THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Beyond the Seat: Exploring Passengers' Ride Comfort in Cars

Physical, Psychological and Functional Comfort Dimensions and Influencing Factors

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Cover:
Illustration of a passenger engaging in smartphone use during a ride, along with factors influencing passengers' perceptions of ride comfort.

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Abstract

While previous car comfort research has predominantly focused on physical discomfort and on drivers, empirical knowledge of passengers' perceptions of ride comfort remains limited. This thesis addresses this gap by adopting a holistic, passenger-centred perspective on ride comfort in cars. The overall aim of this thesis is to increase the understanding of car passengers' perceptions of ride comfort, grounded in passengers' own experiences. To achieve this aim, a mixed-methods research approach was employed, across four empirical studies described in five appended papers. The research progressed iteratively, beginning with a focus on physical comfort, posture, and seat belt fit, and gradually expanding to include psychological comfort, functional comfort and activity engagement. The data collection methods included interviews, questionnaires and video observations from in-car studies on road, as well as free-text responses from a survey of a broader passenger population, enabling exploration of passengers' own perceptions of ride comfort.

The findings show that passenger ride comfort constitutes three interrelated dimensions: physical, psychological, and functional comfort, influenced by individual, artefactual, and contextual factors. These dimensions are dynamically interrelated, such that changes in one dimension may influence others to varying degrees of prominence. Functional comfort, conceptualised as the possibility to engage in activities, plays a central role as activity engagement allows passengers to regulate both physical and psychological comfort. Based on these findings, the thesis presents a holistic Passenger Ride Comfort Framework, illustrating relationships between passengers' perceptions of ride comfort and influencing factors, and provides empirically informed questionnaire tools for assessing passenger ride comfort. These contributions can support future research as well as evaluation and development of interiors in new passenger cars.

In conclusion, passenger ride comfort is a complex, multidimensional phenomenon, affected by the interplay of factors that influence in combination, rather than as isolated factors. Passengers' perceptions of ride are continuously reassessed and may fluctuate in different directions over the course of a ride, not only in response static and dynamic influencing factors, but also due to passengers' focus of attention and activity engagement. Capturing this complexity requires empirically grounded mixed-methods approaches, in which objective and subjective measures are combined to provide a complementary basis for analysis, while interviews and free-text responses support the interpretation of questionnaires and video observations, advancing the understanding of passengers' perceptions of ride comfort.

Keywords: Passenger comfort, ride comfort, car passenger, mixed-methods, empirical studies, physical comfort, psychological comfort, functional comfort.

Preface

This work was carried out at the Department of Mechanical Engineering, at Chalmers University of Technology between March 2021 and March 2026. Parts of the research was conducted within two projects, *Car Passenger Safety – To the next level*, and *Safe and comfortable seat belts, funded* by FFI – Strategic Vehicle Research and Innovation, by Vinnova, the Swedish Energy Agency, the Swedish Transport Administration, the Swedish Vehicle Industry.

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Gothenburg, March 2026
Melina Makris

Appended Papers

The thesis includes an extended summary and the following appended papers:

PAPER A
Makris, M. Bohman, K., & Osvalder, A.-L. (2023). Comparison of Sitting Postures and Shoulder Belt Fit of Rear Seat Car Passengers Over Time in Stationary and Driven Scenarios. *In Proceedings of the IRCOBI Conference*, Cambridge (pp. 690-707).
Contribution: *Makris, Osvalder and Bohman planned the study. Makris conducted the study. Makris analysed the data with assistance from Bohman and Osvalder. Makris wrote the paper with feedback from Bohman and Osvalder.*

PAPER B
Makris, M. Osvalder, A.-L., & Bohman, K. (2026). Passenger Comfort Over Time: Stationary vs. Driven Scenarios and Implications for Study Design. *International Journal of Human Factors and Ergonomics*, 12 (4). IN PRESS.
Contribution: *Makris, Osvalder and Bohman planned the study. Makris conducted the study. Makris analysed the data with assistance from Osvalder and Bohman. Makris wrote the paper with feedback from Osvalder and Bohman.*

PAPER C
Makris, M. Muthumani, A., Herrera, M., Wang, D., Johansson, M., & Osvalder, A.-L. (2025). Drivers' overall comfort experiences of reclined positions in a passenger car with an automated driving function. *Applied Ergonomics*, 126, 104503.
Contribution: *Makris, Muthumani, Herrera and Osvalder planned the study. Muthumani and Herrera conducted the study. Makris, Johansson, Muthumani and Wang analysed the data. Makris wrote the paper with assistance from Muthumani, Johansson and Herrera.*

PAPER D
Makris, M., Johansson, M. Pipkorn, L., & Osvalder, A.-L. (2026). Beyond Physical Comfort: Psychological, Physical and Functional Dimensions of Passenger Comfort and Influencing Factors. Submitted to Transportation Research Interdisciplinary Perspectives.
Contribution: *Makris, Johansson and Osvalder planned the study. Makris conducted the study. Makris analysed the qualitative data with assistance from Johansson. Pipkorn analysed the quantitative data and wrote the method and results of the statistical modelling. Makris wrote the paper with feedback from Johansson, Pipkorn and Osvalder.*

PAPER E
Makris, M., Johansson, M., Bohman, K., & Osvalder, A.-L. (2026). Effects of Smartphone Use on Passenger Ride Comfort. Submitted to Applied Ergonomics.
Contribution: *Makris, Johansson, Bohman and Osvalder planned the study. Makris conducted the study with support from Johansson and Bohman. Makris analysed the data with assistance from Johansson. Makris wrote the paper with support from Johansson, who contributed to writing parts of the discussion section. Feedback was provided by Bohman and Osvalder.*

Additional Publications

Makris, M. & Osvalder, A.-L. (2022). Experimental Setup for Assessing Drivers' Experiences of Reclined Sitting Posture in Automated Vehicles. *In Proceedings of the AHFE Conference 2022*, Vol. 60, pp.117-126, New York, USA.

Makris, M. (2022). Literature Review of Sitting Postures and Belt Fit in Passenger Vehicles. Internal report, Department of Industrial and Materials Science, Chalmers University of Technology, Göteborg, Sweden.

Makris, M., Osvalder, A.-L., Johansson, M., & Borell, J. (2024). Unveiling the complexity of car ride comfort: A holistic model. In *Proceedings of the AHFE Conference 2024*, Vol. 148, pp 653-663, Nice, France.

Johansson, M., Makris, M., & Osvalder, A.-L. (2025). The age factor in ride comfort: Comparing younger and older passengers' perspectives. In D. Golightly, N. Balfe, & R. Charles (Eds.), *Contemporary Ergonomics and Human Factors 2025* (pp. 544–550). CIEHF Conference, St George's Park, Burton upon Trent, UK.

Table of Contents

Chapter 1: Introduction

Comfort is a subjective construct, emerging from the interaction between the human and the environment (De Looze et al., 2003), typically associated with positive experiences, such as feelings of well-being and relaxation. It has been studied across a range of domains, including architecture, healthcare and transportation. Within the automotive industry, comfort is a central consideration (Chen et al., 2025), as it plays a role in sales of vehicles (Vink, 2023) and constitutes an important aspect of how travel is experienced for both drivers and passengers.

In the automotive field, studies have largely focused on ride comfort, which has been defined as the overall comfort and well-being of vehicle occupants during travel (Heißing and Ersoy, 2011). Despite this broad definition, ride comfort has typically been assessed through measures of physical factors related to vehicle dynamics, such as noise, vibration and harshness (Wang, 2024; Wawryszczuk et al., 2023). While these factors influence ride comfort, they provide only a limited representation of the broader ride comfort experience. Another area that has been studied involves perceived discomfort, since discomfort can cause musculoskeletal injuries on long term (Hamberg-van Reenen, et al., 2008). In cars, this is interaction occurs between the seat and individual in the car. For example, studies have investigated perceived discomfort such as fatigue and localised pressure in different body regions (Kyung et al., 2008; Osvalder et al., 2019), and influences of pressure distribution (Lantoine et al., 2022) as well as thermal conditions such as temperature and humidity (Sunagawa et al., 2023). Studies of this interaction have further investigated how physical factors of the individual, such as age, stature, body shape and body mass (BMI) influence perceptions of comfort and discomfort (Kyung et al., 2008; Reed et al., 2013; Bohman et al., 2019; Reed et al., 2013). For instance, older adults have been shown to experience greater discomfort associated with poor belt fit (Bohman et al., 2019), which in turn has shown to increase the risk of improper seat belt use or the use of in-car accessories (Osvalder et al., 2019). Furthermore, interactions between individual physical characteristics, seat properties and activities performed while seated have been investigated to describe their influence on perceived comfort and discomfort (Hiemstra-van Mastrigt et al., 2016). However, while these studies extend the knowledge on factors influencing comfort and discomfort in cars, they remain largely focused on physical factors.

Studies in passenger cars have predominantly focused on driver comfort and sitting postures during driving (e.g. Kyung et al., 2008; Franz 2010; Sunagawa et al., 2023; Li et al., 2024). However, results from these studies are not always directly transferable to passengers, due to different restrictions of the activity and different body postures (Hiemstra-Van Mastrigt, 2015). Unlike drivers, passengers are not constrained by the driving task and therefore have greater freedom to adjust posture and seat settings. With increasing vehicle automation, driving-task demands are expected to decrease, leading drivers to increasingly adopt passenger roles. This shift underscores the importance of understanding passenger ride comfort in future in-vehicle experiences. Passengers, having no driving responsibilities, also have greater freedom to engage in activities such as socialising, resting, or reading during the ride (Jorlöv et al., 2017; Caballero-Bruno et al., 2022). However, unpleasant driving styles or challenging traffic environment can disrupt in-vehicle activities, reduce enjoyment, and affect perceived safety and overall ride comfort (Peng et al., 2024). This broader perspective on ride comfort is particularly relevant for passengers, who have limited control and less ability to anticipate vehicle manoeuvres, which may contribute to motion sickness, anxiety, or safety concerns. Taken together, these studies indicate that passengers' perceptions of ride comfort are shaped not only by physical aspects, but also by driving style, perceived safety, surrounding traffic environment, and in-vehicle activities. This highlights the need for a broader understanding of passengers' perceptions of ride comfort that extends beyond physical factors alone.

