed at all” to “extremely annoyed”) and bipolar (e.g., “calm” or “alert”) semantic scales were used in the current study depending on the variable of interest. The SAM scale was developed to directly assess emotional responses to an object or event. The SAM scale ranges from a smiling figure to a frowning figure for the pleasure dimension and from a wide-eyed figure to a sleepy figure for the arousal dimension. For the control dimension, a larger manikin indicates stronger control. The self-assessment manikin (SAM) has been widely used to measure emotional responses in picture-orientated questionnaires. Compared to descriptive rating methods, SAM has the advantage of being easy and consistent to interpret in the context of what emotions are developed, especially when assessing sound (Bynion and Feldner, 2017). In this user study, only the valence dimension (positive or negative) and arousal dimension were assessed.

The ranking order method was used due to its suitability when making relative comparisons of several stimuli in relation to a given parameter, such as annoyance or discomfort. Namba and Kuwano (2008) suggested that this method could be useful for analysing minor differences between stimuli. In the user study, factors were ranked according to their influence on perceived ride comfort.

The semi-structured interviews were used to collect participants’ experiences in each scenario, as well as the causes of the perceived sound and vibration annoyances. The interview included general and specific questions, as shown in Table 5 of Paper B. The interview began with general questions on perceived comfort and discomfort. The interviewer then posed specific questions for each scenario regarding perception of sound, vibration and induced body movements, leading to further discussion of the causes for comfort or discomfort, the perceived characteristics of sound and vibration, the concordance between sound and vibration, perceived motions in the test car and induced body movements. To fully understand the participants’ experiences, the interviewer always followed up with additional probing questions. Participants were allowed to refer to the questionnaires and raise additional issues in the interview.

3.2 Subjective data analysis

Each participant’s ratings of annoyance caused by sound and vibration, as collected in the questionnaires, were used to analyse experienced sound and vibration. The sound ratings (positive-negative and alert-calm) collected on the questionnaires were compared for all scenarios in each car. The ratings from the questionnaires regarding the relative movement of various body parts, as well as

the concordance between sound and vibration, were investigated for different scenarios and for each of the cars.

The subjective data collected in the interviews, such as the causes of discomfort, were categorized as related to sound, vibration, discordance between sound and vibration and induced body movement. Annoying sound and vibration were further classified according to their characteristics. The number of participants who commented on each category was summarized.

3.3 Objective data collection

Instantaneous sound and vibration were measured during the different driving scenarios. Figure 2 in Paper B shows the locations of the sound and vibration sensors inside the cabin. Sound was measured at the front passenger's left ear. Accelerations of the seat rail and armrest were measured using accelerometers. Table 6 in Paper B lists the details of the accelerometers and microphones used. The sound was measured at sampling frequency of 25600 Hz. Vibration was measured at a sampling frequency of 1024 Hz. The participants' body movements were collected through observations using two cameras mounted inside the car, as shown in Figure 2. Lower body movement was recorded using a camera installed in the sun visor above the driver. Upper body movement was recorded by a camera installed in front of the participant.

3.4 Objective data analysis

The A-weighted sound pressure level of the sound measuring in each test scenario was calculated in one-third octave bands in the range of 20–10000 Hz. The frequency range for the analysis was selected to cover the range of human hearing with significant sound level. During start/stop (Scenario 2), the first-time engine switching on/switching off was analysed because in the EV, only first-time switching on/switching off was accompanied by designed intentional sound. For accelerating and decelerating (Scenarios 3-1 and 3-2), the first period of acceleration or deceleration period was analysed. For the scenarios of constant speed (Scenarios 4-1 and 4-2), long bumps and cornering (Scenario 6) and rough roads (Scenario 8), the last ten-second sound was selected. For the sound during speed bumps (Scenario 5) and bridge joints (Scenario 7), the sound of the last impact was analysed. The overall A-weighted sound pressure level of each scenario was calculated for the entire duration of the scenario assessed.

The frequency spectrum of vibration was analysed by applying a Fourier transform. Vibration was analysed between 0.5–50 Hz to cover significant vibration transmitted to the seat and armrest with high human sensitivity. The selected vibration signals were correlated with the selected sound components.

Participants' body movements were observed on the recorded video by the same observer and classified as either active movement or induced movement. Active movement included both conscious and unconscious posture changes. Induced body movements were body movements observed to be caused by the vibration of the car. These were divided into lateral upper body movement, lateral lower body movement and longitudinal upper body movement.

Chapter 4 Experienced ride comfort in a combustion engine car

The occupants' experiences were analysed in association the measured sound and vibration to understand the influence of sound and vibration on overall ride comfort in a CV. The overall results show that static comfort was mainly influenced by ingress, sufficient room, seat adjustment and seat support. Dynamic discomfort was affected by induced body movement, distinct vibrations in body parts and annoying sounds.

4.1 Static comfort

As Figure 4 shows, enough room was of the greatest importance in the presence of static comfort. In the interviews, three participants (P1, P2, P6) reported insufficient legroom and four participants (P3, P4, P6, P8) reported insufficient upper body room because their knees or elbows touched the centre console. In the interviews, participants attributed the experience of relaxation when seated to adequate seat support, seat dimensions, seat contour and seat stiffness.

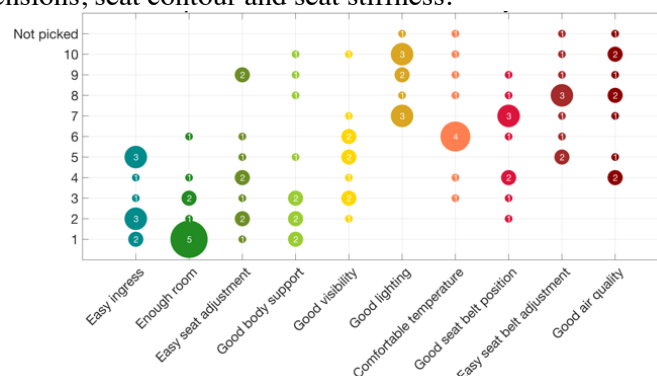


Figure 4. Ranking of factors influencing initial comfort in the stationary CV. The full descriptors are listed in Table 6 of Paper B.

4.2 Dynamic discomfort

Figure 5 indicates that dynamic discomfort in the CV was mainly caused by “not enough support”, “hard to relax” and “not enough room”. Participants associated these three experiences with induced body movement, distinct local vibration, annoying sound and discordance between sound and vibration.

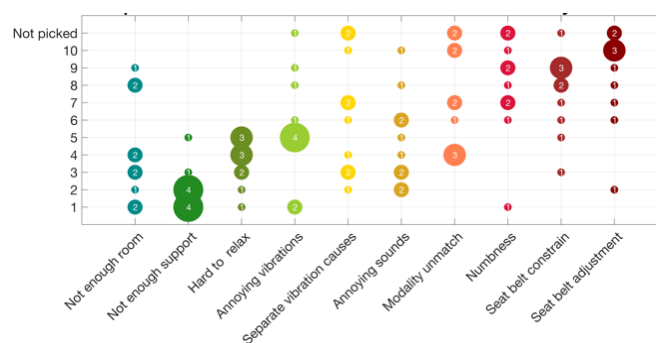


Figure 5. Rankings of factors influencing discomfort in scenarios 2–8 in the CV. The full descriptors are listed in Table 7 of Paper B.

4.3 Experienced sound and sound annoyance

As summarized in Table 6 in Paper B, tyre noise and wind noise were the main causes of perceived discomfort in the CV at low to medium speeds (20–80 km/h) and at higher speeds (above 80 km/h). In the interviews, participants commented that loudness and low frequency were the characteristics of tyre noise that caused annoyance. Participants also reported that sharpness, loudness and fluctuation strength were the characteristics of wind noise that induced annoyance.

During start/stop, sound developed from silent to audible low-frequency sound. There were notable low-frequency components in the measured sound. These low frequencies were attributed to rigid body resonances in the car induced by the engine starting.

As Table 6 of Paper B shows, all participants reported that engine sound and tyre noise grew louder as speed increased from stationary to 50 km/h. In the interviews, participants commented that the sound indicated increasing speed and that they did not find it annoying. Wind noise was the major sound when accelerating from 50 to 100 km/h. Five participants (P2–P4, P6, P7) reported noting wind noise in this scenario. The maximum value of fast averaging A-weighted sound pressure level (L_{pAFmax}) identified an increment of 8 dBA when speed increased from the 0–50 km/h range ($L_{pAFmax} = 60$ dBA) to the 50–100 km/h range ($L_{pAFmax} = 68$ dBA).

At a constant speed of 120 km/h, wind noise and tyre noise were the main audible sounds reported. From the comments listed in Table 6 of Paper B, three participants (P2, P4, P8) attributed sound annoyance to fluctuating and loud wind noise at 120 km/h. When the driving speed was lower (constant speed of 60 km/h), six participants (P1, P2, P4, P5, P7, P8) judged the sound as less annoying than that during a constant speed of 120 km/h. In the interviews, participants attributed the decrease in their perceived sound annoyance to the decrease in perceived sound pressure level and wind noise. The equivalent A-weighted sound pressure level was 71 dBA at 120 km/h and 65 dBA at 60 km/h. The participants judged the sound at 60 km/h more positive than the sound at 120 km/h, as Figure 6 shows. In the interviews, participants attributed this to the reduction in sound pressure level and in high-frequency components.

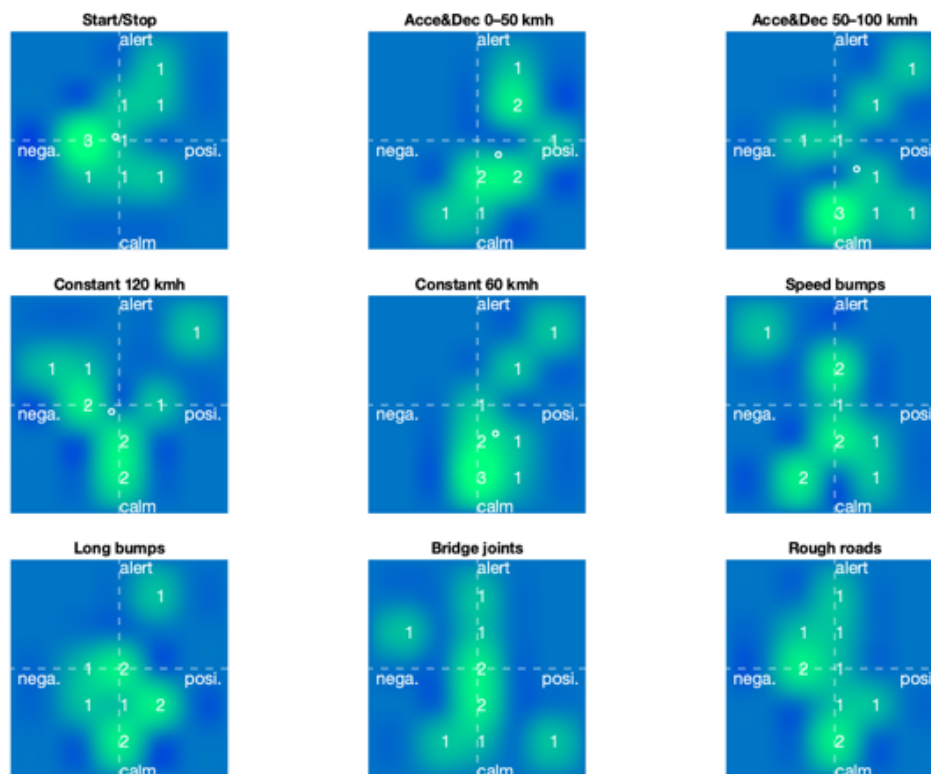


Figure 6. Sound characteristics in the CV (N = 10). The horizontal axis represents how positively or negatively the sounds are perceived. The vertical axis represents the level of activeness or calmness of the sounds. The white circle represents the average value.

As Table 6 of Paper B notes, participants noted loud tyre noise when the car went over bumps. The objective measurements identified an increment of around 12 dBA in sound levels before and at impact (the maximum A-weighted sound pressure level of 68 dBA at speed bumps and 56 dBA between bumps). Three participants (P1, P6, P10) rated the impact sound as negative (see Figure 6, Paper B). In the interviews, participants attributed this negative perception to enduring tones after impact.

When driving over long bumps and cornering, eight participants (P1, P4, P5–P10) commented that they focused less on sound due to experiencing pronounced body movement. Six participants (P1–P3, P5, P6, P8) rated the sound as calming (see Figure 6).

Four participants (P1, P2, P4, P8) noted that the impact sound from driving over bridge joints was loud and annoying. The variation in the maximum sound level between the impact sound and sound before/after impact identified an increment of around 14 dBA.

In the rough road scenario, eight participants (P1, P2, P4–P6, P7, P9, P10) commented that they focused less on sound due to their perception of vertical bouncing and lateral body movement. However, five participants attributed their difficulties in relaxing in their seats to wind noise (P1, P4, P8, P6), low-frequency engine sounds and rough tyre noise (P6, P7).

4.4 Experienced vibration and vibration annoyance

At lower driving speeds, participants associated vibration discomfort in the CV mostly with low-frequency lateral and longitudinal oscillations (see Table 7 of Paper B). When braking from 60 km/h, four participants (P1, P3, P4, P8) reported longitudinal oscillations. The oscillations were more noticeable at higher speeds than at lower ones (P1, P3, P4, P8). This accounted for greater vibration annoyance at higher speeds. When driving over long bumps, nine participants (P2, P6–P8, P10) reported difficulty in relaxing and attributed this to lateral body movement.

The participants felt that visual input from the environment helped them to establish their expectations for vibrations and therefore attenuated their annoyance with the expected body motion. For instance, occupants expected some bouncing if they saw a large bump coming up. Occupants were thus more annoyed by horizontal motion, especially lateral motion. Longitudinal oscillations also caused discomfort. Participants commented on longitudinal oscillation mainly in context of shaking after an event, such as deceleration, braking or impact.

In this study, only two participants used the armrest, and both reported discomfort caused by distinct vibration transmitted through it. This might also be confirmed by peak vibration measured at the armrest in the range from 16 to 30 Hz. Thus, other participants might have perceived distinct vibration from the armrest and experienced discomfort as a result if they had used the armrest during the ride. The recorded videos showed that adjustments in arm position (observed for P1–P4, P8, P9) increased more noticeably during the scenario long bumps and cornering than in other scenarios.

In the interviews, participants noted that discordance between sound and vibration was an important cause of dynamic discomfort, especially when driving over bridge joints. Participants mentioned that they naturally preferred less sound and vibration when riding. Nevertheless, they would rather experience concordant sound and vibration levels during impacts than louder sounds with less vibration.

It is interesting to note that experienced sound and vibration interfere with each other. For instance, passengers focused less on sound when they experienced pronounced body movement caused by vibration (Scenario 6 and 8). However, eight participants commented that annoying sounds still made it difficult to relax whilst seated and aggravated overall discomfort.

4.5 Other factors that influence ride comfort and discomfort

In this study, seat dimension and seat contour had different effects on occupants' experience depending on whether the car was stationary or in motion. In a stationary car, the majority of participants reported insufficient seat length. They therefore perceived insufficient longitudinal seat support when the car was stationary. When the car was in motion, longitudinal seat support was rated as more insufficient and was an aggravating factor in dynamic discomfort.

Moreover, the indicators that participants used to judge seat comfort were different for static versus dynamic conditions. In static situations, occupants attributed their experience of seat comfort to the combined effects of seat stiffness, dimensions and contour. For instance, insufficient seat length and soft foam resulted in improper distribution of contact pressure, causing discomfort in the stationary car. Insufficient seat width and the wing angle of the seat bolster caused static stress on the sides of thighs and corresponding discomfort. Under dynamic conditions, judgements of seat support focused on upper body movement and legroom. Participants attributed lateral upper body movement to insufficient upper body support, even though the distances moved were not pronounced. Discomfort caused by insufficient lower body support was mostly reported for larger movement (e.g., when the knees knock against the car door or centre console).

A variety of factors influenced overall perceived ride comfort (such as seatbelt and temperature issues) but were not a topic of focus in the current study. In this study, the seatbelt constraint was assessed in the questionnaires for both stationary and driving scenarios. In their interview reflections, however, participants did not judge the seatbelt constraint as annoying. This might be because all participants were accustomed to the feeling of seatbelt constraint from everyday passenger experiences.

Air temperature was judged to be of least importance when ranking influences on static comfort. This could be because the air temperature was controlled to be around 21 °C for all participants. During the test ride, participants did not report discomfort caused by temperature.

Chapter 5 Experienced ride comfort in an electric car

In the EV, the influences of sound and vibration differed among the various driving scenarios. Factors contributing to static comfort were ranked similarly in the EV and the CV in terms of their contribution to comfort. The overall results indicated variation in dynamic discomfort between the CV and EV: dynamic discomfort was mainly attributed to “insufficient support” in the CV but “annoying sound” in the EV.

5.1 Static comfort

In the EV, as Figure 7 shows, “Enough room”, “Easy seat adjustment”, “Easy ingress” and “Good body support” had a strong influence on initial comfort, similar what was found in the CV. Four participants (P2–P5) reported that they did not get enough support from the backrest because the bolster was too wide at chest level.

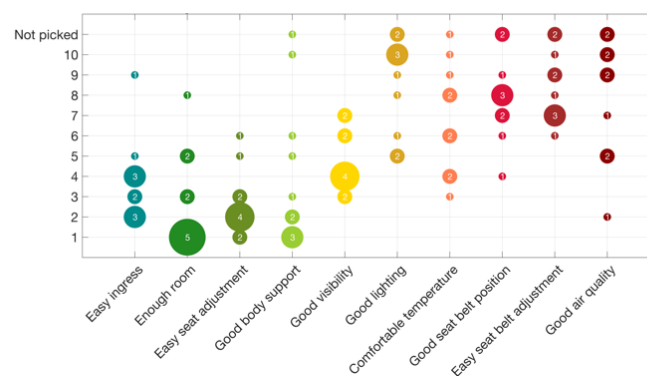


Figure 7. Ranking of factors influencing initial comfort in the stationary EV. The full descriptors are listed in Table 6 of Paper C.

5.2 Dynamic discomfort

As Figure 8 shows, dynamic discomfort in the EV was mainly attributed to “annoying sounds”. In the interviews, participants associated “not enough support” with upper body movement, distinct vibration, annoying sound and discordance between sound and vibration.

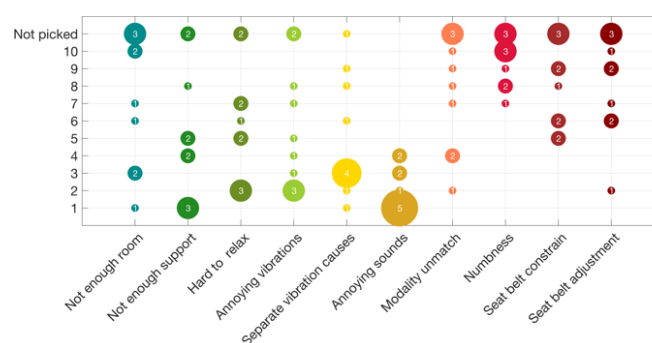


Figure 8. Ranking of factors influencing dynamic discomfort in the EV. The full descriptors are listed in Table 7 of Paper C.

Figures 3 and 4 in Paper C indicate that the annoyance caused by sound and vibration varied depending on the scenario, except P9 did not experience sound or vibration annoyance in the EV in any scenario.

For two scenarios, the instantaneous judgement of sound annoyance was clearly more pronounced for the EV than for the CV. For the scenario of acceleration and deceleration 0-50 km/h, six participants (P2–P6, P8) rated the sound in the EV as more annoying, while P1 reported that sound in the CV was more annoying. For scenario constant 60 km/h, eight participants (P1, P3–P8, P10) rated sound in the EV as more annoying, while P2 rated sound in the CV as more annoying.

The vibration annoyance was rated greater in the CV than in the EV in scenarios start/stop, acceleration and deceleration 0–50 km/h, acceleration and deceleration 50–100 km/h, constant speed 120 km/h and rough roads. During start/stop, six participants (P1–P4, P6, P8) judged the sound in the CV as more annoying. In scenario acceleration and deceleration 0–50 km/h six participants (P1–P4, P7, P8) judged the vibration in the CV as more annoying. Six participants (P2–P4, P6, P8, P9) rated the sound in the EV when accelerating between 50–100 km/h as less annoying. While driving at constant 120 km/h, six participants (P1–P4, P6, P8) judged the sound more annoying in the CV than in the EV. The scenario rough road showed the strongest difference, with eight participants (P1, P3–P9) rating vibration in the CV as more annoying and only one person rating the EV as more annoying.

5.3 Experienced sound and sound annoyance

Table 7 in Paper C shows that the sound annoyance in the EV was attributed to high-frequency tonal sounds from the electrical components.

Four participants rated the starting sound of both the CV and EV as annoying, as seen in the characteristics of sound (Figure 5 of Paper C). In the interviews, participants attributed this negative impression to the low frequencies in the CV and the sharp tones of the EV’s signature starting sound. The one-third octave band frequency spectra of the starting sound in the CV (Figure 9) identified a peak at around 25 Hz, related to the second-order vibration of the engine. The EV sound measurement detected several distinct high-frequency peaks in the one-third octave band frequency spectra.

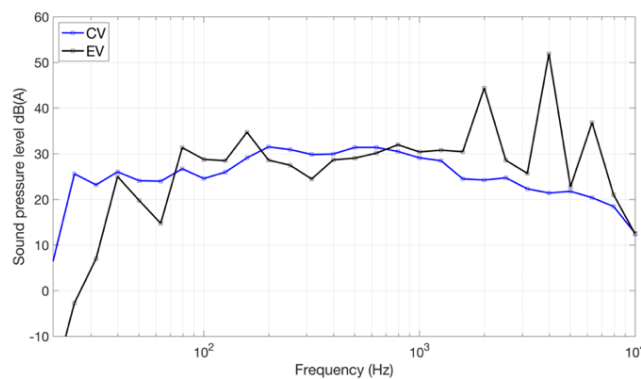


Figure 9. One-third octave band frequency spectra of A-weighted sound pressure levels in scenario start/stop in the CV and EV, respectively, for initial engine on/off (10s).

The sound ratings (Figure 3 of Paper C) also revealed that four participants (P2, P3, P5, P8) were annoyed by acceleration sound in the EV. In the interviews, they attributed their sound annoyance to the high-frequency tones from the electric motor at lower speeds and wind noise at higher speeds. Figure 10 shows distinct high-frequency tonal components. Six participants attributed sharp tonal sounds to their negative perception, as Figure 11 illustrates. Five participants judged the EV’s sound during acceleration between 0–50 km/h negatively (Figure 11).

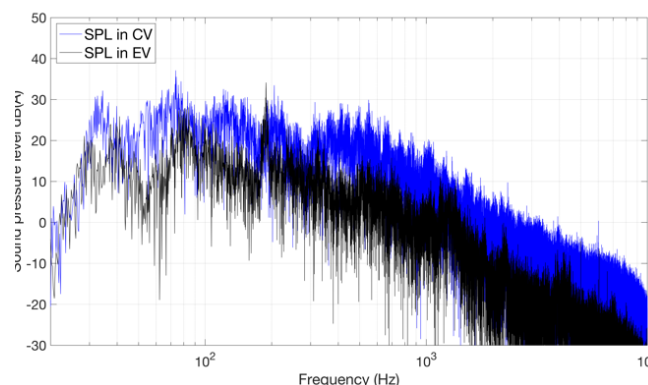


Figure 10. Narrow-band spectrum of A-weighted sound pressure levels in the scenario acceleration/deceleration 0–50 km/h in the CV and EV for the first acceleration and deceleration period.

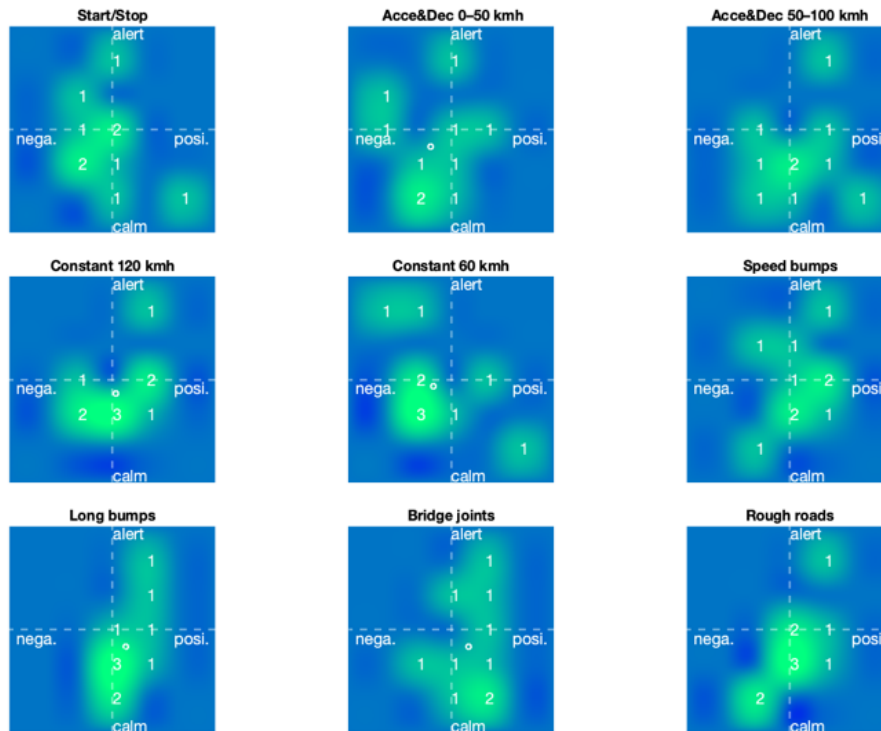


Figure 12. Sound characteristics in the EV. The horizontal axis represents how positively or negatively the sounds are perceived. The vertical axis represents the level of activeness or calmness of the sounds. The white circle represents the average value.

Participants commented that during acceleration between 50 and 100 km/h, high-frequency tonal sounds were less noticeable due to masking by wind noise. Therefore, the sound in the EV at higher speeds was less annoying (P2, P5, P6) and rated more positive (P2, P3, P5, P6, P10) than the sound during acceleration between 0–50 km/h, even if the maximum sound pressure level increased.

At 60 km/h, the sound in the EV was softer due to “the absence of wind noise and the reduction of tyre-road noise”. The equivalent A-weighted sound pressure level dropped by about 8 dBA as speed decreased. In the EV, sound annoyance decreased as speed increased. In the interviews, participants attributed this to high-frequency tonal sound from the electric motor, which became less noticeable when masked by wind noise at higher speeds (P1–P3, P8). Seven participants rated the EV’s sound at a constant 60 km/h more negatively than its sound at 120 km/h (Figure 12).

In the interviews, participants attributed perceived sound annoyance when driving over speed bumps to the loudness of the tyre impact sound. The measurements found about a 12 dBA increment in sound pressure level: The maximum sound pressure level was 44 dBA between the bumps and 56 dBA when going over them.

Six participants (P1–P5, P10) commented that the impact sound in the EV was loud and sharp when driving over bridge joints. The sound was rated as positive by six participants (Figure 12). Participants attributed this to the differences in sound pressure level and the low-frequency components of the sound in the CV. The measurements found that in the CV, the maximum sound pressure level was 63 dBA before/after impact and 77 dBA during impact. In the EV, the maximum sound pressure level was 59 dBA before/after impact and 73 dBA during impact.

5.4 Experienced vibration and vibration annoyance

Table 8 in Paper C indicates that vibration discomfort in the EV was attributed to induced body movement, which dominated the vibration annoyance that participants experienced.

In their rating of vibration annoyance (Figure 4 of Paper C), participants did not report rigid body resonances in the EV during start/stop. The measurements (Figure 9 in Paper C) detected mainly small-amplitude background noise in the EV.

In the interviews, participants attributed their difficulties with relaxing while sitting in both cars to the lateral body movement induced by car's pitching and rolling of the car during scenario 6 (long bumps and cornering) and scenario 8 (rough roads). These reported body movements were confirmed by the camera recordings. Figure 13 presents an example of lateral lower body movement.

