THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

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

Xiaojuan Wang

Department of Industrial and Materials Science
Division Design & Human Factors
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
Front seat passengers’ experience of ride comfort and NVH in modern cars

Xiaojuan Wang


Published and distributed by

Department of Industrial and Materials Science
Division Design & Human Factors
Chalmers University of Technology
SE-412 96, GOTHENBURG, Sweden
Telephone + 46 (0) 31-772 1000

Printed by Chalmers Reproservice

Gothenburg, Sweden 2022
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.
Acknowledgements

The research work presented in this thesis has been funded by China-Euro Vehicle Technology AB, Gothenburg, Sweden.

I would like to express my deepest gratitude to my main supervisor, Prof. AnnaLisa Osvalder, for your support and help, which guide me to this research topic. Your scientific attitude and curiosity towards knowledge always inspire me in my research. Thank you for your careful attention to detail and feedback in many areas, which have helped me professionally and as a person.

I am also thankful to my co-supervisor, Associate Prof. Patrik Höstmad, for your constant support, constructive feedback and encouragement. You always give me useful feedback and are a great help with writing papers. I learned a lot of things from you, such as analysing a research problem and presenting results.

I would like to offer my gratitude to Ingemar Johansson, who is a great project leader and a tireless co-author. I also want to thank Erik Preihs, my former manager and project leader, for your kind guidance in my research project and advice in my career. I would like to express my appreciation to my current manager, Lars Nilsson, and project leader, John Bergström, for your invaluable support. I am also thankful to Jörgen Sjöström, Fredrik Käck, Magnus Hillerborn and Pradeep Singh Chauhan for the advice and support.

Also, thanks to Marianne Karlsson, head of division of Design and Human Factors, and to Oscar Rexfelt and Lars-Ola Bligård at the MTD research school for creating a stimulating work environment. Also thanks to division of Applied Acoustics for support.

Furthermore, thanks to my many colleagues both at Chalmers and at CEVT, for sharing knowledge and advice selflessly. To my friends both in Sweden and at far, thank you for your encouragement and companionship.

Last but not least, I would like to thank Li, my husband and also my best friend: please know that your support was worth more than I can express. I offer my great thanks to my son Lucas for your love and understanding. And to my parents:感谢我的父母，在我人生中的每一步给予我最大的自由与无私的支持。
Appended publications

**Paper A**


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**


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**


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.
Table of Contents

ABSTRACT 1
ACKNOWLEDGEMENTS 2
APPENDED PUBLICATIONS 3
CHAPTER 1 INTRODUCTION 5
1.1 BACKGROUND 5
1.2 AIM AND RESEARCH QUESTIONS 6
1.3 OUTLINE 7
CHAPTER 2 OVERVIEW OF THE FIELDS INVOLVED 8
2.1 THE INFLUENCE OF VIBRATION ON RIDE COMFORT 8
2.2 VIBRATIONS IN REAL AUTOMOTIVE VEHICLES 10
2.3 INFLUENCE OF SOUND ON RIDE COMFORT 11
2.4 SOUND IN REAL AUTOMOTIVE VEHICLES 13
2.5 INTERFERENCES BETWEEN DIFFERENT FACTORS 15
CHAPTER 3 METHODOLOGY 16
3.1 SUBJECTIVE DATA COLLECTION 16
3.2 SUBJECTIVE DATA ANALYSIS 16
3.3 OBJECTIVE DATA COLLECTION 17
3.4 OBJECTIVE DATA ANALYSIS 17
CHAPTER 4 EXPERIENCED RIDE COMFORT IN A COMBUSTION ENGINE CAR 18
4.1 STATIC COMFORT 18
4.2 DYNAMIC DISCOMFORT 18
4.3 EXPERIENCED SOUND AND SOUND ANNOYANCE 18
4.4 EXPERIENCED VIBRATION AND VIBRATION ANNOYANCE 20
4.5 OTHER FACTORS THAT INFLUENCE RIDE COMFORT AND DISCOMFORT 20
CHAPTER 5 EXPERIENCED RIDE COMFORT IN AN ELECTRIC CAR 22
5.1 STATIC COMFORT 22
5.2 DYNAMIC DISCOMFORT 22
5.3 EXPERIENCED SOUND AND SOUND ANNOYANCE 23
5.4 EXPERIENCED VIBRATION AND VIBRATION ANNOYANCE 24
CHAPTER 6 ANALYSIS 27
6.1 COMPARISON BETWEEN THE RESULTS FROM THE LITERATURE STUDIES AND THE USER STUDY 27
6.2 DIFFERENCES IN EXPERIENCED SOUND BETWEEN THE EV AND THE CV 27
6.3 DIFFERENCES IN EXPERIENCED VIBRATION IN THE EV AND THE CV 28
CHAPTER 7 DISCUSSION 29
7.1 THE DEFINITION OF RIDE COMFORT FROM THE OCCUPANTS’ PERSPECTIVE 29
7.2 THE INFLUENCE OF SOUND AND VIBRATION 29
7.3 THE IMPLICATIONS OF THE STUDY METHOD 30
CHAPTER 8 CONCLUSIONS 32
CHAPTER 9 FUTURE WORK 33
REFERENCES 34
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 an 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).](image)

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.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Equivalent comfort contours for sensation magnitudes of 25 and 300. Figure adapted from Fig. 7. In (Morioka and Griffin, 2006).}
\end{figure}

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 (Stelmachowicz et al., 1989) and individual psychological factors such as expectations and experiences (Skagerstrand et al., 2017).
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 (Pelmear 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.](image)

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.](image)

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 ($L_{pA,max}$) identified an increment of 8 dBA when speed increased from the 0–50 km/h range ($L_{pA,max} = 60$ dBA) to the 50–100 km/h range ($L_{pA,max} = 68$ 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.

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.

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.
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.

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).
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.](image)

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 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).](image)

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 established 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 cause 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 sensitive 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.
References


Characteristics and Pressure Measurements at the Occupant-Seat Interface.” SAE Technical Papers.

http://dx.doi.org/10.1016/j.apergo.2016.07.004.