A broader view on passengers' perceptions of comfort during ride has been taken in contexts such as aircrafts and trains (Groenesteijn et al., 2014; Ahmadpour et al., 2016). In these contexts, the view of ride comfort extends to involve factors such as peace of mind, social settings, physical wellbeing and perceived control. Building on this broader perspective, an expert workshop described psychological aspects of comfort in automated vehicles (AVs), including trust, situation awareness, and expectations (Peng et al., 2024), while another study conceptualised comfort in AVs as a multidimensional experience, shaped by the interaction between external conditions, system behaviour, and individual characteristics (Domova et al., 2024). Although these studies have advanced the conceptual understanding of passenger comfort - particularly in AV contexts - they also emphasise the need for empirical insights (Peng et al., 2024). Moreover, research focusing specifically on car passengers' perceptions of ride comfort, independent of automation level, remains limited, despite the relevance for informing both current vehicle design and future AV development.

In summary, although passenger comfort has been conceptualised more broadly in contexts such as air, rail and AVs, research on car comfort has largely focused on physical aspects, often examined in relation to the driver. As a result, deeper understanding of car passengers' car ride comfort remains limited (Kilincsoy, 2018). There is a lack of empirical studies on how car passengers themselves perceive overall ride comfort, and how these perceptions are shaped by various influencing factors. This knowledge gap becomes increasingly important with rising vehicle automation, where passenger perspectives become central for future mobility solutions.

1.1 Aim and Research Questions

To address this gap, this doctoral thesis aims to advance the understanding of car ride comfort from a passenger perspective. By adopting a holistic approach, the thesis offers empirical insights for increased knowledge of passengers' ride comfort, which can support future research and inform the evaluation and development of conventional cars as well as to future mobility contexts. The aim of this thesis is guided by the following research questions (RQs):

RQ1: *What constitutes passengers´ perceptions of ride comfort?*
RQ2: *Which factors influence passengers´ perceptions of ride comfort?*

RQ3: *What relationships exist between passengers′ perceptions of ride comfort and the influencing factors?*

1.2 Delimitations

This thesis focuses on passengers in passenger cars, i.e., road vehicles primarily intended for transporting people rather than cargo and typically seating up to eight occupants. Other vehicle types such as buses, trucks, or vans were not included. The research includes one study conducted in a car equipped with an automated driving (AD) function, in which the participant was studied during AD after transitioning into a passenger-like role. The thesis therefore focuses on ride comfort associated with the passenger role, rather than drivers in conventional cars who actively control the car.

The scope is limited to adult passengers and excludes child passengers, whose perceptions of ride comfort perceptions may differ due to e.g., body size and restraint requirements. The study addresses passengers' perceptions of ride comfort rather than technical measures of vehicle dynamics. Noise, vibration, and harshness (NVH) were considered only when mentioned by participants.

1.3 Thesis Outline

The thesis is structured in the following way:

1. **Introduction** provides background on the research topic, states the aim, and poses the research questions.
2. **Frame of Reference** presents previous research within the field of comfort.
3. **Research Process** specifies the research process, including an overview of the overall process from the first study to the synthesis and Proposed Passenger Ride Comfort Framework.
4. **Summary of Appended Papers** provide the main findings from the appended papers and how each paper contributes to address the research questions.
5. **Findings** provide a synthesis of the findings across the appended papers, and a Passenger Ride Comfort Framework representing the synthesised findings in an illustration.
6. **Discussion** presents how the findings are interpreted, discusses implications of the research process, the contributions of the thesis as well as limitations and future work.
7. **Conclusion** presents the conclusions of the thesis.

Chapter 2: Frame of Reference

This chapter describes the conceptual frame of reference for the thesis. It introduces central definitions that describe how comfort and discomfort are understood, experienced, and influenced by human, artefactual, and contextual factors. The review includes comfort models developed for products in general, as well as frameworks addressing comfort in transportation. Together, these perspectives provide a foundation for analysing passenger ride comfort as a dynamic and multidimensional phenomenon.

2.1 Comfort Definition

While no single accepted definition of comfort exists in scientific literature, a few central assumptions are widely accepted, including that: (1) comfort is subjective and therefore differs among individuals, (2) it is affected by physical, physiological and psychological factors and (3) it is a cumulative state, experienced in reaction to the environmental context (De Looze et al., 2003). Beyond this description, the definition of comfort has been under debate. Comfort and discomfort have been conceptualised as either opposite ends of a continuum or as distinct constructs shaped by different underlying factors. The former perspective treats comfort as a bipolar phenomenon where comfort is positioned at the extreme positive end, and discomfort is positioned at the extreme negative end of a continuum, assuming that comfort and discomfort are caused by the same factors (Ahmadpour et al., 2014). In the latter perspective, comfort is distinguished from discomfort, with the two described as separate constructs influenced by different factors (Zhang et al., 1996). Within this view, discomfort is primarily associated with physical aspects, including feelings of e.g., tiredness, stiffness and numbness, whereas comfort is described as a pleasant and relaxed state (Zhang et al., 1996). Taken together, the view of comfort and discomfort as separate constructs implies that reducing discomfort does not automatically result in comfort; rather, achieving comfort requires that discomfort remains low (Helander & Zhang, 1997). This view is illustrated in the hypothetical model described by Zhang et al., (1996) shown in Figure 1.

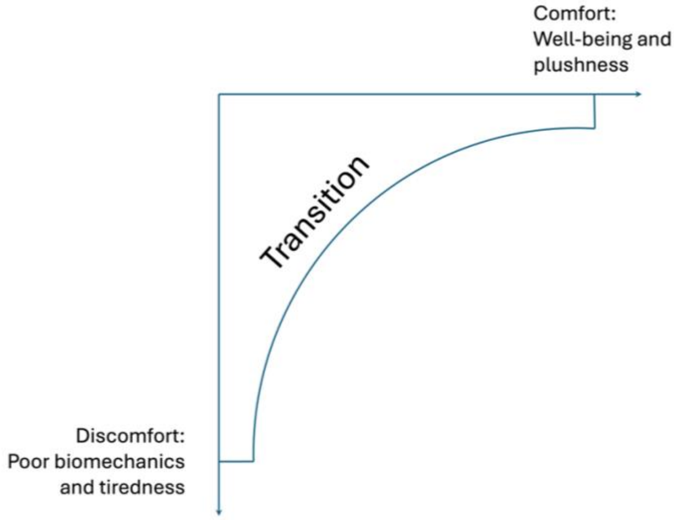


Figure 1. The hypothetical model of comfort and discomfort by Zhang et al. (1996).

This distinction has been particularly acknowledged in research on sitting comfort and discomfort (De Looze et al., 2003). Sitting discomfort is influenced by physical factors of the context (e.g., internal environment and performed task), physical features of the product (e.g., seat shape, angles or firmness), mediated by physical factors of the individual (such as joint angles, tissue pressure and circulation blockage) (Zhang et al., 1996). Sitting comfort, in contrast, involves not only physical aspects but also psychological aspects, such as a sense of well-being and relaxation (Zhang et al., 1996). Although the influencing factors still relate to context, product, and the individual, they extend beyond physical elements to include psychosocial aspects of the context, aesthetic qualities of the product, and the individual's expectations and emotions (Zhang et al., 1996; De Looze et al., 2003). This perspective is illustrated in the theoretical model proposed by De Looze et al. (2003), shown in Figure 2.

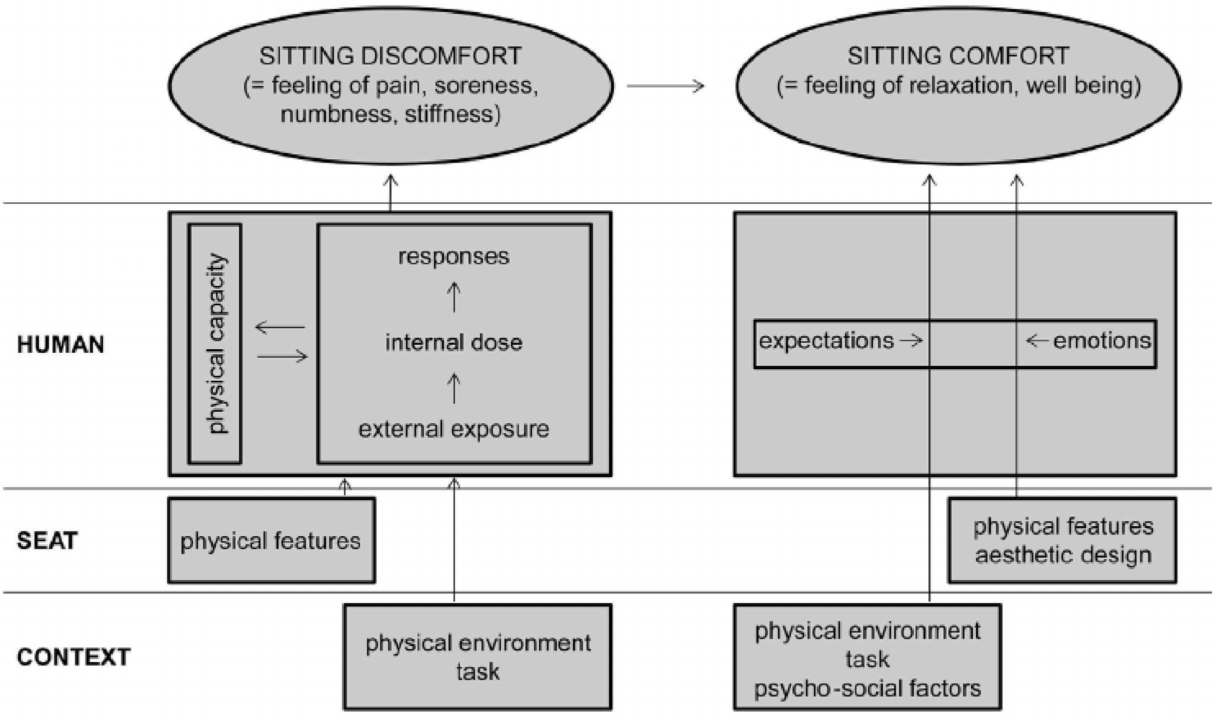


Figure 2. Theoretical model of comfort and discomfort and its influencing factors at the human, seat and context level, proposed by De Looze et al. (2003).