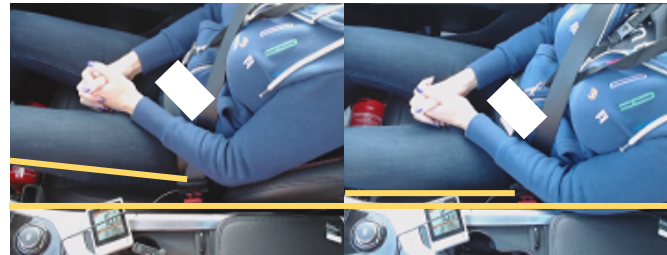


Figure 13. Example of lateral lower body movement.

Participants also reported that active posture adjustments helped them to maintain stability or reduce discomfort. Arm posture adjustments were observed in both the CV and the EV. Figure 14 shows two examples of participants' posture adjustments. The participant shown at the top of the figure relaxed his arms and hands on his thighs at the beginning of the scenario. He tried to grab the grab the car door for better stability when the rolling motion increased. The participant shown at the bottom of the figure changed his leg-crossing postures frequently to find a comfortable sitting posture.



Figure 14. Examples of active arm position (top) and variation in leg position (bottom).

In the EV, six participants (P1–P4, P6–P8) reported prominent lateral body movement during the scenario rough roads. In Figure 15, peaks in lateral vibration at the seat rail could be identified at around 2 Hz in the EV. Nevertheless, no participant reported that this motion and body movement caused annoyance. In the interview, participants associated this with visual input from outside the vehicle, which helped establish appropriate expectations for movement.

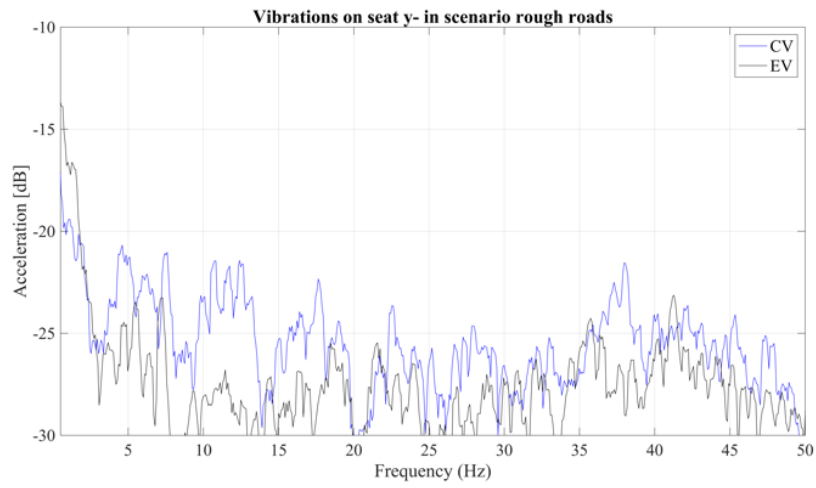


Figure 15. Lateral vibration at the seat rail on a rough road. The frequency resolution is 0.1 Hz. The reference value is 1 m/s².

Chapter 6 Analysis

This chapter analyses the results obtained from the literature reviews and the user study to identify variations in occupants' experiences of sound and vibration, as well as the resulting discomfort.

6.1 Comparison between the results from the literature studies and the user study

The participants' perception of discomfort was affected by simultaneous sound and vibration, a finding that supports the results of the literature studies. The influence of sound and vibration varied depending on the driving scenario.

In the CV, tyre noise was the main causes of perceived discomfort at low to medium speeds, and wind noise was the main cause at higher speeds. These findings confirm the conclusions of previous studies (Qatu, 2012). In the literature studies, engine sounds were more associated with the power and sportiness of a car and not with discomfort (Ih et al., 2009). This was also evident in the user study during start/stop and accelerating.

Previous studies have indicated that seated occupants are more sensitive to vertical and lateral vibrations in the frequency range below 30 Hz. Nevertheless, in the user study, vibration discomfort in the CV was most strongly associated with low-frequency lateral and longitudinal oscillation at lower driving speeds. The participants commented that visual input from the environment helped them establish their expectations for vibrational input and the resulting vertical body motion. For instance, occupants expected some vertical bouncing if they saw a large bump coming up. Thus, occupants were most annoyed by horizontal vibration, especially lateral vibration. Longitudinal oscillations were another cause of discomfort. Participants most often commented on longitudinal oscillations in the form of shaking after an event such as deceleration, braking or an impact. This indicates that the horizontal motion of the occupants' bodies could be used as an indicator of dynamic discomfort.

Previous research has found that seated humans are more sensitivity to local vibration at high frequencies (Von Gierke and RR, 1961). Many studies on hand-arm vibration in passenger cars (Giacomin and Woo, 2005; Morioka and Griffin, 2009) have focused on steering wheel vibration. Human body posture also (Nawayseh and Griffin, 2012) shows a significant influence on the perception of vibration. In contemporary passenger cars, the driver's position is quite different from that of a passenger in a relaxed sitting position. It is therefore of interest to study experienced vibration transmitted through the armrest. In the user study, only two occupants reported that they perceived annoying vibration from the armrest. The interviews revealed that most occupants did not use the armrest in the EV because it was too far away and too short. Therefore, they did not report discomfort caused by vibration from the armrest in that vehicle. In the CV, however, some participants experienced vibration from the armrest and changed their arm posture after a short while. Thus, in the CV vibration from the armrest was not judged as annoying. These observations indicate that design and vibration could influence the intended use of armrest, which might make occupants in passenger cars less stable and make it harder for them to relax.

6.2 Differences in experienced sound between the EV and the CV

Similar to the findings of previous studies on sound inside passenger cars (Qin et al., 2020, Qatu et al., 2009, Lindener et al., 2007), low-frequency engine sound, tyre noise and wind noise were the major sounds in the CV during the different driving scenarios. Sound annoyance in the CV was mainly triggered by these factors in the corresponding test scenarios.

Meanwhile, in the EV, sound annoyance was mostly caused by high-frequency tonal sounds from electrical components. When the ranking of influence between the two vehicles is compared, the effect of sound on dynamic discomfort was greater in the EV than in the CV, even if the A-weighted equivalent sound pressure level was lower in the EV than in the CV.

At lower speeds, the high-frequency tones generated by electrical components were more prominent when tyre noise was low and wind noise was absent. These high-frequency tones were also linked to greater sound discomfort in the EV than in the CV. When accelerating from 0 to 50 km/h and when driving at a constant speed of 60 km/h, for instance, the measured A-weighted sound pressure level was lower in the EV than in the CV. Nevertheless, the sound was considered more annoying and judged more negative in the EV than in the CV.

Previous studies have indicated that significant high-frequency tonal components are common sounds inside EVs (Govindswamy and Eisele, 2011). Future studies of dynamic discomfort in EV could therefore take into consideration the high-frequency tonal sounds, especially at lower driving speeds.

6.3 Differences in experienced vibration in the EV and the C

The most prominent difference in vibration between the EV and the CV was identified during start/stop. In the CV, participants were annoyed by the low-frequency vibration induced by rigid body resonances. In some modern passenger cars, engines shut off and restart automatically to reduce energy consumption. In the current study, participants did not perceive great discomfort when the engine switched on and off; nevertheless, they reported vibration discomfort caused by auto start/stop in previous driving experiences. In the EV, there was no significant vibration perceived during start/stop and the designed notification sound only played the first time the motor was started. Participants commented that they expected a sound notification when switching the EV on and off. This difference in vibration and the resulting difference in experienced ride comfort might also be found in an idling scenario.

In other scenarios, participants attributed vibration discomfort in both carts mainly to induced body movement. In the EV, participants reported less vibration transmitted from the seat to the human body. Therefore, vibration in the EV contributed less to dynamic discomfort than it did in the CV. These differences cannot be explained by the different type of motor used in each car. However, EVs are usually heavier due to their batteries, and thus they are more stable (Timmers and Achten, 2016).

Chapter 7 Discussion

This chapter presents the answers to the first two research questions and discusses a methodology that can be applied to assess ride comfort.

7.1 The definition of ride comfort from the occupants' perspective

The literature studies revealed that a variety of factors, such as vibration, ride motion, sound, temperature, seat and seatbelt systems, influence occupants' experienced ride comfort. It is also the case that occupants are exposed to simultaneous inputs from the vehicle and that these inputs vary depending on driving conditions. The majority of the research studies focused on factors that cause "ride discomfort", even if they use the term "ride comfort". It is therefore important to identify those factors that have great influence on perceived ride comfort in a stationary car and during various driving scenarios.

Based on the results of the user study, the perceived ride comfort encompasses two aspects: initial comfort and dynamic discomfort. The two cars tested were similar in terms of the most important factors for initial comfort, which was mainly influenced by ingress, room for the body, seat adjustment and seat support. Causes of dynamic discomfort in the two cars differed, however. In the CV, dynamic discomfort was attributed to induced body movement, distinct local vibration, annoying sound as well as discordance between sound and vibration. In the EV, meanwhile, dynamic discomfort was mainly caused by annoying sound.

7.2 The influence of sound and vibration

The results of the literature studies and the user study show that sound and vibration change according to the driving scenario. Experienced ride comfort correspondingly varies depending on the experienced sound and vibration, which changes depending on the driving scenario and the particular car.

A variety of studies have investigated the contribution of a single attribute in a single car during a single driving scenario. Variation in the effect of sound and vibration under different driving conditions or in different cars has not been a focus of previous research. The user study showed that the influence of sound on dynamic discomfort was more pronounced in the EV and that the causes of sound annoyance differed between the cars. In the CV, it was primarily triggered by tyre noise at medium speeds and wind noise at higher speeds, while in the EV, it was caused by high-frequency tonal sounds from the electric motor particularly in scenarios at a lower driving speed.

When switching the engine on and off, low-frequency sound and vibration were pronounced in the CV. In the EV, in contrast, there was no significant vibration that accompanied the designed starting sound.

The study identified differences between instantaneous responses and overall perception of sound for both cars. Participants attributed their difficulties in relaxing to experienced sound, even if they did not rate sound as annoying in some scenarios. This indicates that short-duration tests might underestimate the influence of sound, regardless of what car is tested. Future studies evaluating sound annoyance in passenger cars could therefore take the length of the trip into consideration. For passenger cars designed for both short and long trips, it is suggested to analyse both shorter and longer test sequences.

Participants attributed vibration discomfort in both cars primarily to low-frequency vibration, induced body movement and the relative motions between different body parts. In the interviews, participants rarely made direct judgements about the characteristics of vibration. Instead, they attributed vibration discomfort to resonance in their body parts and body movement. In ride comfort studies for other passenger cars, it might likewise be difficult for participants to directly describe their experiences of vibration. Induced body movement, local vibration and the relative movement of various body parts are suggested to be used as indicators.

7.3 The implications of the study method

In contemporary CVs, the engine start/stop is even more frequently as automatic start/stop systems are incorporated (X. Wang et al., 2020). It is foreseeable that occupants will experience more low-frequency sound and vibration in future mobility. As this study demonstrates, low-frequency sound during start/stop influences perceived ride comfort in a CV. Participants did not perceive notable vibration discomfort when the engine switched on and off; nevertheless, they commented that in their daily driving, the auto start/stop influenced ride discomfort. It is therefore of interest to include the scenario start/stop in the assessment of dynamic discomfort in other CVs.

At higher speeds, wind noise dominates the interior sound in CVs (Lindener et al., 2007). In EVs, sound usually includes high-frequency tonal components generated by the electric motor (Govindswamy and Eisele, 2011). The user study showed that sound annoyance in the CV was greater at higher speeds. Participants in the user study emphasized the influence of high-frequency tones in the EV and identified them as a source of major discomfort. Moreover, the sound annoyance related to high-frequency tones in the EV decreased as speed increased, due to masking by wind noise at high speeds. These findings suggest that the assessment of sound annoyance could focus more on the experience at higher speeds for other CVs and on the high-frequency tones at lower speeds for other EVs.

This study used two specific car models to represent two types of cars. The results are valid only for the specific passenger cars used in the current study. For other passenger cars, some parameters such as the weight, might differ. However, the cars used in the user study were typical passenger cars without any extreme design. Meanwhile many findings in the current study were correspondent to those from previous studies as discussed above. Therefore, the findings in the current study could provide insights to other CVs and EVs.

In some user studies, the order of test scenarios has been randomized. In this study, nevertheless, the test scenarios were designed in a fixed order to simulate an ordinary daily riding. This allowed to investigate how the occupants' experienced dynamic discomfort developed by time in one scenario order that could be found in real word riding. Nonetheless, there could be disadvantages caused by the influences of scenario order. The participants would relate later scenarios to their experiences in the earlier scenarios. This was observed in the interviews that the participants commented their experiences using comparison with the scenarios before. For instance, six participants (P1, P2, P4–P8) described that the impact sound was loud in scenario 7 (bridge joints) and they compared it with their perception during scenario 6 (long bumps and cornering). This type of comparison might influence the rating of sound annoyance in later scenarios. Moreover, the participants could be tired and difficult to focus on the latter scenarios. Since there was no substantial discomfort reported in the whole test, the influence of scenario order might not have influenced the results to a larger extent.

The ratings and rankings obtained by questionnaires indicate the difference between the experts' and non-experts' experiences were not prominent. The interviews, however, identified some differences between these two groups. The experts could explain their perception in an easier and clearer way compared with the non-experts. For instance, the experts were able to associate the ease of ingress to the height of floor and the architecture of car seat, whilst the non-experts had difficulties in describing their comfortable experience of easy ingress. Meanwhile, the experts sometimes judged their perceived comfort/discomfort according to their occupational experiences instead of their instantaneous experience in the user study. The experts commented much on whether sound/vibration "should be like this" in the interviews.

The number of participants were limited due the covid-19 pandemic. Since the current study was designed to investigate a wide range of sounds and vibrations that could be experienced in different passenger cars under different driving conditions. Moreover, as discussed above, some patterns in the influences of sound and vibration were found. This limited number of participants could therefore fulfil our requirements. Nevertheless, it is difficult to capture the inter-subject variations with only ten

participants. The influence of anthropometry means that a larger population is needed for a comprehensive assessment on overall ride comfort.

This study demonstrated that the influence of single factors (e.g., sound and vibration) and their combined effects on ride comfort vary depending on the specific car and test scenario. Thus, using a single test scenario or investigating a single factor is an insufficient approach to assessing overall ride comfort. In this study, most subjective assessments could be explained by the measured sound and vibration. This indicated that one could control overall ride comfort by controlling factors such as sound, vibration and seat. For instance, reducing high-frequency tonal sounds may reduce experienced sound annoyance in EVs.

Chapter 8 Conclusions

This thesis conducted literature studies and a user study to investigate how sound and vibration influences perceived overall ride comfort in contemporary passenger cars. The first research question relates to the definition of ride comfort from the occupants' perspective and the methodology used to specify the factors that have effects on overall ride comfort. The second research question concerns the specifics of how ride comfort is influenced by sound and vibration.

The literature studies found that there are many laboratory studies of human responses to sound and vibration, and they have produced considerable information on the topic. However, human perception of overall ride comfort is affected by a variety of simultaneous inputs from the car. Moreover, the influences of different factors are not constant in all driving scenarios. There is a lack of studies that consider all the different factors that affect car occupants' experience of overall ride comfort.

The user study concluded that ride comfort encompasses both static comfort and dynamic discomfort. Static comfort was influenced predominantly by ingress, room for the body, seat support and seat adjustment. In the CV, dynamic discomfort was predominantly influenced by Induced body movement, while in the EV the biggest factor was annoying sound.

In the CV, sound annoyance was primarily triggered by tyre noise and wind noise. In the EV, meanwhile, it was caused by high-frequency tonal sound from electrical components and wind noise. The biggest variation in experienced sound annoyance was found at lower speeds. The high-frequency tonal sound from electric motor was significant when it was not masked by wind noise and caused sound annoyance in the EV. In the CV, tyre noise was the predominant annoyance at lower speeds. At higher speeds, wind noise was the major cause of sound annoyance in both cars,

The major differences in experienced vibration discomfort were found when the engine switched on and off. In the CV, low-frequency vibration caused by the rigid body resonances of the car was the major cause of perceived discomfort. In the EV, in contrast, there was no significant vibration transmitted to the human body.

In conclusion, a single test scenario is insufficient to allow a good assessment of ride comfort. The approach used here could be applied to assess ride comfort in a comprehensive sense. It is suggested to focus on different factors and characteristics in the assessments of ride comfort for CVs and EVs.

Chapter 9 Future work

The previous chapters introduced an approach to assess perceived ride comfort and to investigate the influence of various factors on it. This approach allows researchers to evaluate ride comfort under different scenarios and in different cars. It also makes it possible to investigate how single factors influence each other. The study found that the combined effects of sound, vibration and seat were most influential.

Kamp et al. (2011) concluded that activities carried out during the ride also affect body posture significantly. Relaxing, sleeping, reading, talking and using electronic devices were the activities the researchers observed most often during journeys. Fiorillo et al. (2019) anticipated that in the future, passenger car occupants would spend more time conversing, reading or using electronic devices, especially in autonomous vehicles. With the developing of autonomous passenger cars, traditional ride comfort measures might be insufficient for autonomous cars. Occupants' experience will change due to the absence of controllability. Moreover, occupants might be exposed to vibration and acceleration that different from those in traditional cars because of the path trajectories and the control systems (Elbanhawi et al., 2015).

It is therefore suggested to investigate the vibration that perceived by occupants when they are sitting or in other postures, such as lying, in a passenger car seat. To date, the study of comfort in passenger car seat has primarily been investigated through in terms of optimal contact pressure distribution, seat dimensions and the influence of the occupant's anthropometry, mostly in stationary cars. Vincent et al. (2012) found that evenly distributed contact pressure contributes to greater comfort. Vink and Lips (2017) concluded that contact pressure at the front of the seat pan and around shoulders contributed significantly to static seat comfort. Some previous studies have investigated the capacity of vehicle seats to attenuate vibration using seat effective amplitude transmissibility (Mandal et al., 2020; Sharma and Mandal, 2021). Subjective assessments and objective measurements of vibration caused by the seating system (e.g., compressors, fans and valves for height adjustment, lumbar shape and heating and cooling) were studied for a discussion of potential means to them (Haylett et al., 2021).

Variation in vibration transmitted to the car seat contact surface under different road excitation conditions and for different sitting postures have not been of focus on in previous studies. In this study, the specific targets of dynamic discomfort caused by vibration were not obtained due to the limited population of participants during the pandemic. Thus, this study could be extended further. It could be of interest to investigate the vibration transmitted to contact areas in conjunction with subjective judgements of ride comfort/seat comfort. Using this approach, the level of vibration and the comfort rating could be correlated to determine engineering guidelines.

Another future direction could be the application of virtual tools to the evaluation of perceived ride comfort. Mathematical models of various car seats could be used to analyse vibration transmitted from the seat rail to the contact surface under a variety of road conditions. Moreover, car seat model could be further integrated with a human body model to investigate vibration transmission to various body parts. These analytical approaches offer the possibility of being able to predict perceived vibration discomfort in the real world.

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Paper A

Human Response to Vibrations and Its Contribution to
The Overall Ride Comfort in Automotive Vehicles
– A Literature Review

Human Response to Vibrations and Its Contribution to The Overall Ride Comfort in Automotive Vehicles – A Literature Review

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Abstract

The various factors that affect ride comfort, including noise, vibrations and harshness (NVH) have been in focus in many research studies due to an increasing demand in ride comfort in the automotive industry. Vibrations have been highlighted as an important contribution to assess and predict overall ride comfort. The purpose of this paper is to present an approach to explain ride comfort with respect to vibration for the seated occupant based on a systematic literature review of previous fundamental research and to relate these results to the application in the contemporary automotive industry. The results from the literature study show that numerous research studies have determined how vibration frequency, magnitude, direction, duration affect human response to vibration. Also, the studies have highlighted how body posture, age, gender and anthropometry affect the human perception of comfort. An analysis was made of the consistency and inconsistency of the results obtained in the different studies. The deviations of the research results from real-world ride comfort in automotive vehicles were analyzed and divided into three groups: appreciable and consistent with industry results, appreciable and inconsistent with industry results and not appreciable in industrial results. The overall conclusion from this literature study was that there is much information available from laboratory studies regarding human response to vibrations, but there is a lack of studies that take into account all the different parameters that affect the overall ride comfort experience for automotive vehicle occupants.

Introduction

Transportation has become a distinctly important part in people's daily life. During the past three decades, the average annual distance travelled by car per person has greatly increased as has the speed of travel [1–3]. And the time investigated in transportation by vehicles involving professional activities and private activities has increased [2, 4]. The physiological responses, such as the increase in heart rate, respiration rate, cardiac output [5,6], muscular activities and muscle tension [7] during vehicle riding, indicate that a comfortable riding experience in a vehicle is critical in improving the performance of the drivers, reducing the tiredness of the passengers, and improving the safety as well as long-term health [5–7]. The expectation and demands on the higher level of ride comfort for vehicle occupants has resulted in an increasing interest for the subject in the contemporary automotive industry as well as in academic research.

The majority of the research studies have focused on the factors that cause 'ride discomfort' even if the term 'ride comfort' has been employed. However, comfort and discomfort have been pointed out as two independent aspects [8]. Comfort is a physiological and psychological experience, resulting in well-being as well as relaxation of the human [9], whilst discomfort is associated with physical

constraints and poor biomechanics [10]. A conceptual model of comfort and discomfort, which has the transitions between comfort and discomfort in the intersection of two orthogonal axes, has been suggested [8]. Based on this comfort model, there are negative human responses leading to ride discomfort, but also positive human responses that could benefit ride comfort. Therefore, it is necessary to analyze both the negative and positive aspects of the human responses to various stimuli [11].

The various factors affecting ride discomfort have been classified into ambient factors (i.e., thermal comfort, air quality, noise, pressure gradient), dynamic factors (i.e., vibration, shocks and acceleration), ergonomics factors (i.e., spatial comfort, functionality, seat comfort) [12] and multi-stressors [13]. Multi-stressors focus on the combined effect of several modalities, such as simultaneous haptic and visual factors. Vibrations have been highlighted as one important factor in the assessment and prediction of the overall ride comfort, which might degrade the overall comfort, cause motion sickness, interfere with activities during ride and in the long term be a part of impaired health [13–15].

The purpose of this paper is to present an approach to describe ride comfort and discomfort with respect to vibrations for automotive vehicle occupants, with a main focus on vibrations. The study is based on a systematic literature review of published research related to automotive vehicles as well as on laboratory studies of human response to vibrations. The consistencies and inconsistencies between the studies are also discussed to find a more accurate whole picture of human responses to vibrations. In addition, the literature findings and measured vibration data from real-world automotive riding were compared and were applied to the contemporary automotive industry.

Method

The method used was a literature search in scientific journals in relevant areas of sound and vibration, ergonomics, vehicle NVH, biomechanics, and industrial health for vibration and comfort. The search words were found in the title, abstract or as keywords.

Human response to vibrations

Introduction to human responses to vibrations in automotive vehicles

Vibration is one critical stimulus that produces discomfort during ride. The vibrations that humans are exposed to are divided into two categories: Whole-body vibrations (WBV) and local vibrations. For

WBV the vibration motion is transmitted to the human body via a supporting surface, for instance the automotive seat, or the floor that people are standing. For local vibrations, parts of the human body are in contact with a vibrating area. The most common local vibrations people experience during vehicle riding include hand-transmitted vibrations and feet-transmitted vibrations [13].

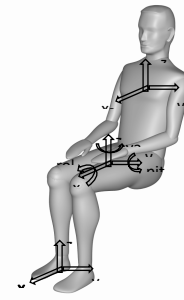


Figure 1. The 12-DoF coordinate system defined in standards [19] for the translational and rotational motions on human body.

The frequency range of the vibrations, presented in discomfort studies in automotive vehicles, especially in passenger cars, are said to be between 0.5–300.0 Hz [13]. At frequencies below 20.0 Hz, WBV is the major cause of discomfort during vehicle riding compared to local vibrations. This is because: (i) the human body is more sensitive to WBV at low frequencies [15]; (ii) the vibrations transmitted to the vehicle seat are usually below 20.0 Hz for lateral as well as vertical vibrations [13] and below 30.0 Hz for fore-and-aft vibrations [16]. At frequencies higher than 20.0 Hz, the vibrations are intuitively attenuated by the soft tissues of the human body [15] and the motions of various body parts will mainly be localized around the locations of contact areas with the vibrating surface [13]. The vibration discomfort at high frequencies are mainly caused by the resonance and biodynamic responses of the various human body parts [15]. The frequency range of 100.0 [13]–300.0 [17,18] Hz has also been investigated to cover steering-wheel vibrations in passenger cars.

The coordinate system that is suggested in ISO 2631 [19] and BS 6841 [20] defines the orientations of the seated human exposed to WBV (Figure 1). It contains six directions of the supporting surface of the seat, including fore-and-aft, lateral, vertical, roll, pitch and yaw, as well as three translational directions (i.e., fore-and-aft, lateral, vertical) on the backrest and the feet. The terms fore-and-aft, lateral and vertical present translational motions in the x-, y- and z-axis in the coordinate system, respectively. Roll, pitch and yaw present rotational motions around the central axis x-, y- and z- in the coordinate system, respectively. This 12-degree-of freedom (DoF) coordinate system has been widely applied in many research studies [21,22], text books [12,13] and is also used in this paper.

When subjects have had long-term exposure to local vibrations, for instance, occupational exposure to power tools, observable injurious effects might occur [13]. In vehicle ride, the vibrations transmitted to hands and feet are usually of low magnitudes and short duration [23]. Their effects on the human body are associated more with degraded comfort than health problem [13,23].

The overall results from the literature study show that the consequences of human exposure to whole-body vibrations can be summarized in four groups: (i) degraded comfort; (ii) motion sickness; (iii) interferences with activities during riding; and (iv) impaired health [13]. They are distinguished based on cause mechanism, human sensitivity, and effects on the human [13]. However, motion sickness and impaired health, for instance low back pain (LBP), introduce negative physiological and psychological responses as well as increase the level of ride discomfort.

Evaluation of degraded comfort

Evaluating and predicting degraded comfort due to vibrations depends on the characteristics of both the vibration and the subject. As summarized in Figure 2, the characteristics of the vibration include frequency, magnitude, direction, and duration, whereas the subject's characteristics cover intra-subject variables (i.e., posture and orientation) and inter-subject variables (i.e., age, gender and anthropometry) [13].

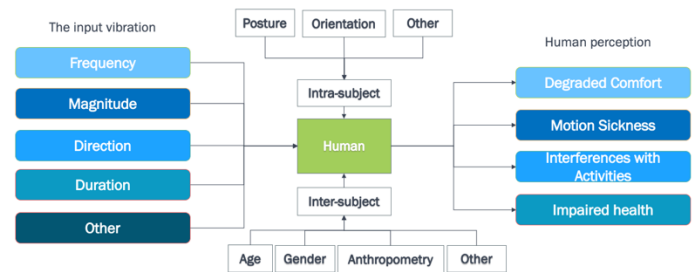


Figure 2. The factors that affect human perception of degraded comfort due to vibrations [13].

Various experimental methods have been employed to obtain the quantitative relation between objective vibration data (i.e., acceleration) and subjective data (i.e., the level of discomfort). One widely used method is equivalent comfort contour, which shows the amplitude of acceleration required at different frequencies to achieve the same level of discomfort. To develop the equivalent comfort contours, magnitude estimation [21,24] and magnitude production [25, 26] are major methods. A comparison between these two methods have been performed and the conclusion was that magnitude estimation would likely overestimate the human perception of discomfort, whilst magnitude production would probably underestimate the human perception of discomfort [27].