Adding to the definitions of comfort, functional comfort has been defined as ergonomic support for users' performance of work-related tasks and activities (Vischer, 2007). In the context of workspaces, factors contributing to functional comfort include appropriate lighting for screen-based work, ergonomic furniture for computer users, and enclosed rooms for meetings and collaborative tasks. The term has also been used in relation to products such as earplugs, where the functional dimension of comfort has referred to the usability, efficiency and usefulness (Poissenot-Arrigoni et al., 2023). Although the term functional comfort is not commonly used in the context of sitting comfort, several studies have acknowledged activities and tasks performed while seated as a part of the contextual factors influencing sitting comfort (De Looze et al., 2003).

Further emphasising the interaction between the individual and product of use Vink and Hallbeck, (2012) developed a conceptual model describing how comfort and discomfort emerge through the interaction between product and the user. The model includes the person, the product, and the task which are situated within a specific environment, and together these elements influence the interaction (I) and give rise to human body effects (H), such as tactile sensations, changes in body posture, or muscle activation. The perceived effects (P) are influenced by these human body effects, as well as by the expectations (E) the person holds about the situation. These perceived effects may result in comfort (C), may go unnoticed (N), or may lead to discomfort (D). The relative influence of the environment, person, product, and task varies across contexts, and the ways in which these factors relate to one another may therefore differ accordingly. Overall, the model integrates physical, psychological, and contextual factors, and emphasises that comfort emerges not only from physical factors but also from how users perceive and interpret their interaction with a product (Figure 3).

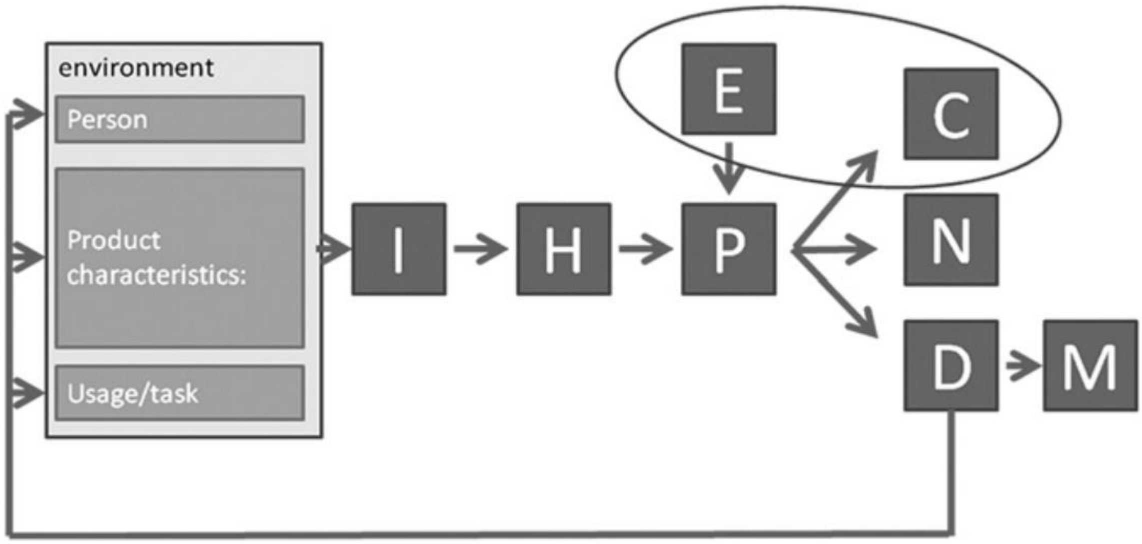


Figure 3. The conceptual model of comfort and discomfort and influencing factors proposed by Vink and Hallbeck (2012).

Together, these conceptualisations emphasise that comfort is shaped by the interaction between the individual, the product, and the surrounding context. In the automotive domain, this interaction occurs during vehicle travel. The resulting comfort is referred to as ride comfort, defined as the overall comfort and well-being of the vehicle's occupants during vehicle travel (Heißing and Ersoy, 2011). Hence, ride comfort could be understood as a multidimensional experience shaped not only by the vehicle and the environment but also by the occupant's posture, perceptions and interactions during vehicle travel. Nevertheless, research on factors influencing ride comfort typically revolves around measures related to vehicle dynamics, involving influencing factors such as temperature, noise, vibration and harshness (Wang, 2024; Wawryszczuk et al., 2023). Although these factors influence ride comfort, they do not fully reflect the overall comfort and well-being of the occupant during a ride.

2.2 Ride Comfort in Cars

Building on these conceptualisations of comfort and discomfort, the following subsection reviews prior research on ride comfort in passenger car contexts. In particular, it examines studies addressing passengers' perceptions of ride comfort (including both comfort and discomfort), in different study contexts (stationary and on-road studies) together with related factors such as sitting posture and seat belt fit, as well as influencing factors including characteristics of the individual and the seat.

Comfort studies in cars have typically been conducted to compare different design concepts (e.g., seat characteristics, seat positions, restraint systems) across individuals with varying characteristics (e.g., anthropometry and age). Data collection commonly involves subjective measures of perceived comfort and discomfort and objective measures of postures and seat belt fit. In the following sections, these approaches are described separately to highlight their respective contributions, although many studies employ both to provide a more comprehensive understanding of perceived comfort and discomfort.

2.2.1 Assessments of Comfort and Discomfort in Cars

Typically, studies of comfort and discomfort in cars collect subjective data using questionnaires and interviews, often to compare different design concepts such as seat characteristics, seat positions, or restraint systems. For example, one study compared two restraint systems by asking children to rate the comfort of both the seat and the seat belt on a 5-point scale (1 = very uncomfortable and 5 = very comfortable) (Jakobsson et al., 2011). Similarly, another study compared children's perceived comfort of two booster cushions, by rating their perceived comfort on a 6-point scale with facial expressions, colouring potential discomfort on figures of a seated child and providing ratings in a semantic scale with opposite words (e.g., including the pairs 'comfortable-uncomfortable', tensed-relaxed' and 'safe-insecure') (Osvalder et al., 2013). The questionnaires were completed at systematic time intervals capturing changes in comfort over time during the ride. While these studies involve children and appear to employ age-adapted questionnaire instruments such as facial expression scales, they nevertheless illustrate common approaches for capturing subjective perceptions of ride comfort in cars.

Compared with child-focused studies, research involving adults often enables more detailed subjective assessments of comfort and discomfort. Such studies commonly capture not only overall comfort perceptions but also elaborations on discomfort intensity, affected body regions, underlying causes, and participants' prior experiences with seats or seat belts. For example, a study compared older and younger adult passengers' seat belt fit and perceived discomfort across two front seat positions in a stationary car, by interviewing participants about perceived comfort and previous experiences of seat belt fit (Bohman et al., 2019). Another study explored older front seat passengers' seat belt fit and perceived discomfort through interviews that captured discomfort across different body regions, its intensity, and underlying causes (Osvalder et al., 2019). Similarly, a pilot study examined adult participants' comfort perceptions of two seats with different back shapes, combining 0–10 ratings of body discomfort with a choice indicating which seat was perceived as more comfortable (Coelho and Dahlman, 2012). Together, these approaches illustrate how subjective assessment methods can provide detailed insight into passengers´ perceived comfort and discomfort, particularly in relation to specific elements in the interaction between the individual, seat belt, seat position and seat characteristic.

In addition to subjective data, studies of comfort in cars commonly collect objective data on sitting postures and seat belt fit, often using video recordings or photos. Video observations are frequently analysed using qualitative approaches in which postures, belt fit, or passenger behaviours are manually categorised by researchers. This process typically involves extracting frames at systematic time intervals and coding them according to predefined posture or belt-fit categories (Jakobsson et al., 2011; Osvalder et al., 2013; Reed et al., 2020b; Reed et al., 2022). For example, observational coding schemes have been used to classify variations in torso posture and shoulder belt positioning relative to the body (Jakobsson et al., 2011). In addition to such qualitative approaches, quantitative methods have also been used to estimate postures through motion capture technologies, including Kinect sensors (Arbogast et al., 2016, Reed et al., 2019) or custom video tracking software capable of estimating body postures in vehicles (Baker et al., 2018). Together, these objective measures provide a way to quantify passengers´ postures and seat belt fit, complementing subjective data by capturing observable behaviours during ride.

2.2.2 Stationary and on-Road Studies

Studies of comfort in cars have been conducted across different contexts, including stationary and dynamic environments. The following section therefore distinguishes between stationary and driving studies, outlining their respective methodological characteristics and applications.

Stationary studies, typically conducted in laboratory settings using mock-ups, allow for more detailed, hands-on measurements of postures and belt fit. For example, through 3D coordinate measurement systems such as the FARO Edge Arm that digitizes body landmark locations and seat belt positions in 3D (Reed et al., 2013; Baker et al., 2021). Although the FARO Edge Arm is a portable device, it is heavy and bulky and requires calibration in the environment it is to be used in, limiting its use to stationary conditions.

In contrast to stationary studies, driving studies provide a more dynamic context for studying comfort, including postures and belt fit. Two main types of driving studies can be distinguished: field operational tests (FOTs) and naturalistic driving studies (NDSs). FOTs are often conducted with a limited number of test drivers, either on controlled test tracks or on predefined routes in real traffic (Jakobsson et al., 2011; Osvalder et al., 2013). In these driving contexts, perceived comfort and discomfort are typically captured through subjective assessment methods, including rating scales, questionnaires, and interviews during or following the ride, as described in earlier studies (Jakobsson et al., 2011). In contrast, NDSs are conducted in real-world settings to explore occupants´ natural behaviours. Such studies typically involve mounting video cameras inside participants' own cars to record occupants during their daily travel routines over extended periods, enabling quantification postures and seat belt fit or use during rides (e.g., (Arbogast et al., 2016; Reed et al., 2022). Compared with FOTs, NDSs tend to place less emphasis on collecting subjective comfort data and instead focus on observing naturalistic behaviours. Instead, NDSs usually serve the broader aim of identifying occupants´ naturalistic postures and seat belt fit during ride, supporting the refinement of test protocols for evaluating restraint performance with anthropomorphic test devices (Arbogast et al., 2016). This focus is particularly relevant for safety assessment, where research emphasizes the need to extend beyond standardised testing by accounting for the variety of postures adopted by occupants (Leledakis et al., 2021).

Although attempts have been made to relate objective measures to subjective comfort and discomfort (Fenety et al., 2000; De Looze et al., 2003), subjective ratings of discomfort have primarily been associated with pressure distribution in car seats (De Looze et al., 2003). However, the relationship between discomfort and in-seat movements is less clear (Reed, 2020; Kruithof et al., 2026), suggesting that observable behaviour alone is not a reliable indicator of discomfort. Consequently, studies of comfort and discomfort in cars often combine subjective and objective measures. Depending on the focus of the study, one type of measure may be primary while the other provides complementary insights.

2.2.3 Influencing Factors

In addition to examining passengers' perceptions of comfort and discomfort, research has explored the factors that shape these experiences. Influencing factors include characteristics of the individual, the seat and restraint system, and aspects of the internal and external context. These factors interact to affect passengers' postures, seat belt fit, and overall comfort, highlighting that overall ride comfort is influenced not only by the attributes of the car but also by the way passengers engage with it. Understanding these factors is essential for interpreting empirical findings and for advancing knowledge of car ride comfort from a passenger perspective.

Individual characteristics of passengers can influence their interactions with the seat and restraint system, affecting not only seat belt fit but also perceived discomfort and behaviour. Specifically, research has shown that body shape, anthropometry, and BMI influence seat belt fit (Reed et al., 2012; Reed et al., 2013; Coxon et al., 2014; Fong et al., 2016). For example, individuals with higher BMI tend to position the shoulder belt closer to the neck and higher on the abdomen, regardless of age and sex, which may increase the risk of discomfort (Bohman et al., 2019). Discomfort can in turn lead passengers to adjust their behaviour, such as using seat accessories (e.g. cushions or seat belt pads) during the ride, a response that may have safety implications (Osvalder et al., 2019). Previous research has also shown that shorter individuals were more likely to use seat belt pads, while cushion accessories were more frequently used by those reporting seat belt discomfort (Coxon et al., 2014). Seat belt discomfort has also been observed among older adults, who were more likely to use seat accessories in attempts to mitigate discomfort (Osvalder et al., 2019). Together, these findings demonstrate that individual characteristics not only influence comfort but also affect how passengers engage with seat belts, emphasizing the importance of designing for both comfort and correct use of restraint systems.

The design of the restraint system, and more specifically the seat belt, further forms an important component of the car interior that passengers interact with during the ride.

The seat belt, a crucial safety feature that saves lives and reduces the risk of injury in the event of a crash (Kahane, 2000), must accommodate occupants of various body shapes in a variety of postures. The optimal belt fit has been defined as the shoulder belt being placed on the mid-portion of the shoulder (Fong et al., 2016), whereas the optimal position of the lap belt has been defined as the belt positioned below the anterior-superior iliac spine, in contact with the upper thigh (Reed et al., 2012; Reed et al., 2013). In addition to individual factors, the seat belt fit is also influenced by car design, such as anchorage locations of the lap belt and shoulder belt (Reed et al., 2013). Taken together, how the seat belt fits across the body influences both comfort and proper restraint use. However, research has shown that occupants may not always be aware when the seat belt deviates from the recommended fit. For example, a user study examining seat belt fit, perceived comfort and safety awareness found that older adults often had limited awareness of non-optimal shoulder and lap belt positioning (Osvalder et al., 2019). Understanding these interactions is essential for the development of restraint systems that can robustly accommodate diverse body types and postures, ensuring that safety performance and comfort are maintained across a wide range of occupants.

In addition to factors related to the individual and the car, ride comfort is also influenced by activities performed while travelling (Hiemstra-van Mastrigt, 2017; Domova et al., 2024). Research in transport domains such as trains and airplanes has shown that passenger activities - ranging from sleeping and socialising to interacting with electronic devices - can influence posture and perceived comfort (Vink et al., 2012; Groenesteijn et al., 2014). Based on research on public transport, Hiemstra-Van Mastrigt et al. (2017) highlighted activities as a central contextual factor associated with variations in sitting postures during travel. Their proposed framework illustrates relationships between human (e.g., stature, BMI, body mass), seat (e.g., dimensions, shape, material), and context (e.g., activities, environment), with the aim to develop a predictive model of passenger comfort and discomfort) (Figure 4). While this work provided an overview of relationships between these variables, it also emphasised the need for further research on passenger seat comfort and discomfort as well as taking more variables into account (e.g., personal space and exposure duration).

Similarly in cars, passengers are not constrained by the driving task and therefore have freedom to adopt a wider variety of postures and adjust their seat position (fore-aft direction) and settings (e.g., seat back angle) in a wider range (Reed et al., 2020a). In addition, because passengers are not constrained by the driving task, they have greater flexibility to engage in activities such as using digital devices, socialising, resting, or reading during the ride (Jorlöv et al., 2017; Caballero-Bruno et al., 2022). For example, activities such as reaching for objects, talking to the driver, playing with electronic devices, or looking out the window have been shown to affect children's postures during ride (Osvalder et al., 2013). Short-duration activities, like reaching or talking, led to momentary posture changes, whereas longer-duration activities, such as using electronic devices, often resulted in a sustained forward-flexed posture with limited movement and the head leaned forward - postures that may be sub-optimal in the event of a crash (Osvalder et al., 2013). Moreover, a naturalistic study of front-seat passengers found that activities influenced posture; for example, when interacting with a phone, the head was more likely to be pitched downward toward the lap (82% of the time) compared with periods when no interaction was observed (13%) (Reed et al., 2020a). Taken together, studies show that passengers may adopt a variety of postures when engaging in activities during ride, which may in turn not only influence passengers´ perceptions of comfort but also may have implications for passenger safety.

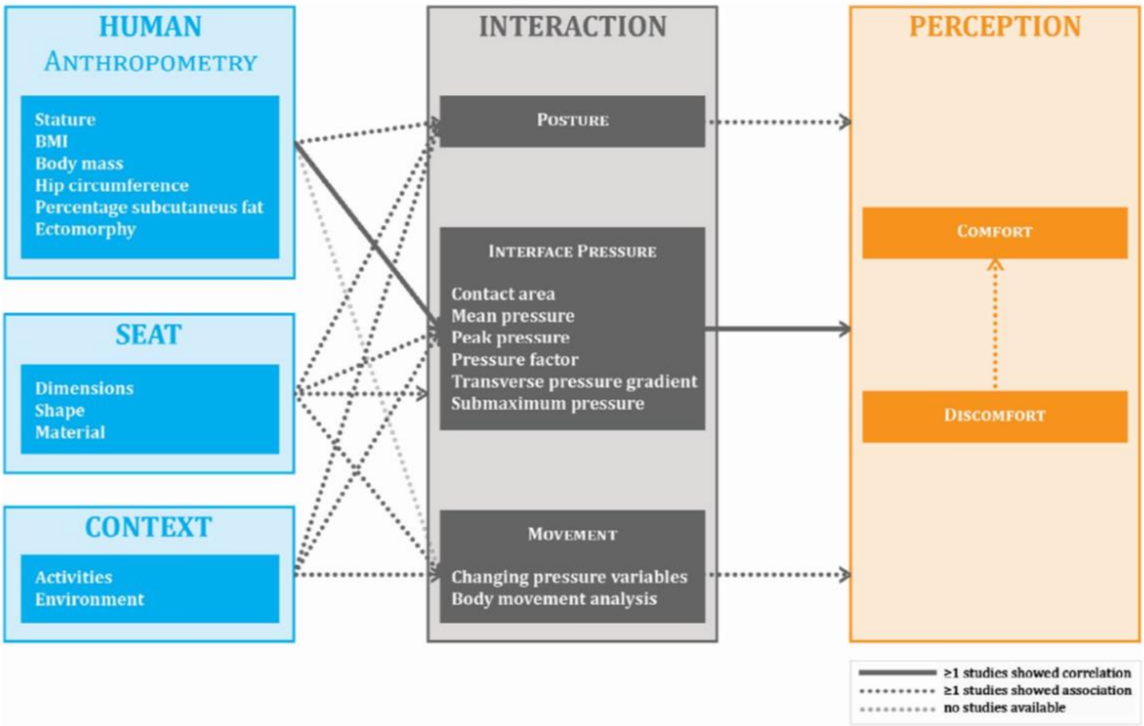


Figure 4. A conceptual comfort framework of passenger seat comfort proposed by Hiemstra-van Mastrigt et al. (2017).

Understanding passenger activities is becoming increasingly important as advancements in vehicle automation introduces various levels of AVs, shifting drivers into passenger roles and expanding the opportunities for engagement in non-driving activities (Domova et al., 2024, Hancock et al., 2019). Since passengers have no direct control over the car, anticipating vehicle manoeuvres may be more difficult and can in turn influence both physical and psychological comfort, resulting in motion sickness, anxiety or safety concerns, which may further infleunce overall ride comfort (Peng et al., 2024). Taking this broader perspective, Peng et al. (2024) proposed a conceptual framework illustrating how AV’s driving styles influence ride comfort (Figure 5). Based on a literature review and an expert workshop with participants from human factors, psychology, and engineering, the framework distinguishes between physical and psychological layers. The physical layer includes aspects such as vibration, temperature, noise, and seating comfort, whereas the psychological layer comprises trust, perceived safety, engagement in non-driving activities, situation awareness, and expectations. It also highlights the role of exposure duration, as prolonged motion, noise, or inactivity can lead to discomfort. However, while the work identified a broad range of comfort influencing factors, it primarily examined factors related to driving styles and further underscored the need for empirical insights (Peng et al., 2024).