To further understand the coherences between the discomfort perception and the human biodynamical responses, experimental studies to measure the forces and accelerations have been conducted to analyze the apparent mass (APMS) [28,29], the driving-point mechanical impedance (DPMI) [30, 31], or transmissibility [32,33]. The APMS is significantly influenced by the weight of the subject [29]. In order to compare many subjects, the normalized APMS (NAPMS) was used to eliminate the effect of body weight [30]. There are two suggested methods to calculate the NAPMS: (i) the APMS at each frequency normalized by the APMS at a reference frequency [34]; and (ii) the APMS at each frequency normalized by the quotient of sitting weight and sitting height [30]. The first method of normalization is more frequently used. The reference frequency could be selected as the lowest frequency used in the experiment [29]. Sometimes the

static supported weight by the seat was assumed to be the APMS at the reference frequency [34]. DPMS and transmissibility are also important human body biodynamical responses to analyze the causes of human perception deviation. DPMS is the complex ratio between the dynamic forces that was applied on the subject and the consequent body responses in terms of velocity at the same location of excitation [34]. Transmissibility represents the complex ratio between the input force and the biodynamic vibration response in a location other than the input location, for example, to various locations along the spine and to locations at the head [34]. Both the DPMS and the transmissibility are also suggested to be normalized with the data obtained at a reference frequency before analysis [34]. In order to measure the transmissibility to the spine or to the viscera for seated subjects, a data correction method is required to eliminate the effect of local tissue-accelerometer vibration from the surface measurement (i.e., measurement conducted on the skin) [35], especially for vertical vibrations. For fore-and-aft vibrations at frequencies below 35.0 Hz, the measured data on the skin do not require a correction [35]. The resonance frequencies and the damping ratios of the local tissue-accelerometer system is shown in Table 1. The limitation of this correction method is that the mass of accelerometers should be less than 30.0 gram, and applicable at the frequencies below the natural frequency of the local system [35].

Table 1. The natural frequencies and damping ratios of the local tissue-accelerometer system over the vertebra L3 and on the abdominal wall in vertical direction [35].

Vertebra L3		Natural frequencies (Hz)	Damping ratios
Accelerometer mass (g)	6.4	29.9	0.42
	15.8	25.9	0.34
	25.4	23.6	0.30
	34.5	22.3	0.26
Abdominal wall		Natural frequencies (Hz)	Damping ratios
Accelerometer mass (g)	6.4	11.1	0.37
	15.8	10.6	0.32
	25.4	10.2	0.31
	34.5	9.60	0.28

In addition to experimental methods, virtual calculation methods have been developed to reduce individual deviation, improve reliability of research studies and cost-efficiency. The majority of the human biodynamic models can be divided into three groups: i) lumped-parameter models [36,37], ii) continuous-element models [38, 39], and iii) detailed anthropometry-based models [40,41]. In lumped-parameter models, the human body is modelled as several lumped masses connected by springs and dampers (i.e., dashpots) [34]. The lumped-parameter models are mostly employed to calculate the modulus and phase of the APMS in one dimension. In continuous-element models, the human body is modelled consisting of rigid elements and deformable elements, for instance, beams, rods and mass elements [34]. Using the continuous-element models, the axial or torsional forces and deformation on the body parts can be calculated and analyzed. These two models are efficient at calculating the data of riding comfort and take less computation time. Detailed

anthropometry-based models are developed to represent the human body including bone structure, muscle, fat, soft tissues and organs by finite elements. They are usually coupled with the model of seat to reflect the nonlinear behavior of the seat-occupant system to evaluate and predict seat comfort. Most of the virtual analysis considers the seat-occupant system separately from the rest of the vehicle. Some research also combines the occupant and the real-world riding vibrations in the same analysis [41].

The frequency-dependence of vibration discomfort

A frequency-dependence of vibration discomfort indicates that the human sensitivity to vibration discomfort varies with frequency, which is shown in Figure 3. Meanwhile, the effect of frequency on human perception of degraded comfort is also affected by the vibration magnitude [24], the direction of the vibration [24], the human body posture [42] and human body orientation [43] of the subject, and the age, gender, and anthropometry of the subjects [29].

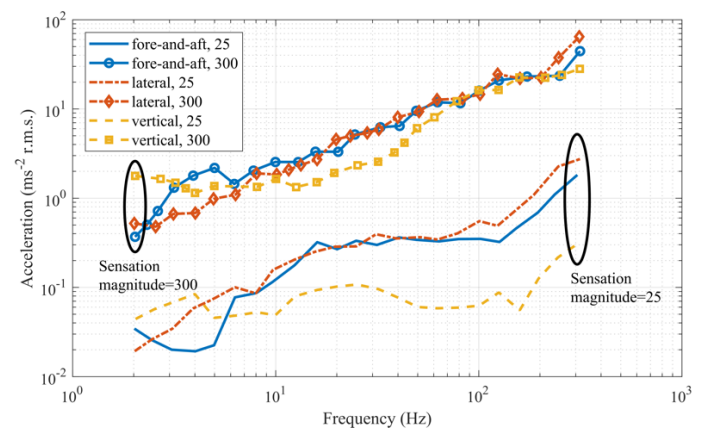


Figure 3. Equivalent comfort contours for sensation magnitudes of 25 and 300. Figure adapted from Fig. 7. In [24].

Vertical vibration

When exposed to vertical vibration, human has greater sensitivity at low frequencies compared to high frequencies [24], with the greatest sensitivity at around 5.0 Hz [26,44]. In some other studies, the frequency of the greatest sensitivity was found in the vicinity of 3.15 Hz [45]. This relatively lower peak frequency might be associated with the stationary footrest employed in the experiments. A stationary footrest which introduces more relative motions between the seat and the feet, and thus, alters the human sensitivity towards a lower frequency range particularly at low vibration magnitude [21,45].

The peak values of the human sensitivity in the equivalent comfort contours could be partially explained by the resonance behaviors of the human body or parts of the body. When subjects were exposed to vertical vibrations, the resonance of the vertical NAPMS occurred approximately at 5.0 Hz [29,46]. A greater value of NAPMS means either more parts of human body were resonating, or the human body was vibrating in larger motion. Either phenomenon is a cause of a high level of vibration discomfort.

The similar pattern has also been identified in the principal resonance frequency of DPMS, whose range is between 4.0–6.0 Hz [30,47]. Moreover, DPMS exhibits two additional resonances. The second significantly higher impedance was observed in the ranges of 8.0–12.0

Hz [30,47], which are in line with the relatively higher sensations at 8.0, 10.0 and 12.0 Hz [24]. The third resonance of DPMI was between 50.0–70.0 Hz [30,44].

Table 2. The most affected body parts in exposure to vertical vibrations with different magnitude and frequencies reported in experiments [21,30,45,48]. Names of body parts were listed in descending order of the number of times it has been reported by test subjects.

Vertical		Magnitude	
		Low (< 0.1 m·s ⁻² r.m.s.*)	High (> 0.5 m·s ⁻² r.m.s.)
Frequency (Hz)	1	ischial tuberosities	head and chest
	1.25	ischial tuberosities and lower abdomen	shoulder and chest
	1.6	ischial tuberosities and lower abdomen	shoulder and chest
	2	ischial tuberosities and upper torso	chest
	2.5	ischial tuberosities and lower abdomen	chest
	3.15	lower thighs and ischial tuberosities	chest
	4	ischial tuberosities and lower thighs	chest
	5	ischial tuberosities and lower thighs	spine, chest
	6.3	ischial tuberosities, lower thighs and chest	chest
	8	lower thighs and chest	chest and lower abdomen
10	lower thighs, ischial tuberosities and feet	lower thigh, lower abdomen, legs, and feet	

* r.m.s. refers to root-mean-square

It is of practical importance to investigate the effects on various body parts. As shown in Table 2, below 10.0 Hz, when subjects were exposed to low-magnitude vertical vibrations, the most affected body parts were at lower abdomen, lower thighs and ischial tuberosities [21,48]. At high vibration magnitudes, the spine [30,46], head [46], neck, shoulders and chest [21,45] dominated to the vertical vibration discomfort. The increasing significance in upper torso was also identified in [30,49], and could explain the additional peak in DPMI between 50.0–70.0 Hz [30]. Moreover, the seat-to-head transmission (STHT) is one critical cause of human discomfort under whole-body vertical vibration below 100.0 Hz [23]. Above 20.0 Hz, a decrease in STHT was identified with increasing frequency [49], which was consistent with the decrease in human sensitivity [24,29,30].

Horizontal vibration

As shown in Figure 3, the frequencies of highest sensitivity are between 2.0–2.5 Hz for fore-and-aft vibration [21,24], and 1.0–2.0 Hz for lateral vibration [24,50]. Human sensitivity to horizontal vibrations decreased with increasing frequency [21,24].

The greatest sensitivity to horizontal vibrations could be partially explained by the human biodynamic responses. The first and second resonances of fore-and-aft APMS occurred between 0.7–1.0 Hz and 1.0–3.0 Hz [28,51], respectively. In [52], an additional resonance was observed in the range of 3.0–5.0 Hz. This might be caused by the free-hanging feet posture using in the study. When seated subjects were exposed to lateral vibrations, the first and second pronounced peaks in lateral APMS were identified in the vicinity of 0.7 Hz and 1.5–3.0 Hz, respectively [51,53].

The primary peak frequencies in the horizontal DPMI have shown a good consistency with the human sensitivity. The first pronounced peaks in fore-and-aft and lateral DPMI were between 2.0–4.0 Hz, and around 2.0 Hz, respectively [31]. An additional peak in the range of 5.0–7.0 Hz was also observed in exposure to lateral vibration [31].

The changes in human sensitivity and biodynamical responses could be associated with the affected body parts. As shown in Table 3, a reduction of discomfort on the upper torso with increasing frequency was reported when subjects were exposed to fore-and-aft vibration [21]. At frequencies above 6.0 Hz, the most affected body parts were identified to be the lower abdomen, ischial tuberosities, and lower thighs [21,48]. This finding is supported by the studies of the transmissibility and mode shape of the human body [28], in which the bending deformation of the lumbar spine, lower thoracic spine, and the shear deformation of soft tissues at the ischial tuberosities dominated to the vibration discomfort.

The reported affected body parts in exposure to lateral vibrations has been shown in Table 4. At approximately 1.6 Hz, the greatest sensitivity to lateral vibrations was mainly associated with the shoulders, chest, lower abdomen, ischial tuberosities, and lower thighs [21]. The discernible peak in the range of 5.0–7.0 Hz was reported with discomfort perception at the upper torso and lower abdomen [31].

An increase in human sensitivity to fore-and-aft vibrations was observed in the frequency range of 125.0-160.0 Hz [24]. Between 125.0–200.0 Hz, human sensitivity to lateral vibrations increased with increasing frequency [24]. However, few research studies regarding biodynamic characteristics of human body at frequencies above 100.0 Hz could be found.

Table 3. The most affected body parts in exposure to fore-and-aft vibrations with different magnitude and frequencies reported in experiments [21,28,48]. Names of body parts were listed in descending order of the number of times it has been reported by test subjects.

Fore-and-aft		Magnitude	
		Low (< 0.1 m·s ⁻² r.m.s.)	High (> 0.5 m·s ⁻² r.m.s.)
Frequency (Hz)	1	head, shoulders, and lower abdomen	chest, shoulders, and head
	1.25	lower thighs, ischial tuberosities, lower abdomen, and head	ischial tuberosities, lower abdomen, chest, and head
	1.6	lower thighs, ischial tuberosities, lower abdomen, and head	lower thighs, ischial tuberosities, and chest
	2	head, ischial tuberosities, and lower abdomen	head, ischial tuberosities, chest, shoulders, and neck
	2.5	lower thighs, lower abdomen, and head	lower thighs, ischial tuberosities, chest, lower abdomen
	3.15	head, chest, and lower abdomen	lower thighs, ischial tuberosities, and lower abdomen
	4	lower thighs, ischial tuberosities, lower abdomen, and neck	ischial tuberosities, lower thighs, and head
	5	lower thighs, ischial tuberosities, lower abdomen, and neck	lower abdomen, ischial tuberosities, lower thighs, and chest
6.3	lower thighs, ischial tuberosities, and lower abdomen	lower abdomen, ischial tuberosities, and lower thighs,	

	8	lower thighs, ischial tuberosities, and lower abdomen	lower thighs, lower abdomen, and ischial tuberosities
	10	lower thighs, ischial tuberosities, and lower abdomen	lower thigh, legs, feet, and ischial tuberosities

Table 4. The most affected body parts in exposure to lateral vibrations with different magnitude and frequencies reported in experiments [21,31]. Names of body parts were listed in descending order of the number of times it has been reported by test subjects.

Lateral		Magnitude	
		Low ($< 0.1 \text{ m}\cdot\text{s}^{-2}$ r.m.s.)	High ($> 0.5 \text{ m}\cdot\text{s}^{-2}$ r.m.s.)
Frequency (Hz)	1	lower thighs, ischial tuberosities, lower abdomen, shoulders, and head	lower abdomen, ischial tuberosities, shoulders, and head
	1.25	lower thighs, ischial tuberosities, lower abdomen, and shoulders	lower abdomen, shoulders, head, and ischial tuberosities
	1.6	lower thighs, ischial tuberosities, and shoulders	ischial tuberosities, lower abdomen, lower thighs, and chest
	2	lower thighs, ischial tuberosities, lower abdomen, shoulders, and chest	ischial tuberosities and lower abdomen
	2.5	lower thighs and ischial tuberosities	ischial tuberosities, lower thighs, and lower abdomen
	3.15	lower thighs and ischial tuberosities	lower abdomen and lower thighs
	4	lower thighs, arms, lower abdomen, and chest	ischial tuberosities, lower abdomen, arms, and lower thighs
	5	lower thigh, ischial tuberosities, and arms	ischial tuberosities, lower abdomen, lower thighs, and arms
	6.3	lower thigh and ischial tuberosities	lower thighs, ischial tuberosities, and lower abdomen
	8	lower thigh and ischial tuberosities	lower thighs, ischial tuberosities, and lower abdomen
10	lower thigh and ischial tuberosities	ischial tuberosities, lower thigh, legs, and feet	

Rotational vibration

Generally, the seated human body showed a decreased sensitivity with increasing frequency when exposed to pitch or roll vibration [54–58]. Low-frequency pitch or roll motion at the seat will induce noticeable fore-and-aft or lateral motion in the plane of the seat, respectively. The induced translational motion dominated in the vibration discomfort when subjects were seated considerably far from the center of rotation [59]. The current standards [19] suggest that rotational motions should be evaluated twice: (i) evaluate the rotational motion, and (ii) evaluate the induced horizontal translational motion. The root-sum-square (r.s.s.) value of these two components has been suggested to determine the total effect on human perception to vibration discomfort [13].

A similar level of discomfort were reported when subjects were exposed to roll and lateral vibration, with or without a backrest [58]. Nevertheless, when seated without a backrest, human body exhibited a higher sensitivity to pitch than to fore-and-aft vibrations [54]. The difference in discomfort perception could be explained by the motions of the feet. In exposure to fore-and-aft and pitch oscillation,

the seated subject will exert pressure at the feet to maintain stability, but this is more difficult during pitch oscillation as the feet move vertically with the footrest [54].

At frequencies less than 30.0 Hz, seated human has higher sensitivity to pitch than to roll [56,57]. The differences between human perception to roll and pitch could be partially associated with the biomechanical structure of the ischial tuberosities. The subjects could adjust their centers of pressure between the ischial tuberosities without instability when exposed to roll or lateral vibration [58]. However, in order to maintain stability in exposure to pitch or fore-and-aft vibrations, muscular effort or a reaction force at the feet is required [54].

In addition, below 0.5 Hz, the discomfort caused by lateral vibrations could be reduced by the compensation of a roll vibration [55,58]. However, above 0.5 Hz, the roll-compensation vibration increased the discomfort caused by lateral vibrations [58].

The magnitude-dependence of vibration discomfort

The influences of vibration magnitude to human perception of discomfort have also been one critical research aspect in many studies [24,30,46,47,60]. The current standards [19,20] suggest evaluating the degraded comfort caused by vibrations of various magnitudes using the same frequency-weightings. However, human shows high nonlinearity in the both human sensitivity to vibrations [24,61], and the biodynamical responses [30,46,47]. In general, the frequency-weightings for vibration discomfort in current standards have reasonable consistency with the experimental results at medium and high vibration magnitudes [24]. Nevertheless, the current standards underestimate human sensitivity at frequencies close to the biodynamical resonance, and overestimate the human sensitivity at frequencies away from the principal biodynamical resonance frequencies [45].

Vertical vibration

As shown in Figure 3, with increasing vibration magnitude, the rate of growth of human sensitivity to vertical vibrations decreases over the frequency range between 10.0–20.0 Hz [24]. The frequency of greatest discomfort also decreased [24,45]. The pattern of a decreased peak frequency and a reduction in the corresponding peak magnitude with increasing vibration level have also been identified in the vertical APMS regardless the subjects were seated [29,46], standing [62], or recumbent [43,63].

A reduction in peak frequency of DPMI has also been observed with an increased vibration level at the first and second resonance frequencies, whilst the third resonance frequency was not affected by the vibration magnitude [30]. The magnitude and the phase of DPMI decreased with increasing vibration intensity within the first two resonance frequencies [30]. Above 20.0 Hz, the effect of vibration magnitude on DPMI was not significant because at high frequencies, the impedance was majorly influenced by the biodynamic responses of the body parts that close to the vibration input locations [30]. Hence, the magnitude-dependence of human sensitivity to vertical vibrations at high frequencies cannot be explained by the changes of DPMI [24].

At frequencies below 10.0 Hz, the resonance frequencies and the corresponding vertical transmissibility also decreased with increasing vibration magnitude [46].

The alteration in human sensitivity to vertical vibration discomfort at a variety of vibration level could be partially explained by the fact that different vibration levels might affect different parts of the human body [21,46]. As shown in Table 2, with increasing vibration magnitude, the discomfort was more significantly associated with shoulders and chest, while the effects on ischial tuberosities and lower thighs were considerably reduced [21]. The decreased resonance frequency might be associated with the thixotropic properties of the soft tissues entailing a reduction of the tissue stiffness with increasing vibration magnitude, and consequently, shift the resonance frequency towards a lower range [57,58].

Horizontal vibration

The human sensitivity to horizontal vibrations has also shown a noticeable magnitude dependence. The equivalent comfort contour at low magnitudes showed similar pattern to the threshold of perception [24]. At high magnitudes, human sensitivity showed a significant decrease with increasing frequency [24].

As shown in Figure 3, below 2.0 Hz, human sensitivity to fore-and-aft vibrations increased with increasing frequency at low vibration magnitudes, whilst decreased with increasing frequency at high vibration magnitudes [24]. Below 1.6 Hz, human sensitivity to lateral vibrations decreased with increasing frequency at low vibration levels but increased with frequencies at high vibration levels [21]. The frequency of greatest sensitivity to horizontal vibrations increased with increasing vibration level [24].

With increasing horizontal vibration magnitude, feet was reported with an increase significance of discomfort as shown in Table 3 [21]. This might be because the subjects required to exert extra forces on the feet in order to maintain stability [54]. When investigating the most affected body parts during horizontal vibrations, the contact areas between human body and seat pan are always highlighted as shown in Table 3 and 4 [21]. The horizontal vibration transferred to the upper torso including head, neck and shoulders was limited [21], hence, resulted in small changes in sensation with increasing magnitude.

The direction-dependence of vibration discomfort

Human has different sensitivity to the vibrations of different directions with the evidence of the different shapes of equivalent comfort contours obtained for fore-and-aft, lateral and vertical vibrations [21,24] as shown in Figure 3. Below 2.0 Hz, human sensitivity to vibrations varied very little for all three directions [21]. The threshold of perception in vertical vibrations was found to be higher than the threshold in horizontal vibrations between 2.0–4.0 Hz, and lower than the threshold in horizontal vibrations above 10.0 Hz [24]. Above 4.0 Hz, generally, human sensitivity to vertical vibrations was greater than the sensitivity to horizontal vibrations at any vibration magnitude [21,24,45]. The effect of magnitude on human sensitivity to vertical vibrations was also more significant than on the sensitivity to horizontal vibrations over the frequency range 1.0–10.0 Hz [21].

When subjects are exposed to horizontal vibrations, human sensitivity to horizontal vibrations also shows direction-dependence. In the range of 1.6–3.0 Hz, a greater sensitivity to lateral vibration than to fore-and-aft vibration was observed for low-magnitude vibration [21]. And between 3.0–4.0 Hz, the seated subjects reported greater sensitivity to fore-and-aft vibrations than to lateral vibrations at low-magnitude vibrations [21]. At high vibration magnitude, human showed generally higher sensitivity to fore-and-aft vibrations than to lateral vibrations [21]. With the vibration magnitude increased, a reduction cross-over frequency, at which human sensitivity to vibrations of different axes are identical, could be expected [21].

With increasing frequency, the variation of human sensitivity to horizontal vibrations were greater than to vertical vibration. This could be explained by the differences in the dominating affected body parts [21]. When exposed to horizontal vibrations, the shear movement between subjects and seat pan is the major reason of degraded comfort, and the vibration is not considerably transferred to the upper torso, thus, the location of discomfort shows limited change with increasing vibration magnitude [21]. In contrast, when exposed to vertical vibrations, the most affected body parts change from contact areas to the upper torso, which is the major reason for higher sensitivity to vibration magnitude [21].

The effect of intra-subject variables on vibration discomfort

The intra-subject variables including posture and orientation have significant effects on the human perception of vibration discomfort. The frequency of greatest sensitivity increases or decreases significantly when the human posture changes [21,24]. The biodynamic responses also differ among the subjects sitting upright [29,46], standing [62], lying[41,64], and driving a passenger car [60].

Hand posture

Drivers have their hands on the steering-wheel instead of in the lap. The vertical APMS for subjects sitting in driving posture exhibited two discernable resonances in the ranges of 5.1–8.3 Hz and 8.0–12.0 Hz [60]. While sitting in passenger posture, the vertical APMS showed a single resonance in 6.5–8.6 Hz [60]. The additional distinct resonance at driving posture might be associated with a greater relative motion at the hand and arm when subjects sitting with hands on the steering-wheel. Both resonance frequencies for drivers and passengers are relatively higher than the results obtained when subjects sitting on a rigid seat, which was indicated to be around 5.0 Hz [21,24,45]. The primary resonance frequency and the corresponding magnitude for a driver is lower than that for a passenger [60].

Furthermore, the effect of vibration magnitude on the resonance behavior of vertical APMS is also affected by the human body posture. When sitting in a driving posture, human body was less sensitive to the influence of vibration magnitude compared with the human sitting without backrest [60].

Backrest

The effect of backrest have also been in focus in some studies to investigate how the human sensation differs when sitting with or without backrest [45,64], with various backrest inclinations [45].

The presence of an upright backrest increased the human sensitivity to vertical vibration over the frequency ranges below 7.0 Hz and above 10.0 Hz, and reduced the sensitivity between 7.0–10.0 Hz [45]. The frequency of greatest sensitivity increased from around 3.0 Hz to around 4.0 Hz [45], and the resonance frequency in vertical APMS increased from 5.0 Hz to 5.5 Hz [64]. Above resonance frequency, the magnitude of vertical APMS increased after the presence of a rigid backrest [45,64,65]. With increasing vibration magnitude, a greater reduction of resonance frequency in vertical APMS was observed when subjects were sitting with a backrest [29]. In fore-and-aft vibrations, however, the human sensitivity to vibrations when sitting with a backrest was considerably lower than without backrest [54]. The differences between human sensitivity to fore-and-aft and vertical vibrations might be associated with the delay in motion of head and upper body when subjects were exposed to fore-and-aft vibrations between 0.2–1.6 Hz [54]. The presence of a backrest reduces this delay, and thus, reduce the fore-and-aft discomfort [54].

The human sensation to pitch vibrations increased with the presence of backrest increase over the range 0.6–1.6 Hz [54]. In exposure to pitch vibrations, the head, neck, and shoulders dominated more significantly to the discomfort at low frequencies when seated with a backrest [54]. While subjects sitting without a backrest, the significant discomfort body parts were the contact areas between human body and seat due to the difficulties in maintaining stability [54].

The human response to vibration has also a dependence on the rigid backrest inclination. In general, the increase of backrest inclination decreased the human sensitivity to vertical vibrations, especially at resonance frequency [29,45]. When the backrest was employed with inclination larger than 60°, the human sensitivity is lower than that of no backrest [45]. An increase by 1.0–3.5 Hz in the resonance frequency of the vertical APMS was observed with increasing inclination of rigid backrest [60, 63, 64]. This could be explained by the fact that with increasing inclination, the most affected parts changed from buttocks and thighs to the back and shoulder [45], at the same time, the contact area between body and backrest increased [63]. However, the resonance frequency of vertical APMS decreased with increasing inclination of a foam backrest [64].

The rigid backrest also induced greater influences of inter-subject variables compared with the cases of no backrest or with foam backrest [66]. When subjects were sitting with a rigid backrest, the resonance frequency of vertical APMS increased with an increase in age [29], and decreased with an increase in body mass index (BMI) [29] more significantly. This is because the stiffness of the human body decreases when human are sitting with a foam backrest [64].

Footrest

Human sensitivity to vertical vibrations is affected, in addition, by footrest. An increase in the height of footrest causes an increased knee height and reduced contact areas between lower thighs and seat pan. when subjects were sitting with an increased foot support, vertical APMS increased, and thus, the resonance frequency decreased [52,67].

Different postures of feet during experiments would affect the biodynamical response of the human body. The frequency of greatest sensitivity to lateral vibrations was lower when subjects put their feet closely [21] than had their feet apart [24]. This deviation might be

explained as a decrease in the relative movements of thighs and lower legs in lateral direction when subjects had their feet closely together.

The differences among footrests employed in a variety of experiments, such as stationary footrest or the footrest vibrating with the seat pan, is an important reason for the deviations of human sensitivity, especially at low frequencies [21]. The increasing phase differences between the seat and the feet at frequencies below 4.0 Hz was indicated to induce increasing vibration discomfort [68].

Orientation

The resonance of the vertical APMS of recumbent subjects occurred in the frequency range of 9.0–10.5 Hz [43,63]. Unlike the findings in the investigation of seated subjects, the sensitivity on back was relatively lower compared to other body parts for recumbent subjects [43]. The nonlinearity was mainly associated with the soft tissues, especially the biodynamic responses of the abdomen [43].

The principal resonance frequency of vertical APMS for standing subjects was between 5.5–7.0 Hz [62]. There were two additional broad resonances in the range 7.0–6.0 Hz and 13.0–18.0 Hz [62]. The principal and the second resonance frequencies are similar for standing subjects and seated subjects, which imply that the dynamic mechanisms of the upper body for both orientations are similar [62].

The effect of inter-subject variables on vibration discomfort

The human sensitivity to vibrations has shown a significant dependence on the inter-subject variables including age, gender, and anthropometry [29]. The changes in resonances of APMS with increasing age or increasing BMI were greater than the changes caused by the presence of a rigid backrest or increasing magnitude from 0.5 to 1.5 m·s⁻² r.m.s. [29]. Meanwhile, the effect of inter-subject variables on human sensitivity is affected by the vibration magnitude. At low vibration magnitude, the influences of age and BMI to the vertical APMS is higher than at high vibration magnitude [29].

Age

The resonance frequency and the corresponding peak magnitude of vertical APMS increased with the increasing of age [29]. The dependence on age has also been associated with some age-related factors, for instance, posture and anthropometry. Senior population have degraded musculoskeletal characteristics compared with younger population, including disc degeneration, muscle weakening and loss of elastic tissue in the ligaments [69,70]. When senior population is sitting in passenger cars, their postures would consequently be more forward-leaning [69,70]. The fat would be redistributed on the human body with aging and results in a higher BMI, an increased upper body fat deposition [69,70]. The cortical thickness throughout the whole spine will be considerably decreased [71], thus, the standing height of senior population decreases [69,70]. All these changes would alter the biodynamical responses of human body.

Gender

Gender affects significantly the biodynamic responses of human body. The decrease in resonance frequency of vertical APMS with increasing

vibration magnitude was considerably significant for males than for females when sitting with an inclined rigid backrest [29]. This could be partially associated with the gender-related factors including anthropometry differences [29]. The body weight supported by the reclined backrest is more significant for male. Even if eliminate the differences in anthropometry, the differences between genders are still noticeable. The mean value of NAPMS for males and females was similar [72]. While, females have a slightly higher NAPMS over the frequency range 15.0–40.0 Hz [65], and less distinct peaks of DPMS [30]. At the resonance frequency of vertical APMS, males have a higher NAPMS regardless sitting with and without a backrest [29].