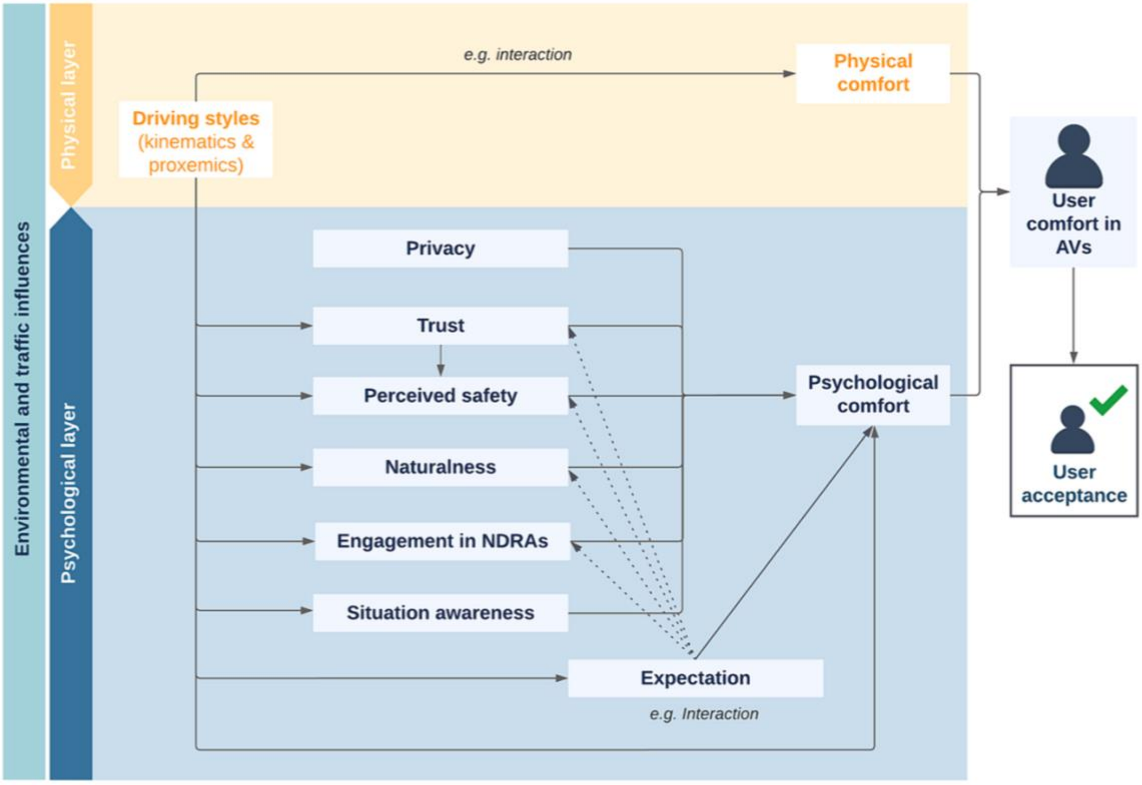


Figure 5. A conceptual framework illustrating how AV driving styles influence user comfort in automated driving proposed by Peng et al. (2024).

Adding to the factors influencing comfort in AVs, Domova et al. (2024) proposed a framework developed through a multidisciplinary literature review involving human factors, psychology, and transportation research (Figure 6). The proposed framework structures comfort-related aspects into three categories: environment-related (e.g., road conditions, traffic, weather), vehicle- and automation-related (e.g., system transparency, automation level, vehicle dynamics), and user-related (e.g., physical state, trust, situation awareness, engagement in secondary activities). It conceptualises comfort in AVs as a multidimensional and dynamic experience, shaped by the interaction between external conditions, system behaviour, and individual characteristics. Moreover, the framework reflects a shift in the user's role from active driver to passive occupant, introducing psychological dimensions of comfort such as perceived control. While the framework provides a comprehensive conceptual perspective, the study emphasises the need for studies of combinations of factors that collaboratively influence user's comfort (Domova et al., 2024).

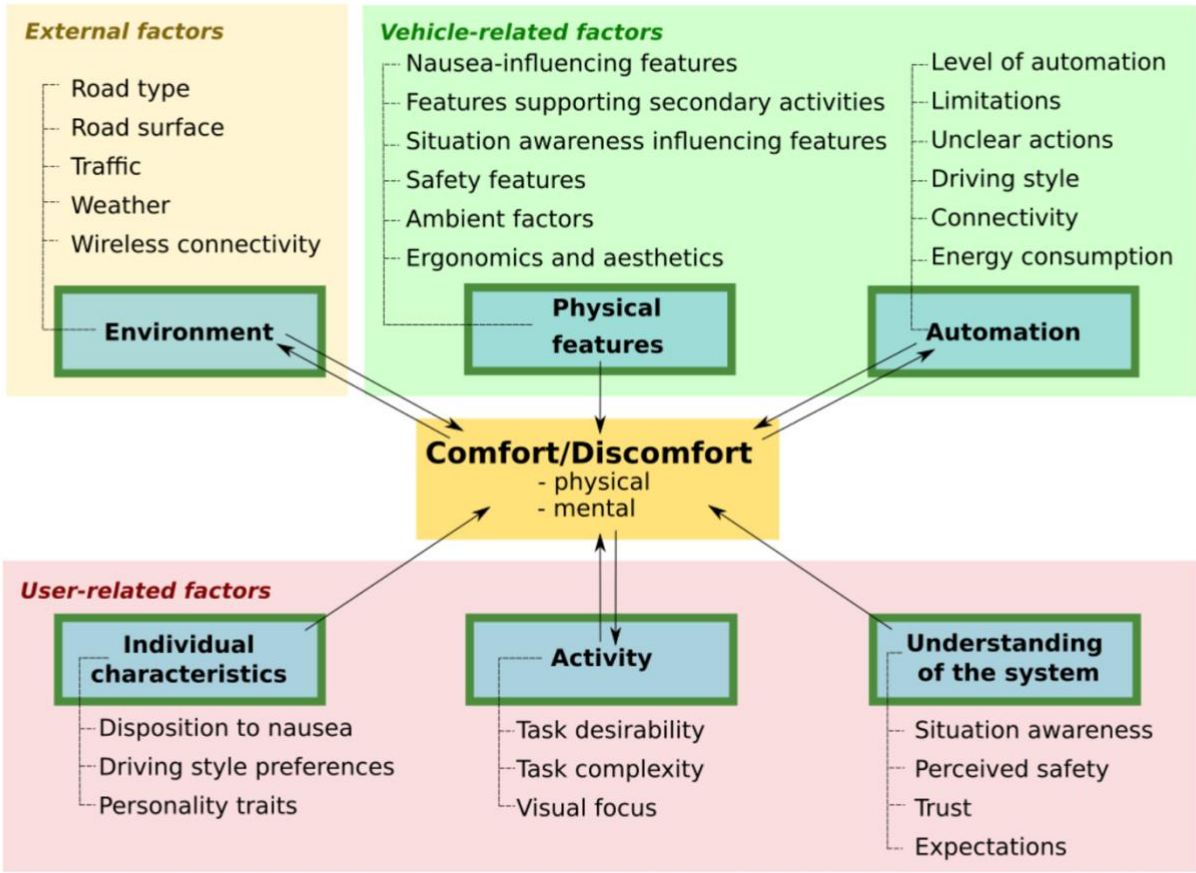


Figure 6. A conceptual framework for understanding comfort in AVs, developed through a multidisciplinary literature review encompassing human factors, psychology, and transportation research, proposed by Domova et al. (2024).

2.3 Summary

Across the reviewed definitions of comfort, studies and conceptual models and frameworks, comfort is consistently described as a multidimensional, time-dependent, and subjective experience, influenced by physical, physiological and psychological factors in relation to the environment. Studies of ride comfort in cars often combine subjective and objective measures in stationary and driving studies, and primarily examine physical factors related to temperature, noise, vibration and harshness (Wang, 2024, Wawryszczuk et al., 2023) or physical factors related to seat, seat belt, and individual (Bohman et al., 2019; Osvalder et al., 2019). Furthermore, these studies indicate that passengers' perceptions of ride comfort are shaped not only by static, physical aspects, but also by driving style, perceived safety, surrounding traffic environment, and in-vehicle activities. This highlights the need for a broader understanding of passengers' perceptions of ride comfort that extends beyond physical factors alone. Based on these perspectives, this thesis adopts the view that comfort is a subjective experience influenced by various factors, and consequently, understanding passengers' ride comfort requires approaches that capture lived experiences. For conceptual clarity, the terms are used in the following way throughout the thesis:

- **Ride comfort** - the overall phenomenon, encompassing physical, psychological and functional comfort

- **Perception of ride comfort -** how passengers interpret, experience, and describe ride comfort, typically expressed through interviews or free-text responses.
- **Perceived ride comfort -** how passengers evaluate and judge ride comfort in the empirical studies, typically expressed through ratings.

Chapter 3: Research Process

This chapter describes the overall approach that has guided the work within this thesis. It presents the overall research approach, methods used for data collection and analysis, the study design of each empirical study and their relation to the appended papers.

3.1 Methodological Stance

Grounded in my multidisciplinary background combining mechanical engineering with design and human factors, the research integrates technical and human-centred perspectives to study passengers' perceptions of ride comfort. Building on this perspective, the research followed an iterative process, adopting a quasi-experimental, mixed methods approach (cf. Creswell, 2014; cf. Creswell & Plano Clark, 2017).

The studies in this thesis followed an iterative approach, with each of four studies building on insights from the previous ones, progressively expanding the understanding of passengers' ride comfort by broadening the scope for each study. The work began with an in-car study in the rear seat, focusing primarily on physical comfort, providing foundational knowledge of posture, seat belt fit, and bodily discomfort, while also capturing insights on psychological comfort through interviews. The second in-car study extended the scope by investigating both physical and psychological comfort dimensions, while interviews also revealed aspects related to functional comfort. As the two first in-car studies broadened the scope of ride comfort by identifying physical, psychological and functional dimensions, the third study comprised a large-scale web survey, conducted to explore passengers' perceptions of ride comfort across dimensions. The findings informed refinements to measurement instruments, such as aligning phrasing of questionnaire items with participants' own descriptions of comfort. Furthermore, the large-scale web survey study informed the focus of the final in-car study, by directing it to functional comfort related to activity engagement, investigating the influence of smartphone usage on ride comfort. This iterative research process supported a systematic development of both the empirical focus and the measurement instruments, ensuring that the investigation of passengers' ride comfort remained grounded in passengers' own experiences while allowing sequential studies to address emerging dimensions in a structured manner.

Each study adopted a mixed methods approach in which objective and subjective, qualitative and quantitative data were collected in parallel and analysed in relation to each other to examine how different data sources converged, diverged, or complemented one another. Objective data included video recordings capturing postures and seat belt fit, demographics of participants and seat settings. Subjective data included questionnaire responses (in scales or free-text comments) and semi-structured interviews, providing qualitative and quantitative insights into why specific postures and belt fit occurred and how they were perceived. By integrating these complementary data sets and relating observable behaviours to participants' individual rationales, the mixed methods approach enabled a more comprehensive understanding of passenger comfort. This iterative and integrative process contributed to a systematic investigation to capture findings that are both empirically grounded and relevant for understanding of ride comfort.

The in-car studies further followed a quasi-experimental, within-subject approach, where conditions were systematically structured to enable comparisons, while acknowledging that the phenomenon of ride comfort is context-dependent and that influencing factors cannot always be fully controlled. The level of experimental control was adapted to the purpose and character of each study, ranging from naturalistic on-road conditions to more controlled, stationary and test-track conditions. This approach enabled comparisons between stationary versus on-road conditions, upright versus reclined seats in automated driving, and smartphone use versus window gazing.

3.2 Research Collaboration Context

This thesis is based on four studies which were all conducted in collaboration with external stakeholders. The rear seat study (Papers A and B), the reclined seat study (Paper C) and the web survey study (Paper D) were developed within the research project *Car Passenger Safety – To Next Level*, which aimed to enhance protection for a diverse passenger population across varying sitting postures, seat positions, and seating configurations by developing knowledge and assessment methods for real-world seat belt interactions in crash scenarios. The front passenger activity study (Paper E) was conducted within the project *Safe and comfortable seat belts for all*, which aimed to build knowledge and develop evaluation methods for seat belt design, including the refinement of assessment tools and human body models to improve seat belt interaction and occupant safety. Both projects were funded by the Strategic Vehicle Research and Innovation (FFI) programme and conducted in collaboration with the SAFER Vehicle and Traffic Safety Centre at Chalmers University of Technology, together with Volvo Cars, Autoliv Research, and Chalmers University of Technology. The work presented in this thesis has been shaped by the multiple focus areas of the projects but has consistently focused on advancing the understanding of passengers' perceptions of ride comfort.

3.3 The Studies

The following section presents an overview of the studies conducted within this thesis, summarised in Table 1, followed by short descriptions of the design and focus of each study. The empirical data were collected through four studies: the first two were vehicle-based quasi-experiments, the third was a web survey, exploring passengers' perceptions of comfort, and the fourth returned to a vehicle-based study, enabling further examination of passenger comfort under observable conditions. More detailed methodological descriptions are provided in the summary of appended papers, with comprehensive accounts presented in the respective appended papers.

An overview of the studies and their interrelations is presented in Figure 7, showing how the outcomes from each study guided the design of the next and how the cumulative insights contributed to the development of the Passenger Ride Comfort Framework.

Table 1. Overview of the four empirical studies.

Studies	Sample	Study Setup
Rear seat study	19 participants	Right rear seat passenger, ride in daily city and highway traffic and in stationary car in garage (2 x 45 min).
Reclined seat study (in AV L4)	29 participants	Driver in driver's seat, turning into a passenger during AD (SAE L4) on test track, in upright and reclined seat positions (2 x 8 min).
Web survey study	1,115 respondents	Front seat passenger respondents selected comfort items they considered most important for their comfort experience, and elaborated on their choices, in a Sweden-wide web survey.
Front passenger study	30 participants	Front seat passenger, ride in daily traffic in industrial area, with and without smartphone usage (2 x 10 min).

The research began with **The Rear Seat Study**, an in-car study of rear-seat passengers addressing physical comfort through observations of posture, seat belt fit and reported bodily sensations. It was conducted in a vehicle in a stationary context where the vehicle was parked in a garage, as well as in real traffic conditions in daily city and highway traffic. Its focus on physical comfort reflected the safety-oriented character of the research project within which the research was conducted in, where posture, restraint interaction, and bodily responses were central focus areas. Beyond physical comfort, the interview findings added initial insights into perceived psychological comfort, informing the focus of the subsequent study.

The second study was **The Reclined Seat Study**, an in-car study which, in contrast to the previous one, was conducted on a controlled test track. Conducted in an AV, the study investigated passengers' perceptions of ride comfort in a reclined driver's seat - that is, when the driver had transitioned into a passenger during automated driving. It expanded the scope to address both physical and psychological comfort. In addition, interview findings revealed aspects of functional comfort during ride, further broadening the conceptualisation of comfort.

The third study was the large-scale **Web Survey Study**, in which respondents elaborated on their perceptions of comfort as front seat passengers. Based on findings from the two first vehicle-based studies, the large-scale survey was designed to capture passengers' perceptions of ride comfort across a broader population, incorporating not only physical and psychological but also functional comfort. Results from the survey were also used to refine data collection methods and questionnaire wording to better reflect participants' own descriptions of their perceptions of comfort.

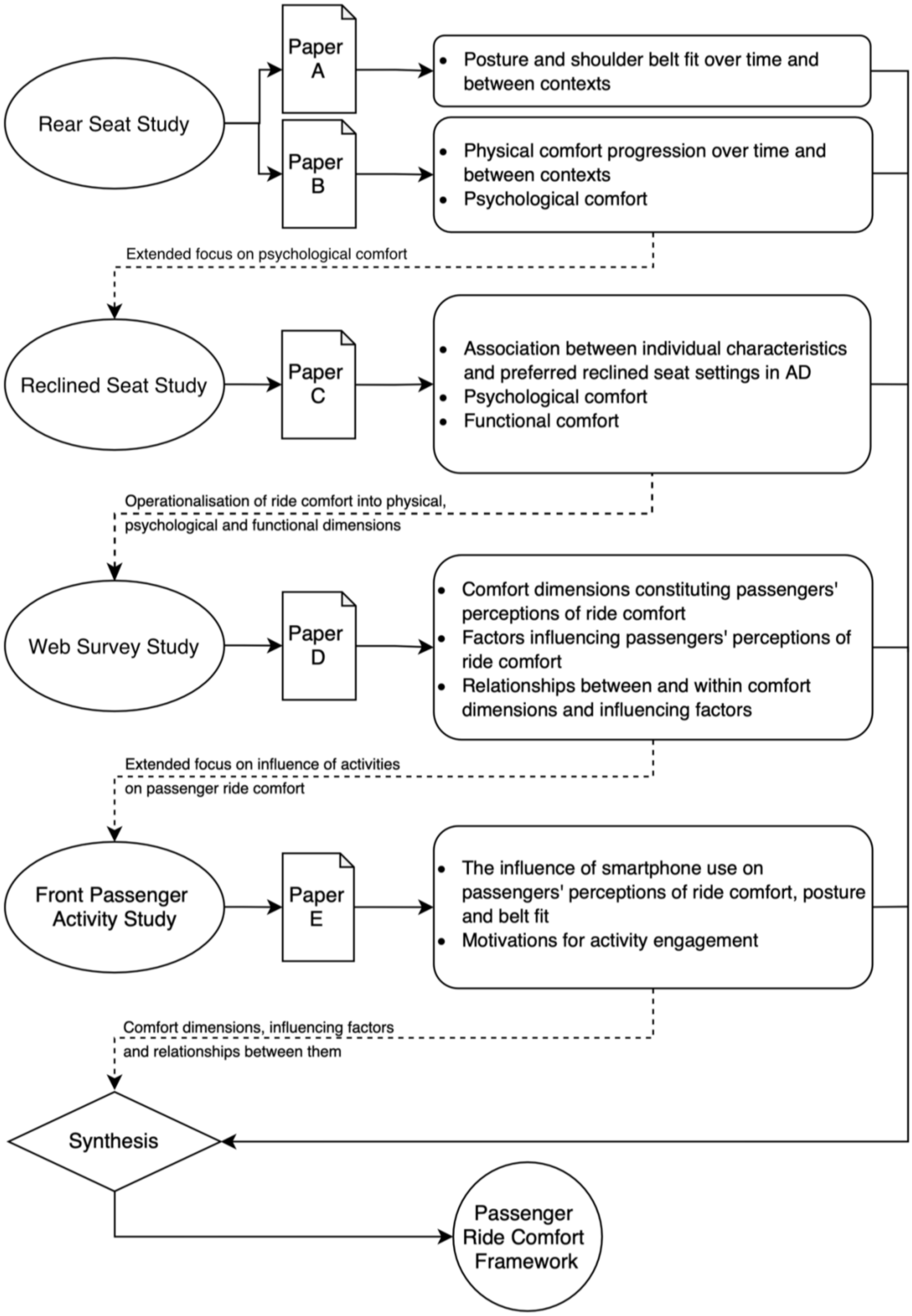


Figure 7. Overview of the conducted studies, showing the appended papers, main outcomes, and how each outcome informed the design and focus of the subsequent study, culminating in the synthesis that resulted in the Passenger Ride Comfort Framework.

The final study was the **Front Passenger Activity Study**, an in-car study conducted in daily traffic in an industrial area. The study examined comfort during activity engagement by comparing smartphone use and window gazing during a ride, investigating passengers' perceptions of ride comfort across physical, psychological, and functional comfort dimensions. Alltogether, the studies illustrate a progressive development from a predominantly physical and discomfort-oriented perspective toward a more holistic and experience-driven understanding of passenger ride comfort.

The iterative research process also shaped the scope of ride comfort addressed in this thesis. Early in the work, my understanding of ride comfort was primarily focused on physical bodily sensations. The first in-car study therefore primarily revolved around localised bodily sensations of sitting comfort and discomfort, along with observations of sitting postures and belt fit. Through the empirical findings and participants' descriptions of their experiences, it became apparent that passengers' perceptions of ride comfort extended beyond localised, physical bodily sensations. Consequently, the scope gradually expanded to include psychological comfort, capturing comfort aspects such as perceived safety, control, and security, as well as functional comfort, related to the possibility to engage in activities. In this sense, the concept of passenger ride comfort was initially approached in a relatively narrow sense centred on physical bodily sensations but progressively developed into a broader perspective encompassing physical, psychological and functional dimensions of comfort. This conceptual development was grounded in the findings of the sequential studies and reflects how my understanding of passengers' perceptions of ride comfort evolved throughout the thesis. The developed questionnaire tools, applied and refined across the studies are provided in Appendix (A1-A4).