Anthropometry

The vertical APMS was considerably affected by body weight at resonance frequency [29]. Nevertheless, the NAPMS at resonance frequency was not significantly affected by the body weight unless it is very high [29]. However, there was no conclusion that how heavy the body weight should exceed to obtain significant effect on NAPMS.

The resonance frequency in vertical APMS decreased with increasing BMI [29], especially when subjects sit with a backrest. This could be explained by the weaker coupling with the backrest for subjects of higher BMI, and thus, the stiffness of the body was reduced [64].

Other factors

The duration of vibrations showed impact to the human perception of vibration discomfort [73]. However, the effect is very complex and has not been quantified. In addition, local vibrations [61,74,75] and input locations on the back [76] also impact the human sensitivity to vibrations. Besides, simultaneous vibrations and noise showed masking effects between each other, and the consequent human perception of discomfort differed from that of only vibrations or noise [77–79].

The duration-dependence of vibration discomfort

The current standards state no conclusions for the duration-dependence of vibration on degraded comfort and defines the vibrations of the same vibration energy to be equivalently exposures, which will cause same level of discomfort [19]. The vibration energy could be calculated by weighted acceleration or by the vibration dose value (VDV) [13]. The discomfort levels caused by the vibrations with the same energy was reported to be very similar by most test subjects [73]. However, in the same experiment, a higher discomfort was also reported when the vibration energy was greater or when the exposure duration was longer [73]. No intuitive methods to establish the effects of the exposure duration and the VDV on vibration discomfort. The exposure duration, the vibration magnitude and the vibration frequency superpose with each other mutually and result in a complex influence on human perception of discomfort [73].

Local vibrations

There have been some studies on the effects of local vibrations on human perception of discomfort, for instance, feet vibrations [61] and hand-arm vibration [74,75].

The threshold of the perception of vibrations in fore-and-aft, lateral and vertical directions on the feet and on the hands of a seated

human body exhibited a U-shape frequency-dependence [61, 74]. The greatest sensitivity occurred in the range between 80.0–120.0 Hz [61] for feet vibrations and 80.0-160.0 Hz [74] for hand-arm vibrations. When excited at the hands, human sensation to discomfort showed the highest values at frequencies 10.0–16.0 Hz for all three directions [74]. The sensitivity decreased with increasing frequency in the range between 1.0–1000.0 Hz [75]. Human sensation ‘amplified’ the perceived vibrations below 50.0 Hz at the hands, and ‘suppressed’ the perceived vibrations above 50.0 Hz [75]. In exposure to vibrations on the feet, human sensitivity to discomfort decreased with increasing frequency over the range above 8.0 Hz [61]. With increasing vibration levels, the information-processing channels on the feet [61] and the hands [74] changed. This could partially explain the nonlinearity of the human biodynamical response when exposed to vibrations on the feet or the hands.

The effect of input location

Some research has studied the effect of input locations on human perception of vibration discomfort, for instance, at different locations on the back [76].

When exposed to fore-and-aft backrest vibrations, subjects reported a greater sensitivity at higher contact locations over the frequencies 2.0–80.0 Hz [76]. The resonance of the APMS of the back was identified at 3.0–6.0 Hz [76]. The locations of contact on the back did not show statistically significant changes of discomfort caused by fore-and-aft backrest vibration [76].

Noise combined with vibration

The human perception of discomfort caused by vibrations is also affected by the simultaneous stimuli [13,77]. Many studies have, for instance, studied the combined effect of simultaneous noise and vibration [77,78]. The visual effect also plays a noticeable role in human perception of vibration discomfort [24], especially at frequencies below 16.0 Hz. Consequently, there is an increasing demand in studying the effects of multi-modality stimuli on human perception of vibrations [13,24,77].

The subjective evaluation of simultaneous noise and vibrations exhibited an inter-dependence between each other [77–79]. When noise was evaluated, higher magnitude vibrations showed masking effects on the discomfort caused by lower levels of noise [78,79], and vice versa. When noise was evaluated relative to vibrations, the discomfort levels of noise increased with increasing duration. Nevertheless, the levels of discomfort caused by vibrations were independent of exposure duration when evaluated relative to noise [78,79]. The masking effect of vibrations on noise decreased with increasing exposure duration, whereas the masking effect of noise exhibited no dependence on exposure duration [78]. The discomfort caused by vibrations reduced due to simultaneous noise [74], however, did not show any significant changes in reduction of the discomfort caused by the noise [78]. The total discomfort caused by simultaneous vibration and noise could be calculated as the r.s.s. value of the discomfort levels caused by the vibration and the noise individually [78].

Vibrations in real automotive vehicles

The experimental studies reviewed in this paper involve the vibration magnitude from the threshold of perception to the threshold of health risk [24], and covers the frequency range between 0.2 [55,59]

and 315.0 Hz [24]. Both ranges of magnitude and frequency are comparatively wider than the vibration levels and frequencies of significance in automotive vehicles [80]. The seats used in existing studies are usually 250–500 mm in length, 180–500 mm wide [24,74] and 420–560 mm above the vibration floor [58,74]. The dimensions of real vehicle seats significantly deviate from those of the experimental seats. In addition, the human postures used in laboratory research studies are usually upright [24,54], and in some studies with the subjects' eyes closed [74]. Nevertheless, the postures during real-world ride are considerably different [60] and will result in different human perception of vibration discomfort.

Automotive vibration frequency range and level

The vibration levels at the seat, the floor and the steering wheel are affected by the road profile, the driving speed, the type of vehicle as shown in Tables 5–8. The vibrations on the floor are generally greater than in the seat for the same vehicle [81,82]. The vibration levels in the seat in commercial or off-road vehicles are relatively higher than the levels in passenger cars [80]. When passenger cars driven at high speed or on roads of greater roughness, the vibrations transmitted to the seat [83,84], the backrest [83] and the steering-wheel [83] in both vertical [83] and lateral [84] directions were more significant than in the fore-and-aft direction. The changes of the vibration levels in the fore-and-aft direction [84] were also less significant. In the majority of the reviewed studies, the weighted vertical vibrations in the seats of passenger cars and buses were less than $0.7 \text{ m}\cdot\text{s}^{-2}$ when the road profiles were smooth, and less than $1.0 \text{ m}\cdot\text{s}^{-2}$ when traveling on slightly rough roads [84–86].

The highest vibrations in the seat was identified to be the contact areas between the seat and the human body, including locations beneath the knee [87], the lower thighs [87,88] and the buttock [89]. The vibrations of significance transmitted to vehicle seats, especially passenger car seats, have usually been below 20.0 Hz for lateral and vertical vibrations [81] and below 30.0 Hz for fore-and-aft vibrations [16,90]. The vibration levels are comparatively higher than the vibrations in the seat. Few studies have investigated the frequency range of the vibrations on the steering-wheel.

Table 5. The vibration levels measured at the seat [16,81–84, 86, 91].

Road	Speed (km/h)	Type	Weighted Seat vibrations			
			Vertical r.m.s. ($\text{m}\cdot\text{s}^{-2}$)	Fore-and-aft r.m.s. ($\text{m}\cdot\text{s}^{-2}$)	Lateral r.m.s. ($\text{m}\cdot\text{s}^{-2}$)	Rotational r.m.s. ($\text{m}\cdot\text{s}^{-2}$)
Off-road	6	AT*	0.42–0.71	--	--	--
Smooth paved	80	P*	0.33–0.53	--	--	--
Worn	--	P	0.13–0.33	--	--	0.12–0.23 roll; 0.02 pitch; 0.71–0.90 yaw
Asphalt	60	P	0.44–0.59	--	--	--
Cobbled	60	P	0.72–0.92	--	--	--
Idling	0	P	0.02–0.05	--	--	--
Long wave	30	P	0.14–1.20	0.05	0.09–0.14	--
Long wave	40	P	0.18–0.22	0.06	0.18–0.29	--

Long wave	60	P	0.64–0.98	0.11–0.17	0.69–1.20	--
Stepped joint	40	P	0.22	0.04–0.07	0.11–0.14	--
Stepped joint	60	P	0.23	0.04–0.08	0.11–0.18	--
Stepped joint	80	P	0.21	0.06–0.10	0.11–0.18	--
Asphalt uneven	30	P	0.39	0.16–0.27	0.17–0.37	--
Asphalt uneven	40	P	0.38–0.42	0.16–0.23	0.19–0.38	--
Tarmac	112	Van	0.30–0.57	--	--	--
Tarmac	4	LT*	0.46–0.92	--	--	--
Tarmac	56	Lorry	0.33–1.04	--	--	--
Tarmac	8	AT	0.29–0.98	--	--	--
Tarmac	64	Bus	0.31–0.65	--	--	--
Mud	--	D*	0.54–1.29	--	--	--
Soil	--	E*	0.09–3.27	--	--	--
Gravel	20	AV*	0.17–0.89	--	--	--
Grass	--	G*	0.92	--	--	--

* P: Passenger car; AT: Agriculture tractor; LT: Lift truck; D: Dumper; E: Excavator; AV: Armoured vehicle; G: Grass roller

Table 6. The vibration levels measured at the floor [81, 82, 91].

Road	Speed (km/h)	Type	Weighted Floor vibrations			
			vertical r.m.s. ($\text{m}\cdot\text{s}^{-2}$)	Fore-and-aft r.m.s. ($\text{m}\cdot\text{s}^{-2}$)	Lateral r.m.s. ($\text{m}\cdot\text{s}^{-2}$)	Rotational r.m.s. ($\text{m}\cdot\text{s}^{-2}$)
smooth	80	P*	0.50–0.90	--	--	--
Off-road	6	AT*	0.63–1.03	--	--	--
Tarmac	112	Van	0.40–0.62	--	--	--
Tarmac	4	LT*	0.46–1.79	--	--	--
Tarmac	56	Lorry	0.39–1.12	--	--	--
Tarmac	8	AT	0.40–1.71	--	--	--
Tarmac	64	Bus	0.30–0.74	--	--	--
Mud	--	D*	0.65–1.14	--	--	--
Soil	--	E*	0.12–2.75	--	--	--
Gravel	20	AV*	0.39–2.17	--	--	--
Grass	--	G*	0.72	--	--	--

* P: Passenger car; AT: Agriculture tractor; LT: Lift truck; D: Dumper; E: Excavator; AV: Armoured vehicle; G: Grass roller

Table 7. The vibration levels measured at the backrest [83].

Road	Speed (km/h)	Type	Backrest vibrations			
			vertical r.m.s. ($\text{m}\cdot\text{s}^{-2}$)	Fore-and-aft r.m.s. ($\text{m}\cdot\text{s}^{-2}$)	Lateral r.m.s. ($\text{m}\cdot\text{s}^{-2}$)	Rotational r.m.s. ($\text{m}\cdot\text{s}^{-2}$)
Asphalt	60	P*	0.36–0.57	--	--	--
Cobbled	60	P	0.48–0.75	--	--	--
Idling	0	P	0.07–0.13	--	--	--

* P: Passenger car;

Table 8. The vibration levels measured at the steering-wheel [83, 90].

Road	Speed (km/h)	Type	Steering-wheel vibrations		
			r.m.s (m·s ⁻²)	Kurtosis	Crest factor
Tarmac	96	P*	0.06	3.09	3.42
Concrete	96	P	0.12	3.45	3.72
Slabs	96	P	0.19	5.27	5.28
Cobblestone	30	P	0.28	3.17	4.27
Low Bump	30	P	0.30	8.05	6.19
Stone on Road	20	P	0.64	10.99	6.71
Expansion Joints	16	P	0.69	10.28	5.24
Bump Road	60	P	0.88	10.15	6.59
Manhole	60	P	0.99	3.25	4.18
Cats Eyes	60	P	1.07	4.67	4.47
Broken Road	40	P	1.22	3.93	4.10
Rumble Strips	80	P	1.24	7.76	6.4
1cm Metal Bar	20	P	1.24	17.12	7.32
Transverse Joints	90	P	1.36	5.11	5.62
Broken Concrete	50	P	1.71	3.19	3.38
Broken Lane	40	P	1.81	3.79	4.32
Country Lane	40	P	1.97	3.43	3.55
Asphalt	60	P	1.63	--	--
Idling	0	P	0.09	--	--

* P: Passenger car;

Seat

The seat pans employed in the research studies are mainly rigid without backrest [21,61]. Only few studies have investigated a foam backrest [33]. The seats employed in passenger cars are usually designed with an adjustable backrest and seat pan. The original angle of backrest inclination is designed around 10°–20°, and the inclination of the seat pans at around 40° [92]. The dimensions of a number of automotive vehicle seats are listed in Tables 9 and 10 [93,94]. The variations in the dimensions of the seat cushions affect the contact areas between lower thighs and the seat cushion. This results in differences in the human biodynamical responses, for instance, the APMS during vibrations. In some studies of seat comfort [95], the occupants reported a preference with not less than 362 mm of thigh support (seat cushion length in Table 9 minus the length between ischial tuberosities and the seat rear edge), as well as 446–483 mm of cushion width at hips (rear insert width in Table 9). The differences in the height of car backrests (Height in Table 10) alters the input locations of backrest vibrations. The human sensation differs with different input locations [76]. At the height of chest level, occupants desired a width of backrest (upper or lower insert width in Table 10) at least 514 mm for a more comfortable lateral support [95].

The primary peak of transmission from floor to seat in vertical direction occurred at around 2.0–6.0 Hz for passenger cars [91,96–98], 2.0–4.0 Hz for agriculture machinery [81,98], 2.0 Hz for van [98], and 1.0–2.0 Hz for loaded bus [98]. The transmission to the seat decreased with increasing frequency in exposure to vertical vibrations [81, 91–98]. A similar principal resonance frequency of transmissibility to backrest was identified also in the range of 4.0–5.0 Hz [86, 97], however, in the range 15.0–20.0 Hz, the transmissibility increased with increasing frequency [97,99]. The resonance of transmissibility to the seat in fore-and-aft direction were observed in the frequency ranges of 1.0–4.0 Hz and 7.0–27.1 Hz for agriculture machinery, van, loaded bus [98], and for passenger cars [100]. In lateral directions, the second pronounced resonances of transmissibility to seat was observed at 19.4 Hz [100]. When the seat was occupied by a human body, the resonances of transmissibility in vertical direction were identified in the vicinity of 3.0 Hz [80, 98, 101]. The resonance of transmissibility in horizontal directions increased due to the relative motion between the human body and the seat [100].

Only one pronounced peak in vertical APMS of the seated human body was observed around 5.0 Hz [97, 102, 103]. The resonance frequency in vertical APMS decreased with increasing vibration levels [102]. The resonance in vertical DPMS of a seated driver was identified between 4.0–5.0 Hz [103,104]. The resonance frequency increased with a less distinct while the inclination of the backrest was increased [104]. The greatest seat-to-head transmissibility was observed in the frequency range of 4.0–6.0 Hz for the automotive vehicle driver [103,104]. The resonance in fore-and-aft APMS occurred between 2.0–2.3 Hz [105].

Table 9. The dimensions of seats used in automotive vehicles [93,94].

Vehicle	Seat cushion				
	Length (mm)	Total width (mm)	Front insert width (mm)	Rear insert width (mm)	Seat height (mm)
P*	500	545	385	305	--
P	500	540	355	355	--
P	480	540	--	--	--
P	480	500	360	360	--
P	500	530	300	300	--
P	485	515	320	320	--
C*	600	600	--	--	200

* P: Passenger car; C: Commercial vehicles;

Table 10. The dimensions of backrests used in automotive vehicles [93].

Vehicle	Backrest cushion			
	Height (mm)	Total width (mm)	Upper insert width (mm)	Lower insert width (mm)
P	570	535	390	390
P	565	505	290	290
P	550	500	255	255
P	510	490	295	295

P	570	530	285	285
P	590	515	315	315

* P: Passenger car;

Postures as driver or passengers

When humans are sitting as passengers in running cars, their postures vary from the postures employed in laboratory experiments. The major differences could be summarized in four groups: (i) posture deviation due to seat dimension and configuration [60]; (ii) macro-movements due to comfort/discomfort [106, 107]; (iii) inter-subject variations [70,71]; and (iv) posture variation due to activities [108].

When sitting as a passenger, the inclined foam backrest and a relatively lower seat height [60] will result in different angles between the upper and lower body, a difference in knee height. Different postures of the head (e.g., upright, tilted sideward, supported by hands, and against the head rest), arm (e.g., on the lap, next to the trunk and legs, crossed, upon armrest, supported only by elbow, and behind the head) and legs (e.g., on the footrest, crossed, wide, and pulled up) [106,108] were also observed. When sitting as a driver, the steering-wheel holding postures is an additional distinct change [60].

Macro-movements, which represent gross changes of human postures, have been identified as a frequent and distinct change of posture during ride [107]. Recurring posture variation could help to perceive comfort because of pleasant stimulation of tactile sensation [106]. Especially in prolonged sitting, frequently engaged non-sedentary activities has been suggested to reduce the discomfort [109]. When sitting in a static seat, the human body would change postures more frequently compared with sitting in a dynamic seat [109]. This could partially be explained by the fact that the human body will act against the posture that was forced by the seat [109] or the demands to alter the pressure distribution at the contact areas [88].

Driving postures differ also between age, gender, and anthropometry [110]. The angles of right elbow, the left hip, the right hip [110], and the angle of spine [69,70] differed significantly between younger and elderly groups when sitting in a passenger car. Gender exhibited a considerable effect on the angles of the left elbow while driving [110]. The body height has been shown to affect the left ankle angle, the left hip angle and the angle of neck [110].

The activities during ride have also affected the body postures significantly [108]. Relaxing, sleeping, reading, talking and using electronic devices have been the most frequently observed activities during journey [108]. In future driving, especially autonomous driving vehicles, passenger car occupants will spend more time conversing, reading, or using electronic devices [111].

Discussion

In recent years, automotive vehicle technology has developed rapidly. The electrical and autonomous driving cars are considered as the future trends by the industry. The NVH characteristics in the new generation of cars differ significantly from conventional automotive vehicles. Moreover, with an aging population, senior people will spend more time traveling in cars. Therefore, it is necessary to reconsider some of

the existing research results and standards to further improve the ride comfort in future cars.

Application of the current standards

The current standards widely used in the automotive industry to evaluate discomfort caused by WBV are ISO 2631-1 [19] and BS 6841 [20]. In these standards, only a single linear frequency-weighting is used to evaluate the discomfort caused by vertical vibrations over a wide range of magnitudes. However, as shown in Figure 4, the impact of vibration magnitude to frequency-weighting is significant over a wide range of frequency. Moreover, at different levels of vibration magnitudes, the discomfort is either underestimated or overestimated by ISO 2631-1 and BS 6841 in the frequency range below 30.0 Hz, which corresponds to the significant vibrations that are transmitted to seats in automotive vehicles.

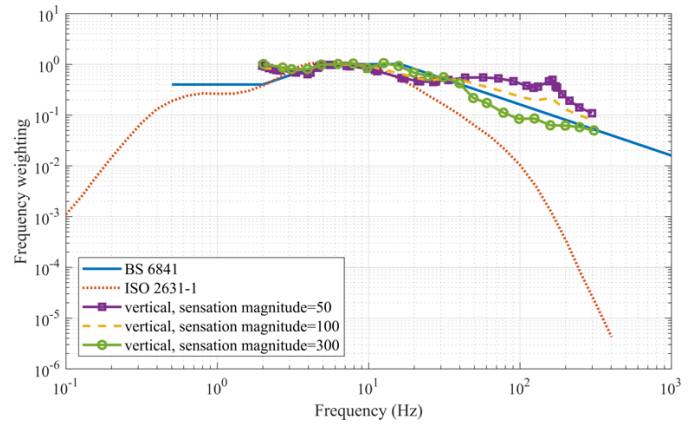


Figure 4. Comparison of frequency weighting between BS 6841 [20], ISO 2631-1 [19], and experimental results of different sensation magnitudes (50, 100, and 300) [24] in the vertical direction.

In addition, the current standards suggest an identical frequency-weighting for fore-and-aft and lateral vibrations. However, from the literature studies, human sensitivity is similar in the two horizontal directions with noticeable deviations especially in the frequency range below 10.0 Hz [21,24] as shown in Figure 5. At low-magnitude vibrations, there is a higher sensitivity to fore-and-aft vibrations, and at high-magnitude vibrations, there is a higher sensitivity to lateral vibrations.

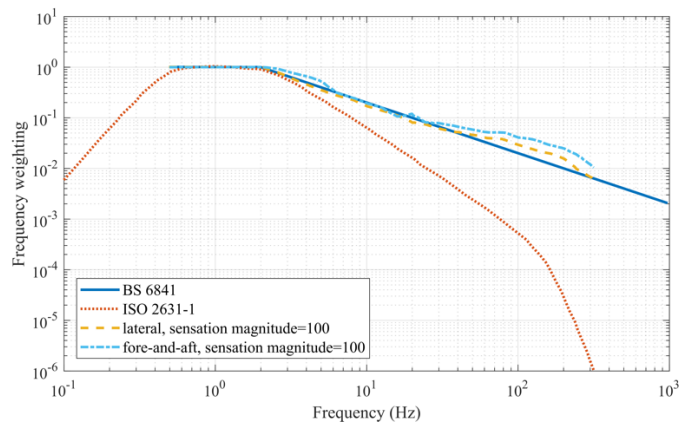


Figure 5. Comparison of frequency weighting between BS 6841 [20], ISO 2631-1 [19], and experimental results [24] in the fore-and-aft and lateral directions.

The comparison between fundamental studies

The majority of the research studies focus on the effects of vibration characteristics (i.e., frequency, magnitude, direction, duration). There have been many experiments investigating the effects of vibration frequency, magnitude, and direction on human perception of vibration discomfort. Meanwhile, there are few studies investigating the effect of duration. This could lead to increasing difficulties in evaluating and predicting ride comfort and health risks, both for occupational and private driving. Compared to vertical vibrations, research studies on horizontal vibrations, rotational vibrations, and vibrations of simultaneous multi-axes are scarce.

Apart from the characteristics of the vibrations (i.e., frequency, magnitude, direction), many other factors affect vibration discomfort. As shown in Table 11, when the vertical vibration magnitude changes from 0.5 to 1.5 m·s⁻² r.m.s., which can be generated by passenger cars on smooth and off-road vehicles on mud roads, respectively, the resonance frequency decreases by 0.5 Hz. For drivers in real world, the effect of vibration magnitude on sensation is even less noticeable [60]. In contrast, changes in intra-subject variables (i.e., posture, orientation), and inter-subject variables (i.e., BMI, age, and stature) with other conditions fixed result in rather significant shifts of resonance frequency.

Special attention should be paid to the age of the target user groups during the design of passenger cars, because it has the strongest impact on the biodynamic responses as shown in Table 11. With an aging population in developed western countries, more senior people will be traveling by car as drivers [70]. On the other hand, in the far east, senior people usually sit in the rear seats, where the vibrations are usually greater compared to the front seats. Therefore, vehicles targeting different markets should take the age of passengers into account in ride comfort evaluation and enhancement.

Only a few studies have been conducted to investigate the impact of intra-subject and inter-subject variables on vibration discomfort. In much of the literature, the subjects' posture and inter-subject information was simply documented as one sentence or even not mentioned at all.

Table 11. Comparison of frequency shifts in various condition changes [29,43,60,62,63].

Condition change			Primary resonance Frequency (Hz)		
Condition	From	To	From	To	Shift
Vertical vibration magnitude (m·s ⁻² r.m.s.)	0.5	1.5	5.2	4.7	-0.5
BMI (kg·m ⁻²)	18	34	0.56	1.7	1.14
Age (year)	18	65	3.6	7.1	3.5
Gender (dimensionless)	Female	Male	4.9	5.0	0.1
Stature (cm)	149	192	3.3	5.8	2.5
Posture (dimensionless)	Driver	Passenger	6.7	7.1	0.4
Posture (dimensionless)	Seated	Supine	5.0	9.75	4.75

The differences between the footrests [52,67] and seats [45,64] induce significant changes in human biodynamical responses. As the inclination of the backrest increased, human sensitivity increased when subjects were sitting with a rigid backrest but decreases while sitting with a foam backrest [64]. In many studies, the apparatus, for instance, the types of footrest and backrest (i.e., stationary or vibrating with seat), the inclinations of the seat pan, the backrest and the footrest and the dimensions of the seat, backrest and footrest was not documented in some studies.

As indicated in the literature studies, human sensitivity to low-frequency vibrations is comparatively greater than to high-frequency vibrations, and human sensitivity is considerably affected by other modalities (e.g., visual) under 16.0 Hz. More research studies investigating the combined effects of visual and vibration is essential, especially for the passengers in the rear seats. The visualization from the windows and the front are much more limited when human is sitting in the rear seat. In addition, the delay in the upper body in fore-and-aft vibrations will increase the difficulty in visualization for the rear seat occupants. It is also necessary to take the road noise and ambient sound levels into account when design or evaluating for different markets.

The reference vibrations employed in various experiments were usually of different magnitudes and frequencies, and for different experimental setups. Hence, the equivalent comfort contours might significantly shift in magnitude. In [21], the reference was a vertical vibration at 0.25 m·s⁻² r.m.s. (frequency-weighted) and 3.15 Hz. In [24], the reference was a vertical vibration of 0.5 m·s⁻² r.m.s. (frequency-weighted) and 20.0 Hz. The equivalent comfort contour, which represents the sensation equal to 100, using a reference vibration of higher frequency and higher magnitude exhibited a relatively greater sensitivity at low frequencies as shown in Figure 6. An identical reference would allow better comparison between the studies.

The majority of studies conducted in real automotive vehicles exhibited only the frequency-weighted r.m.s. vibration magnitudes without the frequency spectrum. However, the human sensitivity is dependent on the vibration frequencies. Lack of the frequency spectrum increases the difficulties in analyzing the human responses to vibration in automotive vehicles.

The first pronounced peaks of vibrations transmitted to the car seat were identified in the range of 1.0–4.0 Hz in horizontal directions [100] and between 2.0–6.0 Hz in vertical directions [91, 99]. The peaks of the vibrations transmitted from automotive vehicles to the human body in vertical direction were identified also in the vicinity of 5.0 Hz [81,101]. This indicates that at low frequencies, the vehicle seats will amplify the vibrations and increase the human perceived discomfort.

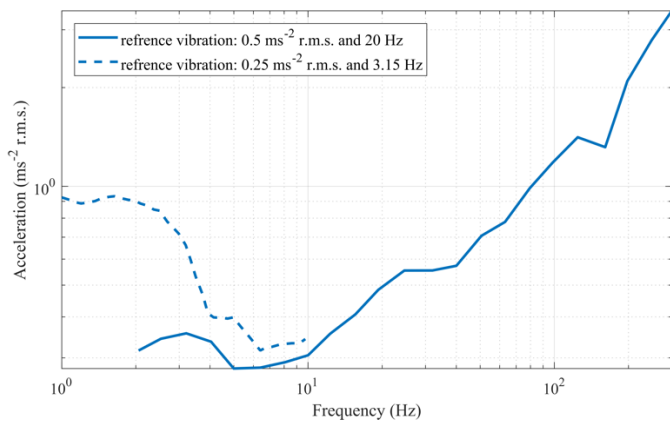


Figure 6. Comparison of equivalent comfort contours (sensation = 100) obtained using different reference vibrations (— : [24], - - - : [21]).

There have been many laboratory studies investigating human biodynamical responses. However, there are few studies investigating APMS, DPMI and transmissibility to the spine, the buttock and the head are much fewer. Little is found in the literature on the effect of car seats (e.g., stiffness and inclination) on the inter-subject deviations in human sensitivity when using automotive vehicles. In addition, there are fewer studies investigating the human perception of discomfort caused by horizontal vibrations and rotational vibrations in automotive vehicles compared to the number of studies investigating vertical vibrations. However, at high speed or for great road roughness, the changes in horizontal vibration levels are significant as shown in Table 5. Studies investigating rotational vibrations in automotive vehicles would provide more knowledge for the design of seat systems.