While some scientific papers use the term '(dis)comfort' to describe both comfort and discomfort, this thesis uses the term 'ride comfort' to describe physical, psychological, and functional comfort, which together constitute ride comfort. The terms are used in the following way throughout the thesis:

- **Ride comfort -** the overall phenomenon, encompassing physical, psychological and functional dimensions of comfort.
- **Physical comfort** – passengers' bodily sensations associated with the absence of physical and physiological discomfort.
- **Psychological comfort** – passengers' emotional states.
- **Functional comfort** – passengers' possibility to engage in activities.

3.4 The Synthesis

A synthesis was performed to integrate empirical findings from the individual papers into a conceptual, descriptive framework of ride comfort, aiming to identify what constitutes ride comfort, the factors influencing it, and the relationships between them.

3.4.1 Cross-Paper Synthesis

The first part of the synthesis developed a conceptual framework of passenger comfort, conducted collaboratively in a team including the thesis author and three researchers through a series of structured sessions.

1. **Review of appended papers A-E:** The appended papers A to E were examined by the thesis author to identify descriptions of comfort dimensions, influencing factors, and observed relationships. Chapter 4 provides a summary of each paper along with an overview of each paper's contributions to the research questions in.
2. **Cross-paper analysis:** A cross-paper analysis was conducted, in which the identified elements of comfort dimensions and influencing factors were listed in a table of elements along with the paper in which they were described. This enabled comparison of similarities, differences, and complementary insights across papers.
3. **Theme grouping process:** To structure the elements of comfort dimensions and influencing factors, all identified elements were mapped out on a whiteboard and grouped in a team of four researchers. The grouping followed an inductive, thematic approach, where themes emerged from the data rather than being predetermined. Based on this review, the table of elements was updated to include the themes and sub-themes for both comfort dimensions and influencing factors.
4. **Mapping relationships:** Once the themes and subthemes were defined, the relationships between comfort dimensions and influencing factors were illustrated on the whiteboard based on relationships reported in the papers.
5. **Synthesis into Passenger Ride Comfort Framework:** The insights were synthesized into a conceptual, descriptive framework of passengers' ride comfort, visualising the comfort dimensions and influencing factors along with their themes, sub-themes and between elements. The illustration served as the initial draft of the *Passenger Ride Comfort Framework*.

3.4.2 Expert Evaluation

The second part of the synthesis comprised an expert evaluation, aimed at assessing the strengths of the influences between the influencing factors and the dimensions of comfort, based on the framework developed through the cross-paper synthesis. The expert evaluation combined a paper-based assessment with a workshop involving experts from both industry and academia.

Paper assessment

Following a paper-based approach, the strength of influence between the influencing factors (individual, artefact, and context) and the comfort dimensions (physical, psychological, and functional) was assessed in two steps. First, within each appended paper, observed influences was graded on a three-point scale: 0 = no observed influence between influencing factor and comfort, 1 = factor mentioned by a few participants, 2 = factor mentioned by some participants, and 3 = factor mentioned by many participants or involving multiple factors within a theme (e.g., several anthropometric factors contributing to physical discomfort). Second, the scores assigned within each paper were summed across the papers. The summed scores were transformed into a three-level strength classification (weak, moderate, strong) using predefined score ranges based on the empirical maximum observed.

Workshop

A total of eight experts participated in the expert workshop - three from industry and five from academia - including specialists from the automotive sector and researchers in user experience and human factors. The experts were introduced to an initial draft of the *Passenger Comfort Framework*, and each expert was then assigned to grade the strength of the influence between the influencing factors (individual, artefact, context) and comfort dimensions (physical, psychological and functional) and using a scale from 0 = no influence, 1 = weak influence, 2 = moderate influence, and 3 = strong influence. The gradings were based on each expert's own professional judgement and experience, drawing on their domain-specific knowledge from industry and research. The experts completed the ratings independently to ensure unbiased initial assessments.

Following the individual ratings, the experts were divided into two groups of four, aiming for an even distribution of industry and academic participants in each group. Each group then conducted a new joint assessment of all relationships. A one-hour session followed in which the relationships were reviewed. Experts were encouraged to discuss differences in reasoning and provide examples from practice and research. Through these discussions, the ratings were refined, either by reaching consensus or by agreeing on an averaged judgement. The group discussions were audio recorded to enable post-analysis, which was used to compile the final ratings and document nuances or indirect influences raised during the workshop. The expert evaluation not only served to evaluate the strengths of the relationships in the initial draft but also suggested refinements to the wording of the themes.

The final strength of influence was determined by equally combining the ratings from the paper-driven assessment and those of Expert Group 1 and Expert Group 2. This combination ensures that the results reflect both evidence from the papers and practical insights from domain experts, providing a more credible and comprehensive assessment of influence in the synthesised framework. The resulting summed score for each influencing factor was then categorised into weak, moderate, or strong influence.

Chapter 4: Summary of Appended Papers

This chapter provides a summary of Papers A to E.

Paper A: Sitting Postures and Belt Fit

Paper A, based on the *Rear Seat Study*, examined sitting postures and belt fit of rear seated car passengers. The aim of Paper A was to compare a stationary and a driven scenario, as well as a stationary scenario over time, to investigate the potential influence that study scenarios and time have on the sitting *postures* and shoulder belt *fit* of rear seat passengers and further identify whether a short stationary study substitute a longer driving study when exploring sitting posture and belt fit in cars.

Nineteen participants completed two 45-minute sessions - a stationary scenario and a driven scenario - in the rear seat of a vehicle, during which postural and belt-fit data were collected using 3D video recordings. Due to data loss, the analysis was based on 13 participants. Passenger posture and belt fit were quantified with a machine-learning–based algorithm, developed from earlier work (Hartleitner et al., 2022, Chen et al.) and refined for the specific in-vehicle camera setup. The algorithm estimated the x (fore–aft), y (lateral), and z (vertical) positions of the upper sternum and the centre of the head, as well as the vertical distance from the upper sternum to the shoulder belt, at five frames per second. Descriptive statistics were used to analyse posture and belt-fit outcomes across study conditions. For the stationary and driven scenarios, averages and 5th–95th percentile ranges were calculated for the head and upper sternum positions in all three axes and for the sternum-to-shoulder-belt distance. Individual participant differences were examined to capture variability in posture and belt fit. To assess temporal effects, the first three minutes of the stationary scenario were compared with the full 45-minute session, enabling an evaluation of whether short-duration stationary measurements adequately represent longer-duration posture patterns.

The results showed that across all comparisons, no statistically significant differences were found in sitting posture (3D head and upper sternum positions) or shoulder belt fit between the stationary and driven scenarios, nor between the first three minutes and the full 45 minutes of the stationary scenario. Average head and upper sternum positions differed by less than the measurement error in all directions (<20 mm in x; <10 mm in y and z), and their ranges of movement were of similar magnitude across conditions. Lateral head and upper sternum positions remained centered around the y-axis in all scenarios. The shoulder belt remained on the shoulder for all participants, and the sternum-to-belt distance differed by less than 10 mm between scenarios and showed similar ranges over time. However, individual variations were noted: eight participants showed a larger average distance in the stationary scenario, meaning the belt was slightly closer to the neck during the driven scenario. These differences were particularly observed in participants with specific body characteristics, such as larger chest circumference, pronounced abdominal fat, shorter sitting height, or higher BMI. During the stationary scenario, the first three minutes showed smaller ranges of movement of the head and upper sternum compared to the full 45 minutes, but without consistent directional alternations that would indicate time-dependent posture changes. The shoulder belt distance showed a smaller range in the first three minutes but did not shift in mean value.

The results suggest that, for the group, sitting postures and shoulder belt positions are overall similar across stationary and driven scenarios, and over time in a stationary context. The observed individual differences in belt fit indicate that certain body shapes may influence how the shoulder belt fits during a ride, which is relevant for safety and comfort considerations. As there were no significant differences in posture or shoulder belt positions over 45 minutes, the findings suggest that short stationary studies can provide a representative overview of passenger postures, though individual variability should be considered in analyses and comfort evaluations. Overall, Paper A demonstrates that the study scenario (stationary vs. driven) and exposure duration do not significantly influence rear seat passengers' postures or shoulder belt fit. The findings support the use of shorter, stationary studies for investigating sitting posture and belt fit. Nonetheless, individual factors, such as body shape and BMI, can lead to variations in belt fit, highlighting the importance of including diverse body types when assessing passengers' postures and shoulder belt fit.

Paper A contribution to RQs	
RQ2: *Which factors influence passengers′ perceptions of ride comfort?*	Although Paper A does not directly investigate passengers' perceptions of ride comfort, it identifies factors associated with sitting posture and shoulder belt fit that can be related to passengers' perceptions of ride comfort. The paper suggests that individual factors such as anthropometrics (body shape) influence seat belt fit, whereas contextual factors (stationary vs. moving car) influence the range of seat belt positions for individuals with certain body shapes. In the stationary scenario, exposure duration did not appear to influence the average positions of the head and upper sternum. However, the movement ranges of posture and shoulder belt position appeared to increase over time, indicating an influence of exposure duration. For passengers with certain body shapes (e.g., larger chest, pronounced abdomen, or short sitting height), the context (stationary vs. moving vehicle) appeared to influence the variation in shoulder belt position, with the belt positioned closer to the neck during the ride.

Paper B: Sitting Comfort and Seat Belt Discomfort

Paper B was also based on the *Rear Seat Study (see description in Paper A)*. This paper describes *sitting comfort and seat belt discomfort* of rear seated car passengers (in contrast to Paper A which investigated sitting *postures* and shoulder belt *fit*). The aim of Paper B was to investigate how scenario type (stationary vs. driven) and exposure duration influence perceived sitting comfort and seat belt discomfort to explore to what extent a short stationary study could be as useful as a longer driving study.