As highlighted in the discussion, knowledge is missing and for many aspects the number of investigations found are few. For instance, the human responses to horizontal vibrations, rotational vibrations, multi-axis vibrations, the simultaneous vibrations and noise and the combination of vibrations and visual in both experimental studies and in real automotive vehicles. As well as the impact of human posture and inter-subject variables to human perception of vibration discomfort. Further investigations into these matters are recommended. The documentation of the experimental setup and test subjects are often meagre. Relative documentation of inter-subject variables will allow more thorough comparison between different studies. Hence, in the future studies, the subjects' age, gender, anthropometry and the upper body height are suggested to be recorded. A figure illustrating the subjects' posture, for instance, the posture of the upper body, and the hands, feet, is suggested. The distance between the seat edges and the subject's ischial tuberosities, the length of thigh support, the height of knee, the angle between thigh and leg, and the distance between feet should also be documented.

Comparison between the experimental studies and the industry results

Before application of the results obtained in laboratory studies, an analysis of the consistency and inconsistency of the results obtained in the different studies was necessary due to considerable variations in the apparatus and exposed vibrations. The deviations of the research results from automotive vehicles were analyzed and divided into three groups: appreciable and consistent with industry results,

appreciable and inconsistent with industry results and not appreciable.

Appreciable and consistent with industry results

The human sensitivity to vibration discomfort measured in real automotive vehicles shows similarity with the results obtained in laboratory experiments, which employed low-magnitude vibrations and footrests that vibrating with seat, at low frequencies, especially below 20.0 Hz. In research studies, the human sensitivity decreased with increasing frequencies [24,29]. When the human is sitting in automotive vehicles, similar biodynamical responses were observed in vertical APMS [97,102,103], vertical DPMI [104] and STHT [104] of the seated human body. The resonance frequencies obtained in both laboratory [24,47,49] and automotive vehicles [97, 104] were in the similar range around 5.0 Hz.

The effects of vibration magnitude on human sensitivity to vibrations were similar in the laboratory experiments and in automotive vehicles. The frequencies of peak values in vertical APMS [29,46] and DPMI [30] decreased with increasing vibration magnitudes in the studies. While in real automotive vehicles, the resonance frequencies of vertical APMS [102] and DPMI [104] also decreased with increasing vibration intensity.

The backrest inclination affected the human perception of vibration discomfort in the studies and in the real automotive vehicles in a similar way. In the research experiments, which employed a foam backrest, the resonance frequency of vertical DPMI decreased with increasing inclination [64]. A similar reduction in resonance frequency was also observed in automotive vehicle drivers [104].

The resonance in fore-and-aft APMS obtained in the automotive vehicles is similar to the result of experimental studies with a slightly concentrated range between 2.0–2.3 Hz [105]. The resonance of transmissibility in horizontal directions increased due to the relative motion between the human body and the seat [100]. This is consistent with the conclusions of responding discomfort body parts in horizontal vibrations [21,28,31,48].

Appreciable and inconsistent with industry results

There were some inconsistencies between the biodynamical responses investigated in laboratory and in real automotive vehicles. The most critical reason for these inconsistencies was deviations in apparatus, for instance, the material of backrest and the inclination.

In some studies, a rigid vertical backrest was employed [64]. The presence of a rigid vertical backrest increased the resonance frequency of the vertical APMS by around 0.3 Hz [64]. In addition, an increase by 1.0–3.5 Hz in the resonance frequency of the vertical APMS was observed with increasing backrest inclination [43,60]. The seat and backrest of passenger cars are covered with soft cushion and both are designed with original inclinations. There was no significant change in the resonance frequency of vertical APMS caused by the presence of reclined foam backrest [97,102]. However, a reduction in resonance frequency was observed in automotive vehicle drivers [104].

Not appreciable in industry results

The vibration magnitudes covered in the reviewed studies concentrate mostly at levels between 0.1–4.0 m·s⁻² r.m.s. [21,50], which are considerably larger range compared with realistic automotive vehicles, especially well-designed passenger cars. The vibration levels at the car seats are usually below 1.5 m·s⁻² r.m.s. as shown in Table 5 and 7. While the vibrations at the steering-wheel are usually below 2.0 m·s⁻² r.m.s. as shown in Table 8.

The frequency ranges covered by the laboratory experiments are between 1.0–20.0 Hz for all three directions [21,50], with only a few exceptions [24,74]. However, the vibrations that transmitted to the passenger car seat in fore-and-aft direction are up to 30.0 Hz [16,90]. Successive studies investigating the human sensation to fore-and-aft vibrations should also cover the range between 20.0–30.0 Hz.

Significant differences in seats were also observed between the experiments and the real-world ride. In some studies, rigid seats without backrest and stationary footrests were employed. Whilst in the real automotive vehicles, the seats and backrests are with soft cushions and larger dimensions. For passenger cars, the presences of headrest and lateral support on the seat and the backrest are very common. The original angle of backrest inclination is designed around 10°–20°, and the inclination of the seat pan at around 40° [92]. In addition, the height of the passenger car seats is usually lower than the height of the rigid seat in the experiments.

In the majority of the laboratory experiments, the subjects employed the upright sitting posture, which is actually not very common in the real-world ride [106–108]. The implication of results from the laboratory experiments in evaluating the vibration discomfort in real automotive vehicles has been limited partially due to the large deviation in postures. In the future driving, especially in autonomous vehicles, people will spend more time in activities including relaxing, sleeping, reading, working on electronic devices and conversing. The changes in human postures will consequently change the human responses to vibrations. Hence, more realistic postures could be employed in the future studies, including sleeping, reading, using electronic devices, relaxing, and conversing. In addition, low-frequency vibrations influenced the human capability of reading [112, 113], writing [114], and also the performance of tracking [115]. Furthermore, the interferences with activities increase with increasing vibration magnitudes, especially in fore-and-aft direction [112,113]. Hence, the research studies of vibrations interference with activities are essential in ride comfort.

Conclusions

Numerous fundamental research studies have investigated the human responses to vibrations, especially the human perception of vibration discomfort. In general, there are much more studies published regarding the effects of vibration characteristics (i.e., vibration frequency, magnitude, and direction) compared to the studies of the effects of exposure duration, the intra-subject variables (i.e., posture, orientation), and inter-subject variables (i.e., age, gender, anthropometry). Both the laboratory studies and the experiments conducted in real automotive vehicles are mainly focusing on the human responses to vertical vibrations compared to horizontal vibrations, rotational vibrations, simultaneous multi-axis vibrations and the combined effects of vibration and noise, vibration and visual. The findings from both research studies and automotive vehicles are compared and categorized into three groups: appreciable and

consistent with industrial data, appreciable and inconsistent with industrial data and not appreciable. Both similarities and inconsistencies are listed in session Comparison between the experimental studies and the industry results. The studies have covered the magnitude ranges for various types of automotive vehicles, including passenger cars, buses and off-road vehicles. Nevertheless, the frequency ranges investigated in the majority of the studies are not sufficient for especially fore-and-aft vibrations. Similar human biodynamic responses have been identified in both fundamental research studies and in the experiments in road vehicles. Additional studies, employing realistic ride postures and larger populations of various age, gender and anthropometric measures are necessary to investigate all the different parameters that affect the overall riding comfort experience for automotive vehicle occupants.

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Definitions/Abbreviations

APMS	apparent mass
BMI	body mass index
DMPI	driving point mechanical impedance
NAPMS	normalized apparent mass
NVH	noise, vibration and harshness
r.m.s	root-mean-square
r.s.s	root-sum-square
STHT	Seat-to-head transmissibility
WBV	whole-body vibration
VDV	vibration dose value

Paper B

Sound and vibration influence on overall ride
comfort in a combustion passenger car
under different driving scenarios

Sound and vibration influence on overall ride comfort in a combustion passenger car under different driving scenarios

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Abstract

Ride comfort is an area of increasing interest, especially as the automotive industry is paying more attention to future technology and sustainable development. A variety of factors, such as sound, vibration and seating system influence the perceived overall ride comfort in passenger cars. However, these influences are not constant across different driving scenarios. The purpose of this study is to identify how human experiences regarding sound and vibration varied in eight different driving scenarios as well as how sound and vibration influence the overall perceived ride comfort. A user study was conducted with ten participants as front seat passengers in a combustion passenger car. Subjective data was collected by questionnaires after each scenario and by a semi-structured interview after completed the whole test ride. Objective measurements of sound and vibration were taken during each scenario. The results showed that static comfort was mainly influenced by ingress, room for the body, seat adjustment and seat support. Dynamic discomfort was affected by induced body movement, annoying sounds and the discordance between sound and vibration. Tyre-road noise and wind noise dominated the perceived sound annoyance at lower and higher speed, respectively. The vibration annoyance was mostly judged by induced body movements. The discordance between sounds and vibrations aggravated the perceived dynamic discomfort. The conclusion was that the influences of sound and vibration on perceived ride comfort change in different driving scenarios, and thus, overall ride comfort should be evaluated in different ways depending on the chosen driving scenario.

Keywords: Ride comfort; Sound; Vibration; Car passenger; Discomfort.

Introduction

Refinement is one of the major tasks that must be accomplished during vehicle development. For all modern cars, this results in consumers expecting a higher level of ride comfort and therefore attracted increasing interest when the automotive industry is paying more attention to future technology (Harrison, 2004; Sheng, 2012). Ride comfort is a critical factor affecting performance, tiredness, safety and the long-term health of car occupants (Van Veen, 2016).

A variety of factors have shown influence on human perception of ride comfort. These include ambient, dynamic and ergonomic factors. Ambient factors usually refer to air temperature, air quality and sounds. Dynamic factors include vibration, impacts, ride motion and acceleration. Visibility, functionality, seat architecture, seatbelt and seat-human interfaces are categorised as ergonomic factors (Wang et al, 2020). The effects of all these comfort factors are not independent; indeed, there are interferences between them. For instance, Huang (2012) concluded that higher magnitude vibrations had a masking effect on the discomfort caused by lower levels of noise and vice versa.

The studies of ride comfort for seated occupants have mainly focused on studying discomfort. However, Helander and Zhang (1997) demonstrated that comfort and discomfort could be independent attributes. They indicated that comfort is associated with well-being and relaxation and does not change as a function of time, while discomfort is mainly related to physical constraints and poor biomechanics. As summarized in other papers, experienced vibrations and ride motion (Wang et al., 2020), perceived sound level and characteristics of the sound (Sheng, 2012) were also attributed to discomfort. According to Helander and Zhang (1997), the experiences regarding discomfort accumulate with time. Therefore, the perception of ride comfort differs between short-term and long-term rides. Kamra et al. (2017) defined static comfort/discomfort as the perception in a stationary car and dynamic comfort/discomfort as the perception in a moving car.

Studies of static ride comfort in passenger cars have focused on ergonomic factors such as roominess and seat-human interference. Pheasant and Haslegrave (2005) concluded that the clearance between knee and car door/centre console were suggested indicators of legroom. Mohamed and Yusuff (2007) suggested to use the clearance between elbow and car door/centre console as an indicator of upper body room. The results in Mergl

(2006) concluded that when sitting, the pressure under the thigh/buttock area should be distributed according to the principle of 25–29% under the buttocks and less than 14% under the thighs and less than 3% under the front of the thighs.

When it comes to dynamic ride comfort, numerous studies focusing on the influences of sound and vibration have been conducted.

Wang et al. (2020) summarized that vibration experienced in passenger cars might degrade the overall ride comfort, cause motion sickness and interfere with activities during the ride. From their review, the greatest sensitivity of a seated human was founded in the range of 4–6 Hz for vertical vibration and 1–4 Hz for horizontal vibration by previous laboratory studies. Studies conducted by Kaderli and Gomes (2015) and Lin et al. (2006) concluded that vibrations transmitted to the seat pan, backrest were more significant in the vertical and lateral direction than in the longitudinal direction. From the studies of Mansfield (2001) and Kilincsoy et al. (2016), the greatest seat vibrations were identified on the contact areas between the seat and the human body, including beneath the knee, lower thighs and buttocks. Wang et al. (2020) summarized that the significant vibrations transmitted to passenger car seats are usually below 20 Hz for lateral and vertical vibrations and below 30 Hz for fore-and-aft vibrations. Whitham and Griffin (1978) indicated that occupants attributed their experience of vibration discomfort to their body movements. According to their studies, in the range of 4–16 Hz, the vibration discomfort was mainly experienced in the upper torso and head. At higher and lower frequency range, the discomfort was majorly reported in the lower body such as abdomen and buttocks. Hiemstra van Mastrigt et al. (2015) found that passive thigh movements had a positive effect on releasing ride discomfort.

Clark et al. (2006) indicated that sound inside the cabin could induce annoyance and discomfort. Qatu et al. (2009) demonstrated that the major energy of interior sound in combustion engine vehicles was concentrated in the low frequencies. They found that the overall interior A-weighted sound pressure level under wide-open throttle was usually between 45–80 dBA for conventional passenger cars. Qatu (2012) concluded that the interior sounds were dominated by tyre-road noises at low-to-medium constant speeds (i.e., 40–85 km/h), and wind noise dominated the interior sounds at higher constant speeds (i.e., above 75 km/h). From the study of Qatu et al. (2009), powertrain sound was noticeable especially during idling, partial throttle, wide-open throttle, cruising, and coast-down, the occupants expected there to be powertrain sounds. Below 40–50 km/h, powertrain noise may be even more significant than tyre-road noise. According to the results of Zeitler and Zeller (2006), sound discomfort was dominated by sound at constant speeds, and the sound under acceleration was attributed to the perception of sportiness.

Most of the previous studies on ride comfort found in the literature have investigated the effects of a single factor, or its influence during a single scenario. However, the human perception of overall ride comfort is affected by a variety of simultaneous inputs from the car. Moreover, the influences of different factors are not constant in all driving scenarios (Wang et al., 2020). Therefore, it is difficult to predict the human perception of ride comfort by investigating only one factor or studying just one scenario.

The purpose of this study is to identify how human experiences regarding sound and vibration varied in eight different driving scenarios as well as how sound and vibration influence the overall perceived ride comfort. The study also should assess the factors that influence the user experience of ride comfort in each scenario.

Method

This user study was conducted in a combustion engine car (CV) during eight typical ride scenarios. A combination of objective and subjective measures was used.

Test car

A typical SUV passenger car with a standard front seat of a modern car (steel frame with foam and trim) was utilized in the test. The data of the test car is listed in Table 1.

Table 1. Specification of the test car

<i>Parameter</i>	<i>Specification</i>
<i>Type</i>	Internal combustion engine SUV
<i>Year of modal</i>	2019
<i>Mass In Running Order</i>	1665
<i>Tyre</i>	235/50 R19
<i>Wheel drive</i>	AWD
<i>Length (mm)</i>	4512
<i>Width (mm)</i>	1866
<i>Motor / engine</i>	4 cylinder, 200 hp

Participants

Ten participants (Table 2), consisting of two females and eight males, were recruited from within the company China-Euro Vehicle Technology AB (CEVT). These participants were chosen because of the limited availability to participants out of company during the Covid-19 pandemic. Four of the participants, who were engineers working with vehicle dynamics as well as noise and vibration testing, had some experiences of riding in electrical cars. The other six participants could serve as non-experts and had minor experiences of riding in electrical cars. All participants reported that they had normal hearing of their age. Nine of the participants (P1–P8, P10) are primary drivers using cars more than 65% of their transportation time. One participant (P9) uses mainly public transports and walking and is most often a passenger when using a car.

Table 2. Demographic data of participants reported by the participants using Questionnaire I, Appendix.

	<i>P1</i>	<i>P2</i>	<i>P3</i>	<i>P4</i>	<i>P5</i>	<i>P6</i>	<i>P7</i>	<i>P8</i>	<i>P9</i>	<i>P10</i>
<i>Gender</i>	Male	Male	Male	Male	Male	Male	Male	Male	Female	Female
<i>Occupation</i>	Experts				Non-experts				Non-experts	
<i>Age</i>	26-35	36-50	36-50	18-25	36-50	36-50	26-35	26-35	26-35	26-35
<i>Height</i>	192	178	188	190	173	188	183	190	182	165
<i>Weight</i>	79	73	87	95	73	90	87	103	78	65
<i>BMI</i>	21	23	25	26	24	25	26	29	24	24

Test scenarios

Eight scenarios were performed in the test ride (Figure 1). The order of the scenarios was designed to mimic an ordinary ride that could be found during real-world riding. All participants experienced the same order of test scenarios to reduce the influence of different scenario order.

First, the participants entered the car, sat in the front passenger seat of the car, adjusted the seat to find a relaxed sitting position under the help of test leader, fastened their seatbelt and then sat for two minutes before assessing the static ride comfort (Scenario 1). The driver then started and stopped the engine three times to simulate the driving conditions at traffic lights (Scenario 2). The driver accelerated from stationary to 50 km/h and decelerated to a halt twice, using 20% and 50% throttle respectively (Scenario 3-1). The car was then accelerated from 50 km/h to 100 km/h using 20% throttle followed by deceleration and coming to a halt (Scenario 3-2). After that, the car travelled at higher (120 km/h) and lower (60 km/h) constant speeds (Scenarios 4-1, 4-2). Later, the car was driven over speed bumps (Scenario 5), long bumps and around corners (Scenario 6), plus bridge joints (Scenario 7) and rough roads (Scenario 8). Table 3 lists the specifications of the test tracks used and the speeds in each test scenario.

Test procedure

The process of this user study is listed in Table 4. Three sessions were included: i) an introduction to the study; ii) the test rides, including simultaneous subjective assessments and objective measurements; and iii) a semi-structured interview.

During the test ride, the participants were not supposed to talk to the driver unless they wanted to terminate the ride of any reason. The participants were required to sit, without doing anything, in a posture they found relaxed until the driver stopped and told them to fill in the questionnaire. Moreover, the participants were not allowed to

change anything in the questionnaire once it had been filled in after each scenario. In the semi-structured interview afterwards, the participants could refer to their ratings and remarks filled in the questionnaires.

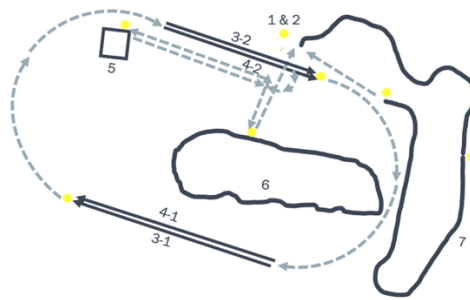


Figure 1. The eight test scenarios. The solid lines represent the test routes and the dashed lines represent transportation routes. The yellow spots are the places for the participants to answer the questionnaires. The nominal transportation speed between the scenarios was set to 60 km/h.

Table 3. The specifications of the ten test scenarios

No.	Test Scenarios	Cycle (km/h)	Specification
1	Initial comfort	N/A	Interior temperature 21°C
2	Start/stop	N/A	
3-1	Acc & Dec	From 0 to 50	20% throttle, straight highway track
	Acc & Dec	From 0 to 50	50% throttle, straight highway track
3-2	Acc & Dec	From 50 to	20% throttle, straight highway track
4-1	Constant speed	120	Straight track and radius about 600 m
4-2	Constant speed	60	Straight track and larger radius
5	Speed bumps	20	8 speed bumps on short straight streets
6	Long bumps and	80	Country road with poorly designed banking
7	Bridge joints	80	6 joints on straight rough road
8	Rough roads	50	Rough asphalt surface

Table 4. The process of user study

Session	Task	Duration
Introduction	<ul style="list-style-type: none"> The moderator explained the expressions utilized in the questionnaires The moderator collected the participants' demographic data using questionnaire (Questionnaire I in Appendix). The participants consented to partake in the study 	30 min
Test ride and questionnaire	<ul style="list-style-type: none"> The participants took ride in eight scenarios as a front seat passenger in the CV. After each scenario, the participants rated their experiences using questionnaires for Scenario 1 and Scenario 2–8, respectively (Questionnaire II and III in Appendix). The participants ranked the factors influencing their experienced ride comfort in the CV using questionnaires (Questionnaires IV in Appendix). 	60 min
Semi-structured interview	<ul style="list-style-type: none"> The participants reflected on the causes of their discomfort in the test ride overall. 	30 min

Subjective data collection

Subjective data was collected using questionnaires in each scenario and semi-structured interviews after completing the whole test ride. In the questionnaire, the ratings of sound, vibration and seat were assessed.

Variables such as seat, sound and vibration according to their influences on perceived ride comfort or discomfort were ranked in descending order. In the interview, the characteristics of sound and vibration and induced body movements were discussed in relation to discomfort.

Questionnaires for ratings on ride experiences in each scenario

The subjective ratings on ride experiences were collected using questions and scales listed in Questionnaires II and III, Appendix I for Scenario 1 and Scenarios 2–8, respectively. Questionnaire II comprises seven ratings regarding the experiences of ingress, frontal and lateral visibility, room for the human body, seat fit, seat stiffness, seatbelt constraint and relaxed sitting. In Questionnaire III, the subjective assessment focused on the dynamic ride comfort caused by sound, vibration, body movements and seatbelt constraint.

The five-point scale used in the questionnaire encompasses a semantic scale and a self-assessment manikin (SAM) scale. A semantic scaling method has been widely used to rate stimuli according to the extents to which they are perceived (Carroll et al. 1959). Both unipolar (e.g., not annoyed at all–extremely annoyed) and bipolar (e.g., calm–alert) semantic scales were utilized in the current study according to the characteristics of interest. SAM has been widely used to measure an emotional response using picture-orientated questionnaires. Compared to descriptive rating methods, SAM has the advantage of being easy and consistent to interpret in context of what emotions develop, especially in assessing sound (Bynion & Feldner, 2017). In the current study, only valence dimension and arousal dimension were assessed.

Questionnaires for ranking of various factors after the test ride

After the test ride, the test subjects ranked factors in a given list in descending order (with 1 representing the greatest influence) according to their influences on the perceived comfort and discomfort. The factors for comfort and discomfort are shown in Questionnaire IV in Appendix. The participants were required to rank only the factors influencing their experiences. According to the designed test scenario 1, the participants experienced mainly ergonomic and ambient factors in the stationary car. In evaluating factors regarding static comfort, therefore, the ergonomic factors (i.e., ingress, room for the body, visibility, seat adjustment, seat support, seatbelt position and seatbelt adjustment) and ambient factors (i.e., air quality, temperature and lighting) were listed. To investigate the influence of sound and vibration on overall discomfort, a ranking was given for enough room, relative movements in various body parts, perceived numbness in various body parts, seat support, seatbelt constraint, seatbelt adjustment, the vibration and sound experienced and the concordance between different modalities.

Ranking order method was utilized due to the advantage on the relative comparison of several stimuli in relation to a given parameter, such as annoyance or discomfort. This method has been suggested for the analysis of minor differences between stimuli (Namba & Kuwano, 2008).

Interview questions

The experiences in each scenario as well as the causes of sound and vibration annoyance were collected in the semi-structured interview. The interview consists of general and specific questions. In the beginning of the interview, participants were required to answer the general questions listed in Table 5. Specific questions shown in Table 5 allow further discussion on the causes for comfort/discomfort, the perceived characteristics of sound and vibration, the concordance between sound and vibration, the recognised ride motions of the test car and the induced body movements experienced in each scenario. For further understanding, the probing questions were always utilized as follow-up questions. The participants were allowed to refer to the questionnaires and raise additional issues in the interview.

Subjective data analysis

To analyse the experienced sound and vibration in each scenario, the ratings of sound and vibration annoyance collected in the questionnaires were studied first for each participant and then between different scenarios. The ratings of valence and arousal cause by sound were compared for all scenarios. The ratings regarding relative movements of various body parts as well as the concordance between sound and vibration were investigated for different scenarios.

The subjective data collected in the interviews, such as the causes of discomfort were categorized into sound, vibration, the discordance between sound and vibration and induced body movements. The attributes of sound and vibration that caused annoyance were categorized according to the sources, frequency composition and

psychoacoustic perception (e.g., sharp). The number of participants who commented in each category was summarized.

Table 5. The interview questions

<i>Ques</i>	<i>Questions</i>
<i>General</i>	<ul style="list-style-type: none"> ▪ How did you experience this ride? ▪ What made you feel comfortable while sitting in a stationary car? ▪ What caused your discomfort while the car was driving? ▪ Was there anything influenced your experiences but not mentioned in the questionnaire?
<i>Specific</i>	<ul style="list-style-type: none"> ▪ What was the major cause of comfort in this scenario? (for Scenario 1) ▪ Did you experience discomfort in the stationary car? If so, what was the cause? (for Scenario 1) ▪ What was the major cause of discomfort in this scenario? (for Scenario 2–8) ▪ How did you feel about the sound in this scenario? ▪ How did you feel about the vibration in this scenario? ▪ Did you recognize ride motions of the car? ▪ Did you recognize movements in your body? ▪ Did you feel the sound and vibration were discordant? Why (if so)?

Objective data collection

The sound and vibration measurements as well as the recordings of human posture were performed to support further understanding of the participants' experiences. Two web cameras were installed in front of the participant and on the sun visor above the driver to capture the participants' upper and lower body movements. The sound and vibration were collected simultaneously using real-time data acquisition systems. Vibration was measured on the seat rail and armrest. Sound was measured by the front passenger's left ear.

Objective data analysis

In order to support understanding of the participant's subjective ratings and reflections, the frequency spectrum of sound, vibration and ride motions were analysed by applying Fourier transform. The A-weighted sound pressure level of measured sound in each test scenario was calculated in third octave band within the range of 20–10000 Hz. The frequency range of the analysis was selected with respect to the human hearing range and the range of significant sound. The vibration and ride motion were analysed between 0.5–50 Hz to cover the range of highest human sensitivity with significant vibration transmitted to seat and armrest. The selected vibration signals corresponded to the selected sound pieces.

The participants' body movements were observed on the video films by the same observer and classified into active movements and induced movements. Active movements consist of both conscious and unconscious posture variations made by the participants. Induced body movements were the reported body movements caused by vibration and ride motion of the car. They were divided into lateral upper body movements, lateral lower body movements and longitudinal upper body movements.

Results

The subjective judgements on experienced sound, vibration and ride motion are presented firstly as a summary for all scenarios and then separately for each test scenario. The subjective judgements consist of the ratings on the comfort/discomfort and the influence rankings of various factors collected by questionnaires. The related characteristics of sound and vibration for these ratings are further elaborated upon in the interviews. In this session, the results from questionnaires and interviews are reported and analysed together.

Summary of all results for all scenarios

The influence ranking of various factors showed in Figure 2 indicated that “enough room for body”, “easy ingress”, “easy seat adjustment” and “good body support” had greater influence on static comfort compared to other factors. From results of Scenarios 2–8 illustrated in Figure 3, dynamic discomfort was mainly attributed to “not enough support”, “hard to relax” and “not enough room”.

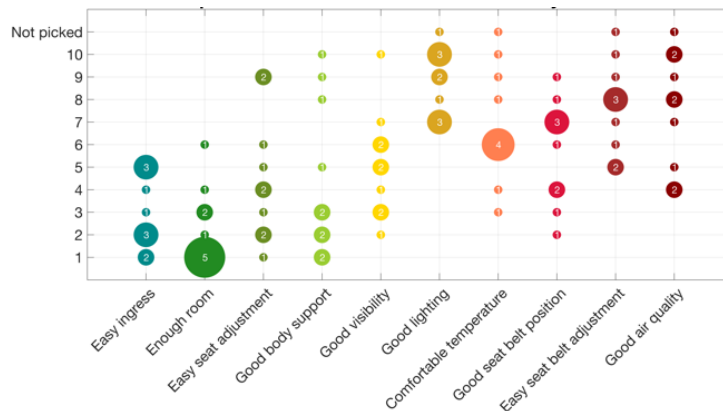


Figure 2. Ranking of factors influencing initial comfort in a stationary car. The full labels are listed in Appendix, Questionnaire II.

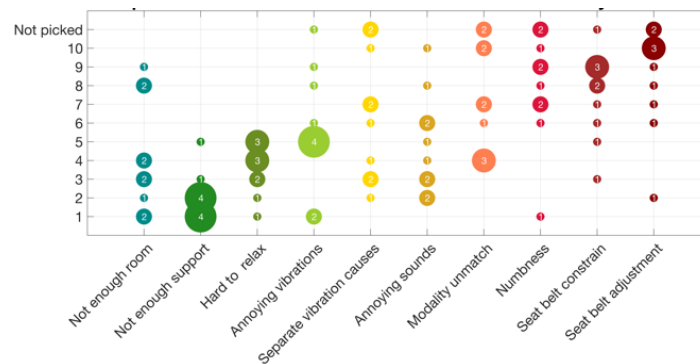


Figure 3. Rankings of factors influencing discomfort according to scenario 2–8. The full labels are listed in Appendix, Questionnaire III.

Figures 4 and 5 illustrate the rating of sound and vibration collected by questionnaires after each scenario. The annoyance caused by sound and vibration varied with driving scenarios. The results also indicate the difference in sensitivity between participants. The subjective ratings of P9 and P10 exhibited less variations in the changes in sound and vibration compared to other participants.

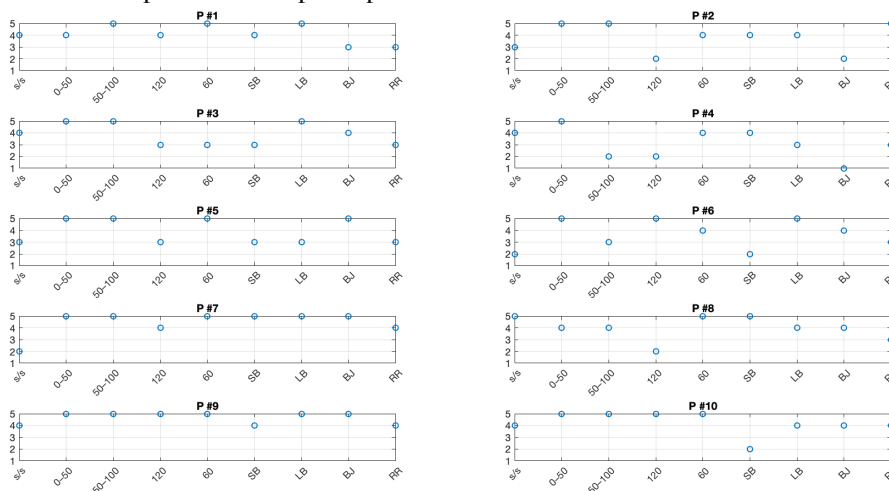


Figure 4. Sound annoyance for each participant. The value “1” stands for “extremely annoyed”, while “5” stands for “not annoyed at all”. The horizontal labels represent “start/stop”, “accelerating and decelerating 0–50 km/h”, “accelerating and decelerating 50–100 km/h”, “constant 120 km/h”, “constant 60 km/h”, “speed bumps”, “long bumps and cornering”, “bridge joint”, “rough roads”

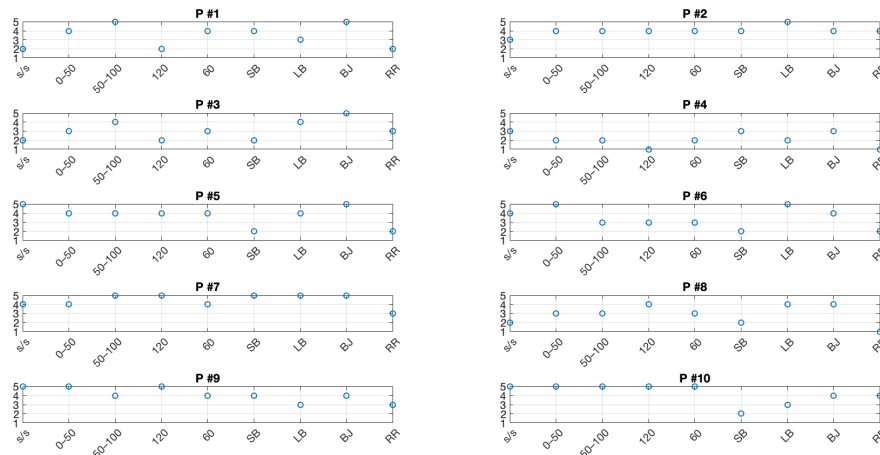


Figure 5. Vibration annoyance for each participant. The value “1” stands for “extremely annoyed”, while “5” stands for “not annoyed at all”. The horizontal labels represent “start/stop”, “accelerating and decelerating 0–50 km/h”, “accelerating and decelerating 50–100 km/h”, “constant 120 km/h”, “constant 60 km/h”, “speed bumps”, “long bumps and cornering”, “bridge joint”, “rough roads”.

Scenario 1: initial comfort

As shown in Figure 2, “enough room” was of the greatest influence to the presence of static comfort. In the interviews, three participants (P1, P2, P6) reported insufficient legroom and four participants (P3, P4, P6, P8) reported insufficient room for upper body because their knees or elbows touched the centre console.

From the interviews, the experience of seated relaxation was attributed to seat support (P1, P3, P4, P6, P8, P9), seat dimensions (P1–P3, P5, P6, P7, P10), seat contour (P1, P4, P8) and seat stiffness (P1–P3, P5, P7). Six participants (P1–P3, P5–P7) reported insufficient length of the seat and insufficient seat support provided. Three participants (P2, P5, P7) preferred a harder surface because they thought a stiffer seat would be more comfortable on a long ride, based on their previous experiences. Two participants (P3, P7) thought the stiffness of the car seat was satisfying due to a feeling of “sinking in”.

Scenario 2: start/stop

Tables 6 and 7 exhibit the comments with respect to sound and vibration collected in the follow-up interview. During start/stop, all participants reported pronounced low frequency sound and vibration. The sound developed from silent to audible low-frequency sound. The low-frequency pressure transmitted to human body was also perceived. From measurements, pronounced low-frequency components could be observed in both measured sound and vibration. These low frequencies were attributed to the rigid body resonances of the car induced by the engine starting.

Scenario 3: acceleration and deceleration

With increasing speed from stationary to 50 km/h, all participants reported that the engine sound and tyre-road noise became louder. They commented in the interviews that the sound was indicating speed increasing and not annoying. As shown in Table 6, wind noise was the major sound during accelerating 50–100 km/h. Five participants (P2–P4, P6, P7) reported wind noise in this scenario. An increment of 8 dBA could be identified in maximum value of fast averaging A-weighted sound pressure level (L_{pAFmax}) when the speed increased from 0–50 km/h ($L_{pAFmax} = 60$ dBA) to 50–100 km/h ($L_{pAFmax} = 68$ dBA).

Three participants (P3, P4, P8) reported longitudinal oscillations during accelerating 0–50 km/h. Only two participants (P3, P8) used the armrest and both perceived noticeable vibration on the armrest which became more pronounced with increasing speed. In the measured vibration on the armrest, distinct peaks could be identified between 16–30 Hz.

Scenario 4: constant speed

At constant speed 120 km/h, wind noise and tyre-road noise were the main audible sounds reported. From the comments listed in Table 6, three participants (P2, P4, P8) attributed sound annoyance to the fluctuating and loud

wind noise at 120 km/h. When the driving speed was lower (constant speed 60 km/h), as illustrated in Figure 4, six participants (P1, P2, P4, P5, P7, P8) judged the sound as less annoying than that during constant speed 120 km/h. In the interview, the increase in subjective sound ratings was attributed to the decrease in perceived sound pressure levels and in wind noise. The equivalent A-weighted SPL was 71 dBA at higher speed and was 65 dBA at lower speed. The participants judged the sound at lower speed as more positive (Figure 6). In the interviews, they attributed this to the reduction in sound levels and in high-frequency components.

Four participants (P1, P3, P4, P8) reported longitudinal oscillations upon braking (P1, P3, P4) in the interviews. The oscillations were more noticeable at higher than lower speed (P1, P3, P4, P8); thus, the vibration annoyance was greater at higher speed.

Table 6. Comments summarized from interviews regarding experienced sound. N represents the number of participants that made judgement on the corresponding parameters.

<i>Sound</i>	<i>LF</i>	<i>Tyre noise</i>	<i>Wind noise</i>	<i>Soft</i>	<i>Loud</i>	<i>After tones</i>	<i>not of focus</i>	<i>sharp</i>
<i>S2</i>	✓ (N=10)							
<i>S3-1</i>		✓ (N=10)						
<i>S3-2</i>			✓ (N=5)					
<i>S4-1</i>			✓ (N=3)					
<i>S4-2</i>				✓ (N=10)				
<i>S5</i>	✓ (N=5)	✓ (N=8)			✓ (N=3)	✓ (N=3)		
<i>S6</i>							✓ (N=7)	
<i>S7</i>					✓ (N=4)			✓ (N=4)
<i>S8</i>		✓ (N=2)	✓ (N=4)				✓ (N=6)	

Table 7. Comments summarized from interviews regarding experienced vibration. N represents the number of participants that made judgement on the corresponding parameters.

<i>Vibration</i>	<i>LF</i>	<i>Longitudinal</i>	<i>Lateral</i>	<i>Vertical</i>	<i>Arm</i>	<i>no pronounced vibration</i>	<i>relative movement</i>	<i>pitching</i>	<i>rolling</i>
<i>S2</i>	✓ (N=10)								
<i>S3-1</i>		✓ (N=3)			✓ (N=2)				
<i>S3-2</i>						✓ (N=10)			
<i>S4-1</i>		✓ (N=4)							
<i>S4-2</i>						✓ (N=10)			
<i>S5</i>				✓ (N=4)				✓ (N=4)	
<i>S6</i>			✓ (N=10)				✓ (N=4)	✓ (N=9)	✓ (N=9)
<i>S7</i>						✓ (N=10)			
<i>S8</i>		✓ (N=2)	✓ (N=3)	✓ (N=4)	✓ (N=2)				

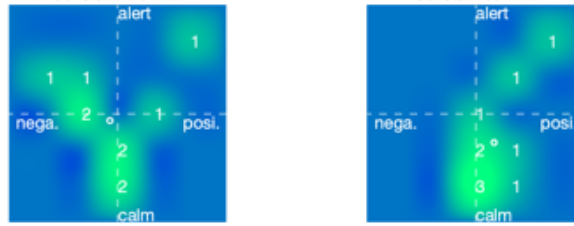


Figure 6. Sound characteristics under scenarios 4-1 (left) and 4-2 (right) (N=10). The horizontal axis represents how positively or negatively the sounds are judged. The vertical axis represents the level of activeness or calmness of the sounds. The white circle represents the averaged value.

Scenario 5: speed bumps

As listed in Table 6, participants perceived loud tyre noise when the car went over bumps. The sound measurements identified an increment around 12 dBA in sound levels before and at impact: the maximum A-weighted sound pressure level at speed bumps was 68 dBA and 56 dBA between the bumps. Three participants (P1, P6, P10) rated the impact sound as negative, as seen in Figure 7. In the interviews, the negative perception was attributed to the long-lasting sound after the impact.

Four participants (P5, P8, P6, P10) reported the vertical bouncing of their body and pitching motions of the car as seen in Table 6. In the interviews, the participants attributed their experienced vibration discomfort to the pitching motions caused by shakes after the impact.

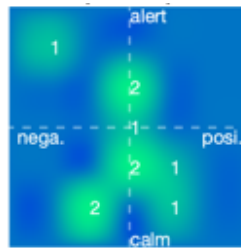


Figure 7. Sound characteristics under scenario 5 (N=10). The horizontal axis represents how positively or negatively the sounds are perceived. The vertical axis represents the level of activeness or calmness of the sounds. The white circle represents the averaged value.

Scenario 6: long bumps and cornering

From the interviews, participants attributed the perceived discomfort majorly to their experienced vibration and induced body movements. Six participants (P1–P3, P5, P6, P8) rated the sound as calming as shown in Figure 8. Eight participants (P1, P4, P5–P10) commented that the focus on sound was significantly reduced due to the pronounced body movements.

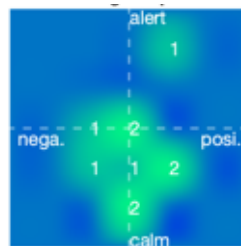


Figure 8. Sound characteristics under scenario 6 (N=10). The horizontal axis represents how positively or negatively the sounds are perceived. The vertical axis represents the level of activeness or calmness of the sounds. The white circle represents the averaged value.

Nine participants (P1–P3, P5–P10) rated the vibration as not annoying. In the interviews, however, the participants reported pronounced lateral and vertical vibration caused by the rolling and pitching motion when driving over long bumps. Nine participants reported difficulty of relaxing sitting and attributed this to the lateral upper body movements (P2, P6–P8, P10) and lower body movements (P1–P5). By observing the recorded videos, the adjustments in the positions of arms (P1–P4, P8, P9) increased noticeably compared with previous scenarios. As illustrated in Figure 9, four participants (P1, P4–P6) reported relative movements between upper and lower body. In the interviews, they commented that these relative movements aggravated the experienced vibration discomfort.

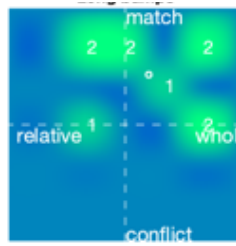


Figure 9. Characteristics of vibrations under scenario 6 (N=10). The horizontal axis represents whether body movements were perceived as a whole or whether relative motion between different body parts was recognised. The vertical axis represents the modality match between the vibration, sound and visual aspects. The white circle represents the averaged value.

Scenario 7: bridge joints

Four participants (P1, P2, P4, P8) reflected that the impact sounds were loud and annoying. The maximum sound level identified an increment around 14 dBA between the impact sound and the sound before/after impact.

Participants reflected that there were no pronounced vibration and ride motions when the tyres went over bridge joints - only audible sound.

Scenario 8: rough roads

The participants attributed the experienced discomfort mainly to the vibration and induced body movements in the interviews. Eight participants (P1, P2, P4–P6, P7, P9, P10) reported decreased focus on sound due to the perceived vertical bouncing (P1, P2, P4, P5) and lateral body movements (P5, P6, P7). However, five participants attributed their difficulties in relaxing sitting to the wind noise (P1, P4, P8, P6), low-frequency engine sounds and rough tyre-road noise (P6, P7).

Discussion

This user study sought to identify the important factors in overall ride comfort under various scenarios. The overall results show that static comfort was mainly influenced by ingress, room for the body, seat adjustment and seat support. Dynamic discomfort was affected by upper body movements, legroom, distinct vibrations in body parts, annoying sounds and the discordance between sound and vibration. The results indicate that the influence of various factors differs between static and dynamic conditions.

Influence of sound and vibration

Like the conclusions of previous studies, the current study found that sound and vibration evoked annoyance and discomfort. Furthermore, the current study highlights that the discordance between sound and vibration could cause discomfort.

In the current study, tyre-road noise and wind noise were the main causes of perceived discomfort in the CV at low-to-medium speeds (20–80 km/h) and higher speeds (above 80 km/h). These findings can be supported by previous studies indicating tyre-road noise and wind noise as the main source of noise (Qatu, 2012). The characteristics of tyre-road noise that caused annoyance were reported in the interviews as loudness and low frequency. Sharpness, loudness and fluctuation strength were reported in the interviews the characteristics of wind noise that inducing annoyance. From the findings of previous studies, engine sounds are more associated with the power and sportiness of a car, rather than discomfort (Ih, Kim, Lee, & Shinoda, 2009). This is also evident in the current study during starting/stopping and acceleration.

According to previous studies, the seated occupant is more sensitive to vertical and lateral vibration in the frequency range below 30 Hz (Wang et al., 2020). Nevertheless, in this study, the vibration discomfort in a CV was more associated with low-frequency lateral and longitudinal oscillations at lower driving speeds. The participants reflected that visual input from the environment helped them establish their expectations of vibrational input and the resulting body motion vertically. For instance, occupants expected some bouncing if a large bump was seen during their ride. Thus, the occupants were most annoyed by horizontal vibration, especially laterally. Longitudinal oscillations were another cause of discomfort. Participants commented on longitudinal

oscillations mainly in context of shakes after the event, such as after deceleration, braking and impact. This indicated that the horizontal motion of occupants' bodies could be used as an indicator of dynamic discomfort.

In this study, only two participants used armrest and both reported discomfort caused by distinct vibration on the armrest. This might also be evidenced by the peaks between 16–30 Hz, which are the frequency ranges of great human sensitivity regarding vibration in the arms (Wang et al., 2020). Thus, the other participants might perceive the distinct vibration on the armrest and the resulted discomfort if they used the armrest during riding.

In the interviews, the discordance between sound and vibration is one important cause of dynamic discomfort, especially when driving over bridge joints. According to the participants' reflections, occupants naturally preferred less sound and vibration during their ride. Nevertheless, they would rather experiencing simultaneous sound and vibration at matching levels in the case of impacts, than experiencing louder sounds with minor vibrations. In future mobility, the visual input which could compensate for the discordance between vibration and sound may decrease because occupants may perform more activities, such as working, relaxing and using electrical devices (Wang et al., 2020). The discordance between vibration and sound, therefore, would probably induce greater discomfort in the future. However, the specifications with respect to concordant levels between sound and vibration have rarely been investigated for passenger cars.

Moreover, the influences of sound and vibration interference with each other. For instance, the focus on sound decreased noticeably when there were pronounced body movements caused by vibration (Scenarios 6 and 8). However, eight participants commented in the interviews that annoying sounds still caused difficulty in relaxing whilst seated and aggravated overall discomfort. This indicates that the instantaneous judgements after short-term scenarios may underestimate the influence of some factors, such as sound. Assessments of dynamic discomfort could consider both instantaneous responses and/or overall judgement depending on the evaluation purpose.

The comments regarding the experienced body movement and seat support also indicate the possibility to assess dynamic discomfort using an approach including both dynamic factors (vibration) and ergonomic factors (seat). The experiences of vibration and seat interfere with each other. On the one hand, the seat comfort experienced during a ride differs from the experience of sitting in a stationary car. A design for a comfortable passenger car seat that ignores exposed vibration and ride motion might be a total failure. An assessment of ride comfort should consider both static and dynamic scenarios. On the other hand, assessing vibration discomfort cannot be simplified to an analysis of transmitted vibration levels or frequency compositions. The induced lower body movements should be seen as an indicator of overall ride and seat comfort. Additionally, the perception of vibration discomfort might differ in the same passenger car with different types of seats. Meanwhile, the design and evaluation of legroom should include the seat support and vibrational inputs from the car. Well-designed legroom in static conditions might result in experiences of insufficient seat support and cause discomfort.

The influences of other factors

Based on the results of the current study, easy ingress is one of the critical factors contributing to static ride comfort and should therefore be included when assessing overall ride comfort. However, previous studies of overall ride comfort (Mohamed and Yusuff, 2007; Pheasant and Haslegrave, 2005) have seldom included ingress, with ingress experience barely described by the user. In the current study, the occupants, had difficulty in explaining what makes an ingress easy. They preferred to evaluate their ingress experience by comparing the test car with other cars. It is therefore proposed to assess ingress experience using paired comparisons rather than a scaling method for a single car.

Seat comfort in terms seat stiffness, contour and adjustment have been investigated in several studies. According to the studies conducted by Mansfield et al. (2014), the influences of seat dimension and seat contour would not vary under different vibrations. Nevertheless, in the current study, seat dimension and seat contour showed different effects on static and dynamic ride comfort. In a stationary car, the majority of participants experienced insufficient seat length. They therefore perceived insufficient longitudinal seat support longitudinally in the stationary car. In a driving car, the longitudinal seat support was even less sufficient and aggravated dynamic discomfort.

Moreover, the participants judged the seat comfort using different indicators under static and dynamic conditions. In static situations, the occupants attributed their experience of seat comfort to the combined effects of seat stiffness, dimensions and contour. For instance, insufficient seat length and soft seat foam resulted in improper contact-pressure distribution, causing discomfort in the stationary car. Insufficient seat width and the wing angle of the seat bolster caused static stress and discomfort to the sides of thighs. Under dynamic conditions, the

judgement of seat support focuses on upper body movements and legroom. The lateral upper body movements were attributable to insufficient upper body support, even though the distances moved are not significant. The discomfort caused by insufficient lower body support usually occurs over larger moving distances (e.g., when the knees knock against the car door or centre console).

It was concluded that adjustments to the seat pan and backrest influence ride discomfort due to the resulting change in posture and seat-human interaction (Li and Huang, 2021). In the current study, participants also emphasised easy adjustment of seat length, longitudinal legroom, backrest inclination and backrest position, due to their influence on both static and dynamic ride comfort.

The seatbelt constraint and air temperature which have shown influences on overall perceived ride comfort, are not presented in the results and discussions, since they were not in focus in this paper. The seatbelt constraint was assessed by the questionnaires in all scenarios. However, the participants did not judge the seatbelt constraint annoying according to their reflections in the interviews. This might be because all participants were used to the seatbelt constraint from their daily ride experience.

From the ranking of the influence on static comfort, air temperature was judged to be less important. This could be because the air temperature was controlled to be around 21°C in the test car. During the test ride, the participants did not perceive discomfort caused by temperature. This indicates that the influence of air temperature on perceived ride comfort could be eliminated by controlling the temperature when investigating other factors.

The influences of study method

In some user studies, the order of test scenarios has been randomized. In this study, however, the test scenarios were designed in a fixed order to mimic an ordinary daily riding. This allowed to investigate how the occupants' experiences of ride comfort developed by time in one scenario order that could be found in real world riding. There could be, however, some disadvantages caused by the influences of scenario order. The participants could relate later scenarios to their experiences in the earlier scenarios. In the interviews, the participants judged sometimes their experiences using comparison with the scenarios before. For instance, six participants (P1, P2, P4–P8) described that the impact sound was loud in scenario 7 (bridge joints) and they compared it with their perception during scenario 6 (long bumps and cornering). This type of comparison might influence the rating of sound annoyance in later scenarios. Meanwhile, the participants could be tired and have less concentration on the latter scenarios. There was no substantial discomfort reported in the whole test, therefore, the influence of scenario order might not have influenced the results to a larger degree.

There were not much difference between the experts' and non-experts' judgements obtained by questionnaires. However, in the interviews, the experts could explain their perception in an easier and clearer way compared with non-experts. For instance, when explained the reason of comfort perceived during ingress, experts could associate the presence of comfort to the height of floor and the architecture of car seat, whilst non-experts had difficulties in describing their comfortable experience of easy ingress. Nevertheless, experts sometimes judged their perceived comfort/discomfort according to their expectations established from occupational experiences instead of their instantaneous experience in the current study. In the interviews, the experts commented much on whether sound/vibration "should be like this".

The number of participants were limited due the covid-19 pandemic. The majority of people were working from home and showed little interest in participating in this type of user study. Since the current study was designed to investigate the influences of sound and vibration on the perceived ride comfort in different driving scenarios, and the results showed patterns of concentrated judgements, this limited number of participants could fulfil our requirements.

The results are valid only for the specific passenger car utilized in the current study. Some parameters such as the weight, might differ in other combustion engine cars. However, the utilized car was a typical car without any extreme design. Meanwhile many findings in the current study were correspondent to those from previous studies as discussed before. Therefore, the findings in the current study could provide insights to other combustion passenger cars.

Conclusions

The overall results of the user study on ride comfort were that there are a number of single factors such as sound, vibration and seat jointly affecting overall ride comfort in a conventional car. Moreover, the overall ride comfort

varied depending on driving scenarios; The individual comfort factors change during dynamic driving and thus the human perception of ride comfort also changes in various driving scenarios.

The specific results of the study were:

- static comfort was influenced mainly by ingress, enough room, seat adjustment and seat support;
- dynamic discomfort was affected by upper body movements, space for the lower body and seat support, as well as annoying sounds, distinct vibrations and discordance between sound and vibration;
- there was interference between vibration and sound. Pronounced vibration lowered the concentration on instantaneous sound and could influence the ratings of sound annoyance;
- tyre-road and wind noise were the main causes of perceived discomfort at low-to-medium speeds (20–80 km/h) and at higher speeds (above 80 km/h) respectively. The tyre-road noises caused annoyance because of the loudness and low frequency. The wind noises caused annoyance due to the sharpness, loudness and fluctuation strength.
- the vibration discomfort was more judged by the induced body movements and the relative movements between different body parts;
- the discordance between sounds and vibrations aggravated the perceived vibration discomfort;

In conclusion, the assessment of ride comfort in a combustion engine car should take into consideration the experienced sound, vibration and the concordance between them. The assessment for ride comfort should be designed with different focuses, corresponding to the driving situation (i.e., city traffic, highway and bumpy roads).

Acknowledgements

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Appendix

Questionnaire I: questions utilized to collect demographic data of participants.

1. What is your gender?
 - Female
 - Male
 - Other
2. How old are you?
 - 18–25
 - 26–35
 - 36–50
 - 51–65
 - over 65
3. What is your height? _____ cm What is your weight? _____ Kg
4. How often do you usually travel by walking, bicycling, car and public transport in an ordinary month? (The sum should be 100%)

walking __%, bicycling __%, public transport __%, car __%, other __%
5. Which car brand and model do most frequently use when you go by car?






Car brand _____ Car Model _____
6. How often do you travel *as a driver* when you use a passenger car?
 - 0–20%
 - 21–40%
 - 41–60%
 - 61–80%
 - 81–100%
7. How often do you travel *as a front seat passenger* when you use a passenger car?
 - 0–20%
 - 21–40%
 - 41–60%
 - 61–80%
 - 81–100%
8. How often do you travel *as a rear seat passenger* when you use a passenger car?
 - 0–20%
 - 21–40%
 - 41–60%
 - 61–80%
 - 81–100%
9. How often are you annoyed by sounds?

	I agree entirely	I agree partly	I disagree partly	I disagree entirely
It is not fun to have a conversation when the radio is on at the same time				
I often recognize disturbing sound sources later than other people around me				
I avoid going to noisy leisure events such as soccer games or leisure parks				
The smallest sound wakes me up				
I work very efficient and fast even in a noisy environment				






	I agree entirely	I agree partly	I disagree partly	I disagree entirely
I hardly hear the traffic noise when I am downtown shopping				
After an evening in a noisy pub I feel extremely exhausted				
When I want to fall asleep, I get hardly disturbed by sound				
I really like to visit quiet areas on a weekend				

Questionnaire II: Questions and scales for Scenarios 1






1.1 Is it easy to get into the car from the right front door?

Difficult						Easy
						






1.2 How about the visibility in frontal and lateral directions when you are sitting in the car?

Poor						Good
						






1.3 Is there enough room for your body in the space when you are sitting?

Crowded						Roomy
						






1.4 How do you feel when you are sitting in this car seat?

Tense						Relaxed
						






1.5 Does the car seat fit your body?

Do not fit						Fit very well
						

1.6 How do you experience the car seat?






Soft						Stiff
						

1.7 Are you satisfied with the constraint of seat belt?






Dissatisfied						Satisfied
						

Questionnaire III: Questions and scales for scenarios 2–8






2.1 How annoyed did you feel when you heard the sounds?

Extremely annoyed						Not Annoyed at all
						






2.2 Did you feel calm or alert when you heard the sounds?

Calm						Alert
						






2.3 Did you feel positive or negative when you heard the sounds?

Negative						Positive
						






2.4 How annoyed did you feel when you felt the vibrations?

Extremely annoyed						Not Annoyed at all
						






2.5 Did you think what you heard, saw and felt match each other or conflict with each other?

Absolutely conflict						Absolutely match
						

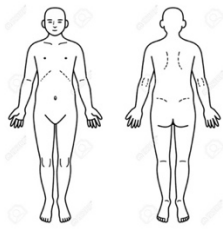
2.6 Did your body move as a whole or was there any relative motions between different body parts?

Relative motions						Move as a whole
						

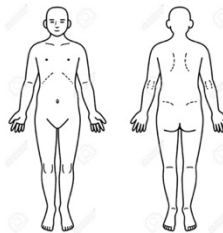
2.7 Did you feel the constraint from the seat belt smooth or abrupt?

Abrupt						Smooth
						

2.8 Did you feel discomfort in any body parts? If any, color then these in red in the human body figure.



2.9 Did you feel numbness in any body parts? If any, color these in blue in the human body figure.



2.10 Do you have comments on your experience that you would like to add here?

Questionnaire IV: Ranking of factors according to their influences on static comfort/dynamic discomfort.

1. How are the following factors affecting your **overall comfort** when you sit in a **standing still car before ride**? Choose the important factors from you testing experience and rank the importance in descending order (i.e., 1 is the most important factor).

<u>Rankings</u>	<u>Factors</u>
	<i>Easy to access through the right front door</i>
	<i>Enough room for my entire body when sitting in the car</i>
	<i>Easy to adjust the seat to find a comfortable posture</i>
	<i>Good support for my whole body (head/neck, arms/forearms, back /lumbar spine, buttock,</i>
	<i>Good visibility in all directions</i>
	<i>Good lighting inside the car at daylight</i>
	<i>Comfortable temperature inside the car</i>
	<i>Good seat belt position on my upper body</i>
	<i>Easy to adjust the seat belt to a proper position</i>
	<i>Good air quality inside the car</i>

2. How are the following factors affecting your **overall discomfort** when you sit as a front seat passenger **after the whole test ride**? Choose the important factors from you testing experience and rank the importance in descending order (i.e., 1 is the most important factor).

<u>Rankings</u>	<u>Factors</u>
	<i>Not enough room for my entire body when sitting in the car</i>
	<i>Not enough support for my different body parts (including for example, head, arms/forearms,</i>
	<i>Hard to find a relaxing sitting posture</i>
	<i>Annoying vibrations at the seat, headrest, car door or from the floor</i>
	<i>Relative motions between different body parts</i>
	<i>Annoying sounds inside the car</i>
	<i>The things I heard, I saw and the vibrations I felt did not match with each other</i>
	<i>Feeling numb in my muscle</i>
	<i>Uncomfortable constrain from the seat belt</i>
	<i>Difficult to adjust the seat belt to a proper position</i>

Paper C

Influence of sound and vibration on perceived overall ride comfort – A comparison between an electric vehicle and a combustion engine vehicle

Influence of sound and vibration on perceived overall ride comfort – A comparison between an electric vehicle and a combustion engine vehicle

Abstract

Replacing internal combustion engines in vehicles with electric motors is a step towards more sustainable transport and reduced environmental impact. There are significant differences in sound and vibration between combustion engine vehicles (CV) and electric vehicles (EV), and these differences may affect occupants' experiences of overall ride comfort. There have been few studies of human perception of overall ride comfort in electric vehicles. The purpose of this study is to identify how sound and vibration influence perceived overall ride comfort of an EV under different driving scenarios and to study differences between an EV and a CV in terms of the influences of sound and vibration on perceived ride comfort. The user study compared the experiences of ten participants' riding in a CV and an EV through eight typical driving scenarios. Subjective data was collected using questionnaires and semi-structured interviews. Objective data on sound and vibration were measured using microphones and accelerometers. The results showed that in both cars, static comfort was mainly influenced by ingress, room for the body, seat adjustment and seat support. In both cars, participants attributed vibration discomfort to induced body movement. In the EV, dynamic discomfort was dominated by pronounced high-frequency tones from electric components. The influence of sound on dynamic discomfort was more pronounced in the EV, and the causes of sound annoyance differed between the EV and the CV. In the CV, sound annoyance was primarily linked to tyre noise at lower speeds and wind noise at higher speeds. Meanwhile in the EV, sound annoyance was caused by high-frequency tonal sounds from the electric motor, especially in scenarios at lower speeds. When switching the CV engine on and off, low-frequency sounds and vibrations were pronounced. The EV produced no significant vibration during start/stop and emitted only a designed signature sound. The conclusion is that under different driving scenarios, sound and vibration have different influence on perceived overall ride comfort in the CV and EV. In the EV, high-frequency tonal sounds from electric components was the main cause of perceived discomfort. The low-frequency sounds and vibrations perceived in the CV during start/stop were absent in the EV. Thus, ride discomfort in the CV and EV are affected by various properties of sound and vibration.

Introduction

Sustainability is important for future generations and has drawn increasing attention in the automotive industry. In the EU, 18% of all greenhouse gas emissions have been attributed to vehicle transport (Omahne et al. 2021). The development of electric mobility helps reduce greenhouse gas emissions by replacing internal combustion engines with electric motors (Omahne et al., 2021). There are differences with respect to sound (Qin et al., 2020) and vibration (Wang et al. 2017) in electric vehicles (EVs) compared to combustion vehicles (CVs). Occupant experiences of ride comfort and discomfort therefore differ accordingly.

The factors influencing occupants' perception of ride comfort or discomfort have been categorised as either ambient, dynamic or ergonomic factors. Ambient factors include air temperature, air quality and sound. Dynamic factors include vibration, impacts, ride motion and acceleration. Ergonomic factors encompass visibility, functionality, seat architecture, seat belt and seat-human interference (X. Wang et al. 2020). There are interferences between several factors and these influenced on overall perception. For instance, Huang (2012) concluded that simultaneous sound and vibration showed masking effects on the discomfort caused by each other.

Numerous studies of vibration have looked at both CVs and EVs. The weighted vibration on the passenger car seats was usually significant below 20 Hz in the lateral and vertical directions and below 30 Hz in the fore-and-aft direction (X. Wang et al., 2020). During start/stop, vibration discomfort was attributed to the low-frequency resonance of the vehicle chassis and the induced resonance in human

organs (Qin et al., 2020). Due to the development of automatic start/stop systems in modern passenger cars, Qin et al. (2020) concluded that vibration discomfort when switching the vehicle on and off has drawn increased interest. Karikomi et al. (2006) found that EVs are different than CVs in terms of torque response. Their study concluded that in EVs without a torque converter, torsional vibration could cause a noticeable deterioration of ride comfort. He et al. (2010) found that in some EVs, vibration could be greater than that of a CV due to resonance between the traction motor and vehicle driveline. Wang et al. (2017) found that mechanical dampers in a CV's driveline, such as the clutch, flywheel and flexible joints, suppress vibration of the coupling between the engine and the transmission system. The majority of EVs lack some of these mechanical dampers, however, due to the use of an electric motor and the need to minimise weight.

Numerous laboratory studies have investigated human responses to sound and vibration. In the review conducted by X. Wang et al. (2020), seated subjects exposed to vibration were most sensitive to discomfort at around 5 Hz for vertical vibration and 2–4 Hz for horizontal vibration. Jia (2014) concluded that the head and eyeballs of a seated subject resonate at around 25 Hz when exposed to vertical vibration and between 20 and 90 Hz when exposed to whole-body vibration. A study by Morioka and Griffin (2008) showed that when excited at the hands, human's sensation of discomfort was greatest at frequencies of 10–16 Hz in all three directions. Arnold and Griffin (2018) found that longitudinal vibration most strongly affected the lower abdomen, ischial tuberosities, and back of the thighs. Lateral vibration was mainly associated with discomfort in the shoulders, chest, lower abdomen, ischial tuberosities and lower thighs.

Sound is another important variable affecting dynamic discomfort. Qatu et al. (2009) indicated that in CVs, sound is concentrated in the lower frequencies and reaches a maximum at around 200 Hz. They found that in CVs, tyre noise dominated perceived sound discomfort at low to medium speeds (40–85 km/h). Lindener et al. (2007) concluded that in CVs, wind noise was the main cause of the sound discomfort at higher speeds (above 100 km/h). Qin et al. (2020) found that structure-borne sound related to the combustion-engine firing cycle at 20–200 Hz is the dominant cause of sound annoyance when a vehicle is pulling away or coming to a stop. Fang et al. (2015) found that in EVs, the main energy of A-weighted sound was concentrated between 1000 and 2500 Hz. The sound generated by electrical components could be more noticeable in EVs than in CVs due to the absence of sound from an internal combustion engine (Qin et al., 2020). Berge and Haukland (2019) indicated that tyre noise became audible at lower speeds in EVs – around 20 km/h. He et al. (2010) concluded that sound radiated by the differential is the main source at low speeds, and sound from the electric motor is the main source at high speeds.

Fastl (2006) noted that assessments of sound are usually based on measurements of physical variables such as frequency, sound pressure level, measured loudness and sharpness. Fastl et al. (2012) found, however, that the ultimate evaluation and impression of a sound is 'filtered' by the human auditory and cognitive systems. Subjects judge a sound according to their sensation of it. Therefore, it has been recommended that measurements of physical magnitudes be mapped with psychoacoustic magnitudes such as auditory loudness, sharpness, fluctuation and roughness. Based on these psychoacoustic variables, the power, tone colour and temporal structure of sounds can be correlated to listeners' perceptions or the influence of a sound on listeners, including the annoyance, speech intelligibility, sleep disturbance and impairment to cognitive performance (Fastl, 2006). Human responses to sound have been shown to be dependent on inter-subject variables such as age, gender (Stelrnachowicz et al., 1989) and individual psychological factors such as expectations and experiences (Skagerstrand et al. 2017).

Most of these previous studies have investigated the influence of a single variable (e.g., sound or vibration) or have been conducted under a single scenario (e.g., at constant speed). However, in the real world, occupants receive a variety of simultaneous inputs from a car. A review of the literature (X. Wang et al., 2020) indicated that these inputs differ under different driving scenarios and in different cars. Humans' responses to sound and vibration vary depending on their frequency and amplitude. The

influences from sound and vibration interfere with each other. Moreover, few studies have examined the relationship between sound and vibration perceived ride comfort in EVs. Thus, it is of interest to investigate the differences in ride comfort and discomfort between CVs and EVs.

The purpose of this study is to identify the influence of sound and vibration on the front-seat passenger's perceived ride comfort in a typical EV during different ride scenarios. It also investigates differences in the influence of sound and vibration in EVs versus CVs.

Method

This user study involved 10 test subjects riding in the front passenger seat of two different test cars, a CV and an EV, during eight different ride scenarios. A combination of objective and subjective measures were used to evaluate ride comfort.

Test cars

Table 1 lists the data for the two test cars. The CV and the EV were of the same model size but they have different characteristics in terms of sound and vibration. A wide range of parameters, such as levels and frequency compositions, were covered by the different test scenarios. The seats were standard front seats of a modern cars (steel frame with foam and trim) but they differed in contour, stiffness and dimensions.

Table 1. Specifications of the test cars

	<i>Specification</i>	
	EV	CV
<i>Type</i>	SUV	SUV
<i>Model year</i>	2019	2019
<i>Mass In Running Order (kg)</i>	2657	1665
<i>Tyre</i>	255/50 R20 109H	235/50 R19
	xl	
<i>Drive</i>	AWD	AWD
<i>Length (mm)</i>	4900	4512
<i>Width (mm)</i>	1940	1866
<i>Motor / engine</i>	408 hp	4 cylinder, 200 hp

Participants

Ten employees of China-Euro Vehicle Technology AB (CEVT), two women and eight men, were recruited to participate. Due to the Covid-19 pandemic, non-employee participants were not recruited. Four of the participants were engineers who worked with vehicle dynamics and noise and vibration testing. They had also some experience with riding in an electric car. The other six participants, who served as non-experts, had limited experience riding in electric cars. Table 2 presents the participants' demographic data. All participants reported normal hearing for their age. Nine of the participants were primary drivers who used cars for more that 65% of their transportation time. One participant mainly used public transport and walking and was most often a passenger when using a car.

Table 2. Participants' demographic data

	<i>P1</i>	<i>P2</i>	<i>P3</i>	<i>P4</i>	<i>P5</i>	<i>P6</i>	<i>P7</i>	<i>P8</i>	<i>P9</i>	<i>P10</i>
<i>Gender</i>	Male	Male	Male	Male	Male	Male	Male	Male	Female	Female
<i>Occupation</i>	experts				non-experts				non-experts	
<i>Age</i>	26-35	36-50	36-50	18-25	36-50	36-50	26-35	26-35	26-35	26-35
<i>Height (cm)</i>	192	178	188	190	173	188	183	190	182	165
<i>Weight (kg)</i>	79	73	87	95	73	90	87	103	78	65
<i>BMI (kg/m²)</i>	21	23	25	26	24	25	26	29	24	24

Test scenarios

Participants went through a total of eight test scenarios as front-seat passengers. The scenarios (Figure 1) were executed in a particular order in order to mimic an ordinary ride. The focus of this study was to investigate how participants judged their experiences in real-world car rides and to reduce variability that could result from presenting the scenarios in a different order to different participants. Therefore, all participants followed the same order of test scenarios.

In scenario 1, participants first entered the front passenger seat of the car, adjusted the seat under the help of driver until they found a relaxed sitting position, buckled the seat belt and sat for two minutes. Then, in scenario 2, the driver switched the engine or electric motor on and off three times. In scenario 3-1, the car accelerated from standstill to 50 km/h and decelerated to standstill twice, at 20% and 50% throttle, respectively. In scenario 3-2, the driver accelerated the car from 50 km/h to 100 km/h using 20% throttle and then decelerated to a standstill. Then, in scenario 4-1 and 4-2, the driver drove at a constant speed of 120 km/h and 60 km/h, respectively. Later, in scenario 5, the car travelled over speed bumps, followed by long bumps and cornering for scenario 6, bridge joints for scenario 7 and rough roads for scenario 8. The solid lines and the dash lines in Figure 1 represent the test routes and travel routes, respectively. Traveling speed was set to 60 km/h between scenarios. Table 3 lays out the specification of the test track and the ten test rides.

Table 3. Specifications of the test scenarios

No.	Test Scenarios	Cycle (km/h)	Specification
1	Initial comfort	N/A	Interior temperature 21 °C
2	Start/stop	N/A	
3-1	Acc & Dec	From 0 to 50	20% throttle, straight highway track
	Acc & Dec	From 0 to 50	50% throttle, straight highway track
3-2	Acc & Dec	From 50 to 100	20% throttle, straight highway track
4-1	Constant speed	120	Straight track and larger radius
4-2	Constant speed	60	Straight track and larger radius
5	Speed bumps	20	8 speed bumps on short, straight streets
6	Long bumps and cornering	80	Country road with poorly designed banks
7	Bridge joints	80	6 joints on a straight rough road
8	Rough roads	50	Rough asphalt surface

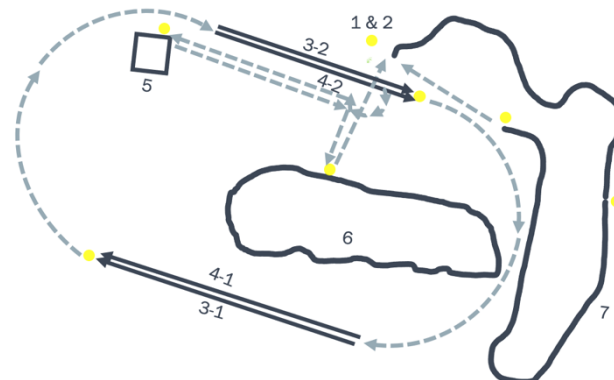


Figure 1. The eight test scenarios. The solid lines represent the test routes and the dashed lines represent the travel routes. The yellow spots are the points where participants answered the questionnaires. The nominal travel speed between scenarios was set to 60 km/h.

Test procedure

As Table 4 indicates, the study consisted of five parts: i) introduction; ii) test ride in the CV, including objective measurements during each test scenario and immediate subjective assessments after each scenario; iii) semi-structured interview to discuss participants' experiences in the CV; iv) test ride in the EV, including objective measurements during each test scenario and immediate subjective assessments after each scenario; v) semi-structured interview to discuss experiences in the EV.

The study was designed to investigate how occupants' experience in the EV would differ from that in the CV. The CV was used as a reference, since the participants reported that they were more familiar with CVs and had only limited experience in EVs. Therefore, all participants started the test in the CV and then, after a semi-structured interview of about 30 minutes, proceeded to repeat the test procedure in the EV.

The participants were not supposed to talk to the driver during the test ride unless they wanted to end the ride. They were required to sit in a posture they found relaxed, and not do anything until the driver stopped and told them to fill out the questionnaire. Participants were also not allowed to change anything in the questionnaire once it had been filled in after each scenario. In the semi-structured interview, participants could refer to the ratings and remarks they had made in the questionnaire.

Table 4. The user study process

<i>Session</i>	<i>Task</i>	<i>Duration</i>
<i>Introduction</i>	<ul style="list-style-type: none"> ▪ The moderator explained the expressions used in the questionnaires ▪ The moderator collected the participants' demographic data using a questionnaire (Questionnaire I in the Appendix). ▪ The participants consented to partake in the study. 	30 min
<i>Test ride in CV and questionnaire</i>	<ul style="list-style-type: none"> ▪ The participants rode as a front-seat passenger in the CV through the eight scenarios. ▪ After each scenario, participants rated their experiences using the questionnaires for Scenario 1 and Scenario 2–8, respectively (Questionnaires II and III in Appendix). ▪ Participants ranked the factors that influenced their experienced ride comfort or discomfort in the CV using questionnaires (Questionnaires IV in Appendix). 	60 min
<i>Semi-structured interview for CV</i>	<ul style="list-style-type: none"> ▪ The participants reflected on the causes of their discomfort during the course of the test ride. 	30 min
<i>Test ride in EV</i>	<ul style="list-style-type: none"> ▪ Same procedure as in CV 	60 min
<i>Semi-structured interview for EV</i>	<ul style="list-style-type: none"> ▪ Same procedure as in CV 	30 min

Subjective data collection

Subjective data was collected using questionnaires and semi-structured interviews. The questionnaire encompassed ratings of sound, vibration and seat, as well as the rankings of factors such as seat, sound and vibration according to how much they influenced the participant's perceived ride comfort or discomfort. In the interview, the characteristics of sound and vibration and induced body movement were discussed in relation to discomfort.

Questionnaires for ratings the ride experiences in each scenario

The subjective ratings of ride experience were collected using the questions and scales listed in Questionnaire II for Scenario 1 and Questionnaire III for Scenarios 2–8 (Appendix). Questionnaire II consists of seven ratings for the experiences of ingress, frontal and lateral visibility, room for the body, seat fit, seat stiffness, seatbelt constraint and relaxed sitting. Questionnaire III asks for ratings of dynamic discomfort caused by sound, vibration, body movement and seatbelt constraint.

The questionnaires used a five-point semantic scale and a self-assessment manikin (SAM) scale. The semantic scale method is well-suited for rating the extent to which different stimuli are perceived during exposure (Carroll et al., 1959). The questionnaires used unipolar (e.g., not annoyed at all–extremely annoyed) and bipolar (e.g., calm–alert) semantic scales depending on the characteristic of interest. Compared to descriptive rating methods, SAM has the advantage of being easy and consistent to interpret in the context of what emotions are developed, especially when assessing sound. It has been widely used to measure emotional responses using picture-orientated questionnaires (Bynion and Feldner, 2017). In this study, only the valence dimension and arousal dimension were assessed.

Questionnaires for ranking the various factors after the test ride

The rank order method was used due to the advantage for the relative comparison of several stimuli in relation to a given parameter, such as annoyance or discomfort. This method has been suggested for the analysis of minor differences between stimuli (Namba & Kuwano, 2008). The factors listed in Questionnaire IV in Appendix were ranked in descending order (with 1 representing the greatest influence), according to their influences on perceived comfort and discomfort after the test ride in one car.

Participants were required to rank only the factors that influenced their experiences. To evaluate the factors regarding static comfort, ergonomic factors and ambient factors were listed. The ergonomic factors investigated consisted of ingress, room for the body, visibility, seat adjustment, seat support, seatbelt position and seatbelt adjustment. The ambient factors studied were air quality, temperature and lighting. With respect to dynamic discomfort, the following factors were ranked: room for the body, relative movement of various body parts, perceived numbness in various body parts, seat support, seatbelt constraint, seatbelt adjustment, vibration and sound experienced and concordance between different vibration and sound.

Interview questions

The semi-structured interview explored participants' experiences in each scenario and the causes of sound and vibration annoyance. The interview included both general and specific questions. The general questions listed in Table 5 were asked in the beginning of the interview. The specific questions shown in Table 5 enabled further discussion on the causes of comfort/discomfort, the perceived characteristics of sound and vibration, the concordance between sound and vibration, the perceived motions of the test car and induced body movement, for each scenario. To fully understand participants' discussion, the interviewer always followed up with additional probing questions. Participants were allowed to refer to the questionnaires and raise additional issues in the interview.

Subjective data analysis

To analyse the experienced sound and vibration in each scenario, the ratings for annoyance caused by sound and vibration collected in the questionnaires were studied for each participant. The ratings for valence and arousal cause by sound, as well as the ratings for induced body movement and concordance between sound and vibration were examined for the different scenarios and for each of the two cars.

The subjective data collected in the interviews, such as the causes of discomfort, were categorized into sound, vibration, discordance between sound and vibration, induced body movement and others. Sounds and vibrations that caused annoyance were further classified according their source (e.g., tyre), frequency composition and psychoacoustic perception (e.g., sharp). The number of participants who commented in each category was summarized.

Table 5. Interview questions

<i>Type</i>	<i>Questions</i>
<i>General</i>	<ul style="list-style-type: none"> ▪ How did you experience this ride? ▪ What made you feel comfortable while sitting in the stationary car? ▪ What caused your discomfort while the car was moving? ▪ Did anything influence your experiences that wasn't mentioned in the questionnaire?
<i>Specific</i>	<ul style="list-style-type: none"> ▪ What was the major cause of comfort in this scenario? (for Scenario 1) ▪ Did you experience discomfort in the stationary car? If so, what was the cause? (for Scenario 1) ▪ What was the major cause of discomfort in this scenario? (for Scenarios 2–8) ▪ How did you feel about the sound in this scenario? ▪ How did you feel about the vibration in this scenario? ▪ Did you perceive motion while riding in the car? ▪ Did you perceive any movements of your body? ▪ Did you feel the sound and vibration were discordant? If so, why?

Objective data collection

Instantaneous sound and vibration were measured during the different driving scenarios. Figure 2 shows the locations of the sound and vibration sensors inside the cabin. Sound was measured at the front-seat passenger's left ear. Accelerations on the seat rail and armrest were collected using accelerometers. Table 6 lists the information from accelerometers and microphones used. Sound was measured at a sampling frequency of 25600 Hz. Vibration was measured at a sampling frequency of 1024 Hz.

Participants' body movements were collected through observations from two cameras mounted inside the car, as shown in Figure 2. Lower body movement was recorded by the camera installed in the sun visor above the driver. Upper body movement was recorded by the camera installed in front of the participant.

Table 6. Specifications of the measurement instrument

<i>Accelerometer</i>	<i>CV (mV/ms²)</i>		<i>EV (mV/ms²)</i>	
	<i>Brand</i>	<i>Model</i>	<i>Brand</i>	<i>Model</i>
<i>Seat</i>	PCB piezotronics	356A16	PCB piezotronics	44A13-M5
<i>Arm</i>	PCB piezotronics	356A16	PCB piezotronics	HT356A15
<i>Mic</i>	G.R.A.S.	46AE ½' CCP Free-field	G.R.A.S.	46AE ½' CCP Free-field
<i>Camera</i>	Logitech	C920	Logitech	C920



Figure 2. The location of the installed cameras (upper left), microphone (upper right), seat rail accelerometer (lower left) and armrest accelerometer (lower middle).

Objective data analysis

The A-weighted sound pressure level of the measured sound in each test scenario was calculated in one-third octave bands in the range of 20–10000 Hz. The frequency range for the analysis was selected to cover the range of human hearing with significant sound level. During start/stop (Scenario 2), only the first-time engine switching on/switching off was analysed, because in the EV only the first-time start/stop was accompanied by the designed signature sound. For accelerating and decelerating (Scenarios 3-1 and 3-2), the first period of acceleration or deceleration period was analysed. For the scenarios of constant speed (Scenarios 4-1 and 4-2), long bumps and cornering (Scenario 6) and rough roads (Scenario 8), the last ten-second sound was selected. For the sound during speed bumps (Scenario 5) and bridge joints (Scenario 7), the sound of the last impact was analysed. The overall A-weighted sound pressure level of each scenario was calculated for the entire duration of the scenario assessed.

The frequency spectrum of vibration was analysed by applying a Fourier transform. Vibration was analysed between 0.5–50 Hz to cover significant vibrations transmitted to the seat and armrest with high human sensitivity. The selected vibration signals were correlated with the selected sound components.

Participants' body movements were observed on the recorded video by the same observer and classified as either active movement or induced movement. Active movement included both conscious and unconscious posture changes. Induced body movements were body movements observed to be caused by the vibration of the car. These were divided into lateral upper body movement, lateral lower body movement and longitudinal upper body movement.

Results

The subjective judgements of experienced ride comfort and discomfort are presented first as a summary for all scenarios and then separately for different factors. The subjective judgements encompass the ratings for comfort/discomfort and the influence rankings of the factors collected in the questionnaires. The characteristics of sound and vibration attributed to these ratings were further elaborated upon in the interviews. In this section, the results from questionnaires and interviews are reported and analysed together.

Summary of all results for all scenarios

The ranking of factors influencing static comfort were similar for the EV and the CV. The results collected from Questionnaire IV indicated that 'enough room for the body', 'easy ingress', 'easy seat adjustment' and 'good body support' played the biggest role in static comfort.

Looking at the ranking for Scenarios 2–8, dynamic discomfort was mainly attributed to 'not enough support' in the CV but 'annoying sound' in the EV. Meanwhile, 'hard to relax' and 'insufficient seat support' caused greater dynamic discomfort in the CV than in the EV. The interviews revealed that insufficient seat support caused discomfort due to induced body movement. Participants associated difficulties in achieving a relaxed sitting position with induced body movement, distinct vibration in body parts, and annoying sound coupled with discordance between the sound and vibration.

Figures 3 and 4 demonstrate that the reported sound and vibration annoyance varied in different scenarios. Participant P9 did not experience sound or vibration annoyance in the EV in any scenario. The instantaneous judgement of sound annoyance collected after each scenario was clearly more pronounced for the EV than for the CV in two scenarios. For the Accelerating and decelerating 0–50 km/h scenario, six participants rated sound as more annoying in the EV than in the CV. For the constant 60 km/h scenario, eight participants rated sound as more annoying in the EV than in the CV.

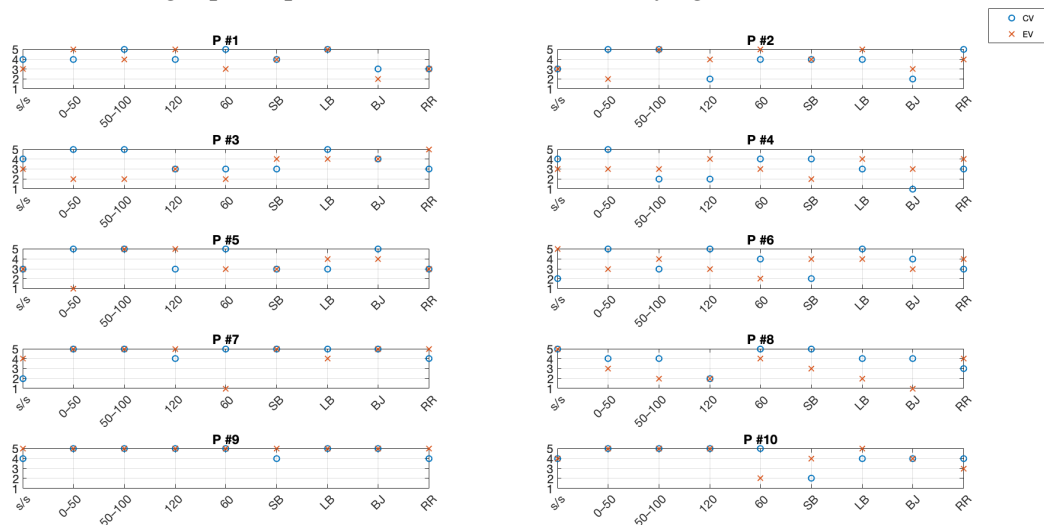


Figure 3. Sound annoyance for each participant. The value '1' stands for 'extremely annoyed', while '5' stands for 'not annoyed at all'. The horizontal labels represent 'start/stop', 'accelerating and decelerating 0–50 km/h', 'accelerating and decelerating 50–100 km/h', 'constant 120 km/h', 'constant 60 km/h', 'speed bumps', 'long bumps and cornering', 'bridge joint' and 'rough roads'.

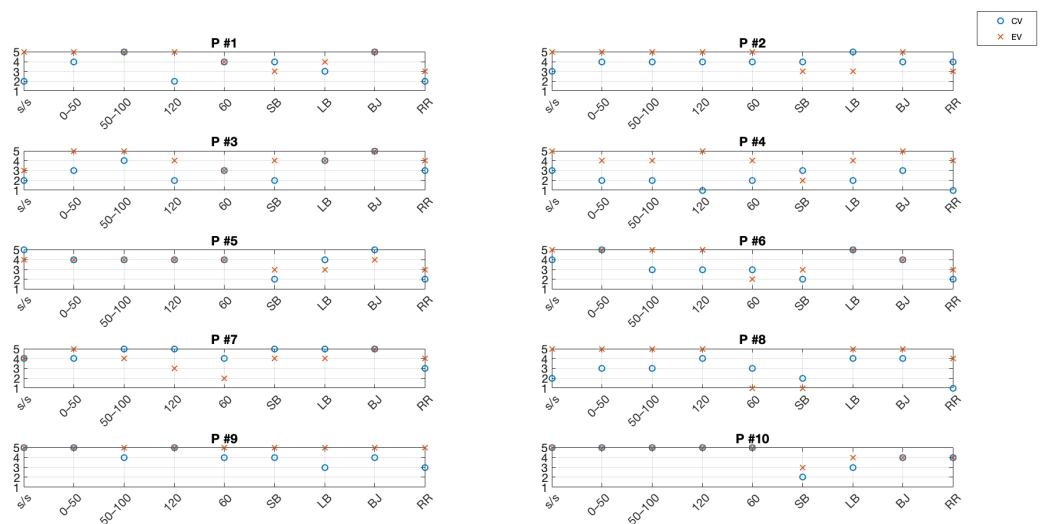


Figure 4. Vibration annoyance for each participant. The value '1' stands for 'extremely annoyed', while '5' stands for 'not annoyed at all'. The horizontal labels represent 'start/stop', 'accelerating and decelerating 0–50 km/h', 'accelerating and decelerating 50–100 km/h', 'constant 120 km/h', 'constant 60 km/h', 'speed bumps', 'long bumps and cornering', 'bridge joint' and 'rough roads'.

In five scenarios, vibration annoyance was rated higher in the CV than in the EV. For the scenarios of start/stop, accelerating and decelerating 0–50 km/h, accelerating and decelerating 50–100 and constant speed of 120 km/h, six participants rated vibration as more annoying in the CV than in the EV. In the

Accelerating and decelerating 0–50 km/h scenario, six participants rated vibration as more annoying in the CV than in the EV. The rough road scenario yielded the clearest preference, with eight participants judging vibration to be more annoying in the CV than in the EV.

Perceived sound and sound annoyance

As Table 7 shows, in the interviews participants reported that experienced sound annoyance in the CV were dominated by tyre noise at lower driving speeds (accelerating 0–50 km/h and constant speed 60 km/h) and by wind noise at higher speeds (accelerating 50–100 km/h and constant speed 60 km/h). During start/stop, low-frequency engine sound dominated the sound annoyance in the CV. In the EV, the biggest sound annoyance was attributed to high-frequency tonal sound from the electric components in the scenarios of lower driving speeds (acceleration and deceleration 0-50 km/h, and constant speed of 60 km/h).

Table 7. Summary interview comments about the sound experience. N represents the number of participants that made a judgement on the corresponding parameters.

Sound	LF* engine	HF* motor	Tyre noise	Wind noise	Soft	Loud	Not a focus	Sharp
S2 (CV)	N = 10							
S2 (EV)		N = 4			N = 10			
S3-1 (CV)			N = 10					
S3-1 (EV)		N = 4	N = 3		N = 5			
S3-2 (CV)				N = 5				
S3-2 (EV)				N = 7				
S4-1 (CV)				N = 3				
S4-1 (EV)				N = 6				
S4-2 (CV)					N = 10			
S4-2 (EV)		N = 6						
S5 (CV)			N = 8			N = 3		
S5 (EV)			N = 9			N = 4		
S6 (CV)							N = 7	
S6 (EV)					N = 8			
S7 (CV)						N = 7		N = 4
S7 (EV)						N = 6		
S8 (CV)				N = 4			N = 6	
S8 (EV)					N = 5		N = 5	

* LF: low frequency; HF: high frequency

The characteristics of sound (Figure 5) illustrate that four participants judged the starting sound in both cars as negative. In the interviews, participants attributed this negative impression to the low frequencies in the CV and the sharp tones of the EV's signature starting sound. The measurement of the one-third octave band frequency spectra of the starting sound in the CV (Figure 6) identified a peak at around 25 Hz, related to the second-order vibration of the engine. The EV sound measurement detected several distinct high-frequency peaks in the one-third octave band frequency spectra.

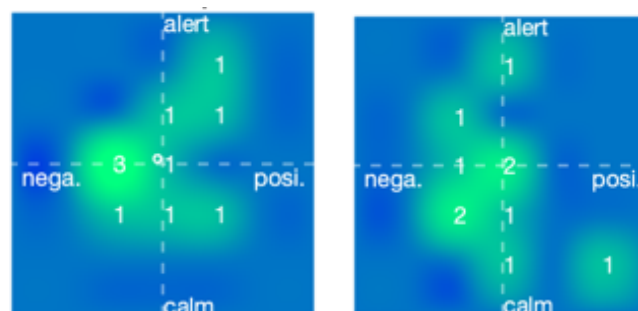


Figure 5. Sound characteristics when start/stop in the CV (left) and the EV (right). The horizontal axis represents positive/negative perception of the sounds. The vertical axis represents active vs. calm scoring for the sounds. The white circle represents the average value.

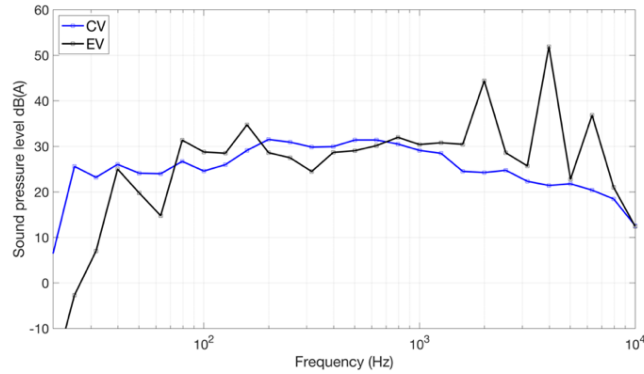


Figure 6. One-third octave band spectrum of A-weighted sound pressure levels in the scenario start/stop scenario in the CV and EV, for the first-time engine on/off (10s).

Tyre noise dominated perceived sound in the CV when accelerating 0–50 km/h and driving over speed bumps (Table 7). When accelerating 0–50 km/h, tyre noise in the CV was associated with increasing speed and thus did not cause annoyance. Three participants (P1, P6, P10) reported sound annoyance in the CV when driving over speed bumps (Figure 3). In the interviews, they attributed their perceived sound annoyance to the loudness of the tyre impact sound.

With increasing speed (accelerating 50–100 km/h and constant speed of 120 km/h), participants reported audible wind noise, which dominated perceived sound in the CV. The sound rating decreased with increasing speed (Figure 3). Participants attributed the variation in sound rating to the increasing loudness and the presence of wind noise at higher speeds. The measurements detected an 8 dBA increase in the maximum sound pressure level between Scenario 3-1 (accelerating 0–50 km/h) and 3-2 (accelerating 50–100 km/h). The equivalent sound pressure level identified a 6 dBA increase between constant speed of 60 km/h and constant speed of 120 km/h. The measurement also showed increased high-frequency composition with speed.

In the EV, participants attributed their experienced sound annoyance to the high-frequency tones from the electric motor at lower speeds (accelerating 0–50 km/h, constant speed at 60 km/h), and to pronounced wind noise at higher speeds (accelerating 50–100 km/h, constant speed at 120 km/h). For instance, when accelerating from standstill to 50 km/h, participants reported high-frequency tonal sound generated by the electric motor. The sound measurements in the EV detected distinct high-frequency tonal components (Figure 7). These sharp tonal components also led six participants (P1, P3–P6, P8) to perceive the sound negatively. The accelerating sound from standstill to 50 km/h was thus rated as more negative in the EV than in the CV (Figure 8).

At higher speeds, participants commented that the high-frequency tonal sound from electric motor was less pronounced due to masking by wind noise. Therefore, sound in the EV when accelerating 50–100 km/h was less annoying (P2, P5, P6) and more positive (P2, P3, P5, P6, P10) than sound when accelerating 0–50 km/h, even if the maximum sound pressure level increased by 7 dB. A similar drop in sound annoyance was also found between the constant speed at 60 km/h and at 120 km/h scenarios.

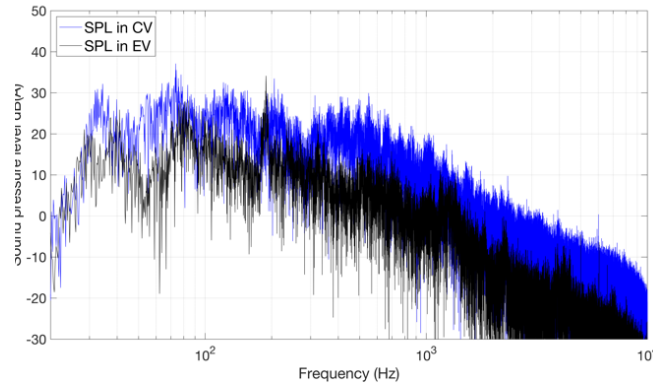


Figure 7. Narrow-band spectrum of A-weighted sound pressure levels in the accelerating/decelerating 0–50 km/h scenario (CV and EV) for the first acceleration/deceleration period.

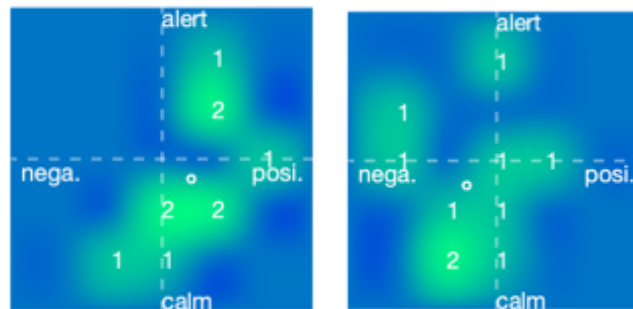


Figure 8. Sound characteristics when accelerating from standstill to 50 km/h in the CV (left) and EV (right). The horizontal axis represents positive/negative perception of the sounds. The vertical axis represents active vs. calm scoring for the sounds. The white circle represents the average value.

As Table 7 indicates, participants were significantly distracted from focusing on sound in the CV during the long bumps and cornering and rough roads scenarios. In the interviews they indicated that this was due to simultaneously experiencing body movement. Nevertheless, in the interviews participants said that sound caused difficulties in achieving relaxed sitting in the CV.

Experienced vibration and vibration annoyance

Table 8 indicates that vibration discomfort in the CV was attributed to low-frequency vibration during start/stop and induced body movement in other scenarios. While in the EV, participants did not experience low-frequency vibration during start/stop.

From the participants' ratings of vibration annoyance (Figure 4), three participants (P1, P3, P8) experienced vibration discomfort during start/stop in the CV. In the interviews, they attributed this to the experienced vibration caused by the rigid body resonances of the CV. Figure 9 shows prominent peaks in vertical vibration at the seat rail, at around 10 Hz and 25 Hz. These two peaks corresponded to the rigid body resonance and second-order engine vibration, respectively. In the interviews, four other participants (P2, P5, P7, P9) commented that they experienced discomfort sometimes in their daily car use when switching the engine on or off, even if they did not perceive vibration annoyance in this test. Participants did not report rigid body resonance when the EV was switched on or off. As seen from the measurement (Figure 9), there were mainly small-amplitude background noises in the EV.

Table 8. Summary comments from interviews about the vibration experience. N represents the number of participants that made a judgement on the corresponding parameters.

<i>Vibration</i>	<i>LF*</i>	<i>Longit udinal</i>	<i>Lateral</i>	<i>Vertical</i>	<i>No pronounced vibration</i>	<i>Relative movement</i>	<i>Pitching</i>	<i>Rolling</i>
<i>S2 (CV)</i>	N = 10							
<i>S2 (EV)</i>					N = 10			
<i>S3-1 (CV)</i>		N = 3						
<i>S3-1 (EV)</i>					N = 10			
<i>S3-2 (CV)</i>					N = 10			
<i>S3-2 (EV)</i>					N = 10			
<i>S4-1 (CV)</i>		N = 4						
<i>S4-1 (EV)</i>					N = 10			
<i>S4-2 (CV)</i>					N = 10			
<i>S4-2 (EV)</i>		N = 6						
<i>S5 (CV)</i>				N = 4			N = 4	
<i>S5 (EV)</i>					N = 8			
<i>S6 (CV)</i>			N = 10			N = 4	N = 9	N = 9
<i>S6 (EV)</i>			N = 5					
<i>S7 (CV)</i>					N = 10			
<i>S7 (EV)</i>					N = 10			
<i>S8 (CV)</i>			N = 3	N = 4				
<i>S8 (EV)</i>			N = 6	N = 3				

* LF: low frequency.

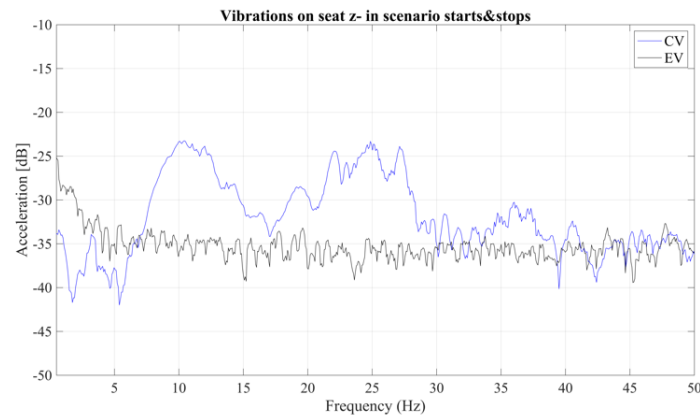


Figure 9. The amplitude spectrum of vibration at the seat rail z- during start/stop.. The Fourier transform (FFT) analysis was based on the first-time engine switching on (10s). The frequency resolution was 0.1 Hz. The reference value is 1 m/s².

In the interviews, participants attributed their difficulties in achieving a relaxed sitting position in both cars to lateral body movement induced by the car's pitching and rolling during Scenario 6 (long bumps and cornering) and Scenario 8 (rough roads). The camera recordings confirmed these reported body movements. Figure 10 presents an example of lateral lower body movement.

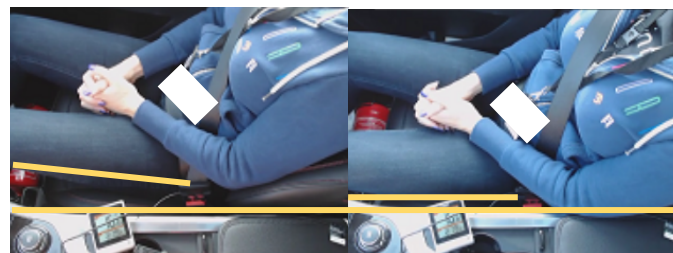


Figure 10. Example of lateral lower body movement.

Participants reported that active posture adjustments helped them to maintain stability or reduce discomfort. These arm posture adjustments (P1–P4, P8, P9) were observed in both cars. Figure 11

illustrates two examples of participants' posture adjustments. The participant shown in the top part of the figure relaxed his arms and hands on his thighs at the beginning of the scenario. When the rolling motion increased, the participant tried to grab the car door for better stability. The participant shown in the bottom of the figure changed his leg crossing posture frequently to find a comfortable sitting posture.



Figure 11. Examples of active arm position (top) and variation of leg position (bottom).

Discussion

The purpose of this user study was to identify the important factors affecting perceived ride comfort and discomfort under various scenarios in an electric car. This study also sought to investigate the similarities and differences between human experiences in an EV and in a CV. The overall results show that easy ingress, roominess, good body support and easy seat adjustment had the most influence on static comfort in both the CV and EV. The most influential factors for dynamic discomfort were slightly different for each type of car: insufficient seat support, which was related to induced body movement, was the most significant variable in the CV, whereas annoying sound had the most influence on perceived discomfort in the EV.

Perceived sound discomfort in the EV and in the CV

Similar to the findings of previous studies on sound inside passenger cars (Qin et al., 2020, Qatu et al., 2009, Lindener et al., 2007), low-frequency engine sound, tyre noise and wind noise were the main annoying sounds reported in the CV under different driving scenarios. Sound annoyance in the CV was mainly triggered by these sounds in the scenarios where they are present. In the EV, sound annoyance was mostly caused by pronounced high-frequency tonal sound from electric components at lower speeds. The effect of sound on dynamic discomfort was more pronounced in the EV than in the CV.

Participants commented that the high-frequency tones generated by electric components were more pronounced when tyre noise was lower and wind noise was absent. These high-frequency tones also entailed to greater sound discomfort in the EV than in the CV at lower driving speeds, even if the A-weighted equivalent sound pressure level was lower in the EV than in the CV. During accelerating and decelerating between 0–50 km/h and driving at constant speed of 60 km/h, the measured A-weighted sound pressure level was lower in the EV than in the CV. Nevertheless, more participants judged these sounds as more annoying and more negative in the EV than in the CV in these two scenarios. Previous studies have indicated that high-frequency tonal components are common inside EVs (Govindswamy and Eisele, 2011). It is therefore suggested that studies of dynamic discomfort in EVs assess high-frequency tonal sound, especially in lower-speed scenarios.

Perceived vibration discomfort in the EV and in the CV

Participants experienced the biggest change in vibration between the combustion engine and electric motor during the start/stop scenario. In the CV, participants experienced low-frequency vibration caused by the rigid body resonances of the car. In the current study, no participant perceived discomfort due to vibration when the engine was switched on and off. Nevertheless, they reported that their own driving experiences, they experienced vibration discomfort sometimes when switching the vehicle on/off. In the EV, there was no significant vibration perceived when switching on and off, and only the designed notification sound was perceived during the first time switch-on. Participants commented that they expected a sound notification when the EV was switched on and off. The pronounced differences in vibration and the resulting difference in experienced discomfort might also occur when idling.

In other scenarios for both cars, participants attributed their vibration discomfort most to induced body movement. In the EV, participants reported less vibration transmitted from the seat to the human body. Therefore, vibration in the EV contributed less to dynamic discomfort than it did in the CV. These differences could not be explained by the combustion engine being replaced by an electric motor. However, EVs are usually heavier due to their batteries and thus more stable (Timmers and Achten, 2016). The studied EV was almost 60% heavier than the CV.

Implications of the study methods

This study used two cars to represent two different car types. There will naturally be differences between the car used in this study and other models of CVs and EVs in terms of sound and vibration. Nevertheless, the findings and the method used here could support research in other passenger cars.

For contemporary CVs, engine switching on/off will be even more frequent as automatic start/stop systems become more common (D. Wang et al. 2020). It is foreseeable that occupants will experience more low-frequency sound and vibration in future cars. As this study demonstrates, low-frequency sound during start/stop could influence perceived discomfort in the CV. Participants did not report vibration annoyance caused by start/stop in this study, but they did comment that in their own cars auto start/stop influenced ride discomfort (P1–P5, P9). It is therefore suggested that assessments of sound annoyance in other CVs include a start/stop scenario. At higher speeds, wind noise was the predominate interior sound in passenger cars (Lindener et al., 2007). The current study found that sound annoyance in the CV was more pronounced at higher speeds than at lower speeds. Therefore, assessing sound annoyance at high speed is also suggested for other CVs.

The sound in EVs usually includes high-frequency tonal components generated by the electric motor (Govindswamy and Eisele, 2011). In this study, participants emphasized the perception of high-frequency tones in the EV and pointed to them as the major source of discomfort. Additionally, in the EV, sound annoyance related to high-frequency tones decreased with increasing speed due to the masking effect of wind noise in the higher-speed scenarios. Hence, when assessing ride discomfort in other EVs, it is suggested to include evaluation on high-frequency tones, especially at lower speeds.

In both cars, the study found differences between participants' instantaneous responses and overall perception of sound. Participants attributed their difficulties in relaxing to experienced sound, even if they did not rate sound as annoying in some scenarios. This indicates that the influence of sound might be underestimated if only short-duration tests are used, regardless of the type of car tested. It could be preferable to control the duration of the ride in future studies of sound annoyance depending on the study purpose. For passenger cars designed for both short and long trips, it is therefore suggested that both short- and long-duration assessments be conducted.

In the interviews, participants rarely had a direct judgement regarding the characteristics of vibration. Instead, they attributed vibration discomfort to resonance in their own body and body movement. In

other studies of ride comfort, participants might also have difficulty directly describing how they assess vibration. It is suggested that induced body movement be used as an indicator.

The results in current study demonstrate that the influence of single factors (e.g., sound or vibration) on ride comfort vary depending on the car and the test scenarios. Thus, using a single-scenario test or evaluating a single variable is insufficient for assessing overall ride comfort. Moreover, the majority of the subjective assessments could be explained by the simultaneous measurements of sound and vibration. This indicated that one could control the perceived discomfort by controlling certain obvious objective parameters of sound, vibration and seat. For instance, eliminating high-frequency tonal sounds may directly reduce perceived sound annoyance in EVs. However, in general, the relationship between perceived discomfort and objective parameters can be complex.

The method used here covers a wide range of sounds and vibrations that passengers may experience in different driving scenarios. As discussed above, some patterns in the influence of sound and vibration were found. Nevertheless, it is difficult to capture variations among different subjects from a study with only ten participants. For the higher-speed and bump scenarios in the CV, participants varied quite a lot in their sound ratings. In the EV, sound ratings for the constant speed at 60 km/h and bridge joints scenarios were likewise spread out. In the CV, ratings of vibration were widely distributed for most scenarios. Therefore, a larger test population is needed to study the influence of anthropometric variation.

Conclusion

The overall conclusions from the user study are that ingress, room for the body, seat adjustment and seat support dominate the static comfort in both the CV and the EV. Annoying sounds were most influential on experienced dynamic discomfort in the EV, whilst body movement was most influential in the CV. Sound annoyance in the CV was primarily triggered by tyre noise and wind noise. In the EV, sound annoyance was caused by high-frequency tonal sound from electric components and wind noise. The most pronounced variation in experienced sound annoyance was found at lower speeds. In the EV, high-frequency tonal sound from the electric motor was significant when not masked by tyre noise or wind noise and caused sound annoyance. In the CV, tyre noise was the predominate sound annoyance at lower speeds. At higher speeds, wind noise was the major cause of sound annoyance in both cars. The major differences in experienced vibration discomfort between the two cars were found during start/stop. In the CV, the low-frequency vibration caused by the rigid body resonances of the car was the biggest cause of perceived discomfort. Whereas in the EV, there was no noticeable vibration transmitted to the human body. In conclusion, sound and vibration exert different influences under different driving scenarios and in different cars. Thus, dynamic discomfort is affected by different sound, vibration and seat properties for CVs and EVs, and variation is pronounced in different driving scenarios for the two cars.

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Appendix

Questionnaire I: questions utilized to collect demographic data of participants.

10. What is your gender?

- Female
- Male
- Other

11. How old are you?

- 18–25
- 26–35
- 36–50
- 51–65
- over 65

12. What is your height? _____ cm What is your weight? _____ Kg

13. How often do you usually travel by walking, bicycling, car and public transport in an ordinary month? (The sum should be 100%)

walking __%, bicycling __%, public transport __%, car __%, other __%

14. Which car brand and model do most frequently use when you go by car?

Car brand _____ Car Model _____

15. How often do you travel *as a driver* when you use a passenger car?

- 0–20%
- 21–40%
- 41–60%
- 61–80%
- 81–100%

16. How often do you travel *as a front seat passenger* when you use a passenger car?

- 0–20%
- 21–40%
- 41–60%
- 61–80%
- 81–100%

17. How often do you travel *as a rear seat passenger* when you use a passenger car?

- 0–20%
- 21–40%
- 41–60%
- 61–80%
- 81–100%






18. How often are you annoyed by sounds?

	I agree entirely	I agree partly	I disagree partly	I disagree entirely
It is not fun to have a conversation when the radio is on at the same time				
I often recognize disturbing sound sources later than other people around me				
I avoid going to noisy leisure events such as soccer games or leisure parks				
The smallest sound wakes me up				
I work very efficient and fast even in a noisy environment				






	I agree entirely	I agree partly	I disagree partly	I disagree entirely
I hardly hear the traffic noise when I am downtown shopping				
After an evening in a noisy pub I feel extremely exhausted				
When I want to fall asleep, I get hardly disturbed by sound				
I really like to visit quiet areas on a weekend				

Questionnaire II: Questions and scales for Scenarios 1






1.8 Is it easy to get into the car from the right front door?

Difficult						Easy
						






1.9 How about the visibility in frontal and lateral directions when you are sitting in the car?

Poor						Good
						






1.10 Is there enough room for your body in the space when you are sitting?

Crowded						Roomy
						






1.11 How do you feel when you are sitting in this car seat?

Tense						Relaxed
						

1.12 Does the car seat fit your body?

Do not fit						Fit very well
						

1.13 How do you experience the car seat?

Soft						Stiff
						

1.14 Are you satisfied with the constraint of seat belt?

Dissatisfied						Satisfied

Questionnaire III: Questions and scales for scenarios 2–8

2.11 How annoyed did you feel when you heard the sounds?

Extremely annoyed						Not Annoyed at all

2.12 Did you feel calm or alert when you heard the sounds?

Calm						Alert

2.13 Did you feel positive or negative when you heard the sounds?

Negative						Positive

2.14 How annoyed did you feel when you felt the vibrations?

Extremely annoyed						Not Annoyed at all

2.15 Did you think what you heard, saw and felt match each other or conflict with each other?

Absolutely conflict						Absolutely match

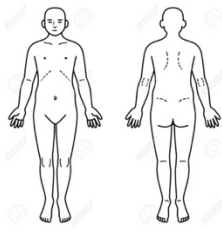
2.16 Did your body move as a whole or was there any relative motions between different body parts?

Relative motions						Move as a whole

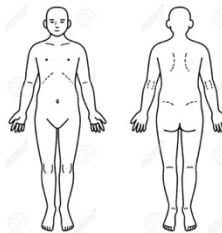
2.17 Did you feel the constraint from the seat belt smooth or abrupt?

Abrupt						Smooth

2.18 Did you feel discomfort in any body parts? If any, color then these in red in the human body figure.



2.19 Did you feel numbness in any body parts? If any, color these in blue in the human body figure.



2.20 Do you have comments on your experience that you would like to add here?

Questionnaire IV: Ranking of factors according to their influences on static comfort/dynamic discomfort.

3. How are the following factors affecting your **overall comfort** when you sit in a **standing still car before ride**? Choose the important factors from you testing experience and rank the importance in descending order (i.e., 1 is the most important factor).

<u>Rankings</u>	<u>Factors</u>
	<i>Easy to access through the right front door</i>
	<i>Enough room for my entire body when sitting in the car</i>
	<i>Easy to adjust the seat to find a comfortable posture</i>
	<i>Good support for my whole body (head/neck, arms/forearms, back /lumbar spine, buttock,</i>
	<i>Good visibility in all directions</i>
	<i>Good lighting inside the car at daylight</i>
	<i>Comfortable temperature inside the car</i>
	<i>Good seat belt position on my upper body</i>
	<i>Easy to adjust the seat belt to a proper position</i>
	<i>Good air quality inside the car</i>

4. How are the following factors affecting your **overall discomfort** when you sit as a front seat passenger **after the whole test ride**? Choose the important factors from you testing experience and rank the importance in descending order (i.e., 1 is the most important factor).

<u>Rankings</u>	<u>Factors</u>
	<i>Not enough room for my entire body when sitting in the car</i>
	<i>Not enough support for my different body parts (including for example, head, arms/forearms,</i>
	<i>Hard to find a relaxing sitting posture</i>
	<i>Annoying vibrations at the seat, headrest, car door or from the floor</i>
	<i>Relative motions between different body parts</i>
	<i>Annoying sounds inside the car</i>
	<i>The things I heard, I saw and the vibrations I felt did not match with each other</i>
	<i>Feeling numb in my muscle</i>
	<i>Uncomfortable constrain from the seat belt</i>
	<i>Difficult to adjust the seat belt to a proper position</i>