Nineteen participants completed two 45-minute sessions in the rear seat of a vehicle, with a 15-minute break between sessions. Objective data of postures and belt fit were collected via 3D video recordings, and subjective comfort data were gathered through repeated 7-point Likert-scale questionnaires and semi-structured interviews. The within-subject design enabled comparisons across scenarios and over time, capturing both observable behavioural patterns and participants' self-reported perceived comfort and discomfort. Ratings of comfort and discomfort were analysed between scenarios and over time using statistical tests, and qualitative interview data were analysed thematically to explore perceptions of comfort and discomfort, including coping strategies, and contextual factors influencing passengers' perceptions. The video data were manually observed to increase the understanding of the postures and belt fits which participants referred to in their interviews. Integrating qualitative and quantitative data provided a comprehensive basis for exploring how scenario type and exposure duration was associated with passengers' perceived comfort and discomfort, capturing when and where discomfort occurs, patterns of postural adjustments and shoulder belt movements, underlying rationale and psychological aspects.

The findings showed that perceived sitting comfort decreased within the first 15 minutes in both scenarios. In the stationary scenario, overall sitting comfort continued to decrease over time, whereas in the driven scenario, it stabilised after the initial decrease. Questionnaire ratings showed that body region comfort decreased significantly over time in both scenarios for the back, buttocks, and thighs. The interview analysis added details to the ratings, showing that participants described perceived discomfort such as fatigue, numbness, or reduced circulation for these body regions. In addition, the video analysis helped explain the increased back discomfort, by showing that participants gradually adopted a more slumped posture over time in both scenarios. In the stationary scenario, additional significant comfort decreases were observed in the ratings of for the arms, legs, and feet, while head comfort ratings also showed a small but non-significant decrease. When it comes to the seat belt, video analysis showed differences in belt fit between scenarios. In the driven scenario, the seat belt tended to move across the chest and toward the neck among participants with certain anthropometric characteristics (e.g., larger chest or higher BMI), and interview findings indicated that for a few of them, such seat belt movement led to discomfort. The interviews further revealed differences in feelings of self-awareness, tiredness, boredom, enjoyment and ease of postural adjustments, which they associated with the contrast in stimuli between the scenarios. For instance, participants described increased attentiveness to in-car cameras and self-awareness in the stationary scenario. In contrast, in the driven scenario, participants described that visual stimuli encouraged engagement in window-gazing and linked haptic stimuli from car movements to more natural postural adjustments.

Overall, the findings of Paper B suggest that initial overall comfort decreases may be detected within the first 15 minutes in both stationary and driven scenarios. The continued decrease in the stationary scenario, combined with interview data, suggests scenario-dependent differences in perceptions of overall comfort. Specifically, increased attentiveness to in-car cameras and increased self-awareness in the stationary scenario appeared to encourage more critical assessment of perceived comfort and discomfort in the stationary scenario. Conversely, the visual stimuli in the driven scenario enabled engagement in window-gazing, which appeared to distract from attentiveness to in-car cameras and self-awareness, and instead contributed to a more enjoyable experience and psychological comfort. It also showed that participants described greater ease of postural adjustments in the driven scenario, and that haptic stimuli from car movement facilitated natural postural responses to vehicle dynamics.

In conclusion, Paper B shows comfort decreases within 15 minutes in both the stationary and driven scenarios. In the stationary scenario, overall sitting comfort continues to decrease between 15 and 45 minutes, associated with increased self-awareness and attentiveness to in-car cameras encouraging more critical assessment of perceived comfort and discomfort. In driven scenarios, comfort stabilises after the initial decrease, associated with ease of postural adjustments and a more engaging experience. Further, Paper B proposes that shorter (~15 minutes) stationary scenarios can be sufficient for capturing early overall comfort decreases, as stationary conditions appear to encourage more critical assessment of perceived comfort and discomfort. Longer stationary scenarios (~45 minutes) are recommended for exaggerating perceived discomfort across multiple body regions over time compared to driven studies, allowing cost-effective assessment of discomfort-related issues in early development stages. Lastly, longer (~45 minutes) driven studies are recommended for capturing more natural postural adjustments and bodily discomfort, as well as shoulder belt movements and shoulder belt discomfort, especially for passengers of various body shapes. The findings further underscore the importance of combining questionnaires to investigate body-region discomfort and changes over time, video observations to capture both postural adjustments fit and movements, and interviews to explore passengers' perceptions of overall comfort.

Paper B contributions to RQs	
RQ1: *What constitutes passengers´ perceptions of ride comfort?*	Paper B shows perceptions of **physical discomfort**, as participants described perceived **fatigue** and **numbness** localized in different body regions, as well as **physiological discomfort** as participants described perceived tiredness and reduced circulation related to a need to stretch. Furthermore, participants described an enjoyable experience, which in the paper was associated with psychological comfort.
RQ2: *Which factors influence passengers´ perceptions of ride comfort?*	Paper B shows influences of scenario **context** (stationary vs. driven) on participants' perceptions of (ride) comfort. For instance, participants associated the contrast in stimuli between the scenarios with self-awareness, tiredness, boredom and enjoyment and ease of postural adjustments. In turn, increased self-awareness appeared to influence perceptions of physical and psychological comfort. Paper B also shows influences of **exposure duration**, **anthropometrics** (BMI, body shape) and **interior configuration** (seat, seat belt, interior space) on participants' perceptions of physical and psychological comfort.

Paper C: Comfort in Reclined Position During Automated Driving

Paper C, based on *The Reclined Seat Study*, investigated passengers' perceptions of ride comfort in a reclined driver seat during AD in a highly automated vehicle (SAE L4, i.e., capable of automated driving within certain conditions). This provided a context in which the driver was transitioned into a passenger. The aim was to explore perceptions of ride comfort in a reclined seat positions during AD, investigate preferred reclined angles and whether these preferences are influenced by stature, to provide insights for designing seats and interior layouts in future AVs.

Twenty-nine participants experienced two short test runs in the driver's seat, first in their self-selected upright position and then in a self-selected reclined position, while the vehicle operated in automated driving mode. The study was conducted on a test track in a controlled environment in speeds up to 30km/h. Data collection included seat parameters (e.g. angle of seat back), and comfort evaluation assessed through questionnaires and semi-structured interviews after each test run. Building on insights from the rear seat study, the questionnaires and interviews in this study had an extended focus on psychological comfort aspects, focusing on perceived safety and trust in the AD context. The within-subject design allowed for comparison between upright and reclined seat positions, while integrating quantitative and qualitative data provided a comprehensive framework for examining physical comfort, seat belt comfort, and contextual factors. Data were analysed using statistical tests to identify associations between stature and chosen seat back angle and differences in comfort ratings between upright and reclined positions, while qualitative interview data were thematically analysed to explore additional aspects of comfort in automated driving. This approach contributed to increased understanding of passengers' perceived ride comfort and captured functional comfort aspects, i.e. the ability to comfortably perform a desired activity such as observing or intervening.

The findings of Paper C showed that participants generally experienced low physical discomfort in both upright and reclined positions, although the reclined position caused slightly more discomfort in the head, upper back, shoulders, and arms due to limited support. On average, participants chose a seat back angle of 25° in the upright position and a seat back angle of 42° when reclined. However, after experiencing the reclined position in motion, they adjusted to a slightly more upright position of 38°, suggesting that initial preferences in static settings may overestimate the preferred recline angle. Taller participants tended to select marginally more reclined positions, but stature had only a moderate influence, especially in reclined settings. Furthermore, taller individuals tended to choose a more reclined seat back angle in both the upright and reclined positions, but the correlation between stature and chosen seat back angle in the reclined position was slightly weaker. This suggests that stature influences chosen seat settings for upright driving, where accessibility to pedals, steering wheel and road visibility is essential. In contrast, the reclined position shifts focus away from the driving task, possibly explaining why the stature plays a lesser role. Hence, individual preferences and attitudes such as trust in AD functions likely influence the choice of reclined seat back angle. The willingness to use a reclined seat also appeared to be influenced by contextual factors. For instance, almost no participants wanted to sit reclined during city driving, while a few were positive toward sitting reclined on country roads, and most could imagine sitting in a reclined position on motorways, highlighting the influence of external context on preferred seat position. The findings indicated that designing seats for AD should balance physical support with functional requirements for control and observation.

In general, physical discomfort was low in both upright and reclined positions, which may be explained by the short exposure duration. Nevertheless, analysis showed that participants perceived slightly more discomfort for a few body regions (head, shoulders, arms, and backside of the thighs) in the reclined position. Interview analysis showed that this discomfort was associated with inadequate physical support for these body regions in the reclined position, likely explained by that the seat was not specifically designed for reclined postures. This highlights the importance of designing seats intended for reclined positions in AVs. In addition, the reclined position caused concerns related to psychological comfort aspects among most of the participants, who experienced a lack of control while reclined. The perceived lack of control was associated with a reduced view of the road and thereby reduced ability to observe the traffic, as well as with decreased ability to intervene with the AD system in case of an unexpected event. This further relates to functional comfort aspects, as the possibility to intervene requires being able to reach control functions, such as pedals and the steering wheel. Further, the fact that most participants re-adjusted to a more upright seat back angle after experiencing their initial choice in AD suggests that passengers' do not want to recline as much as expected from static experiments, due to perceived lack of control.

In conclusion, Paper C shows that the willingness to use a reclined position while riding as passengers in AD is shaped by perceptions of overall ride comfort, in terms of physical, psychological and functional aspects. Although stature showed a moderate correlation with chosen seat back angles in both upright and reclined positions, it played a lesser role while reclined in AD, where the driving task was reduced. Further, the study shows that drivers may prefer reclined positions in AD, if they have the possibility observe the traffic and easily intervene with the system if needed. Hence, perceived control remains important when choosing a reclined position in AD, especially until sufficient experience and trust towards the AD system is developed. Additionally, the results imply that regardless of stature, drivers experiencing AD in motion do not want to recline as much as expected from static experiments, due to perceived lack of control. Therefore, the automotive industry needs to revisit their expectation for reclined angles and how to design to make drivers feel comfortable and safe during AD. Future research should explore reclined seating in designs intended for AD, across varying speeds and road environments, over longer durations, and with solutions that support traffic observation and system interaction.

Paper C contributions to RQs	
RQ1: *What constitutes passengers'*	Paper C shows that perceptions of ride comfort not only involve **physical comfort**, but also **psychological comfort,** by describing perceived control, a sense of security and trust, and perceived safety. Further, it introduces the concept of **functional**

perceptions of ride comfort?	**comfort**, in the **possibility to engage in activities**, involving the activities of **observing the surroundings** and **intervening**.
RQ2: *Which factors influence passengers´ perceptions of ride comfort?*	Paper C implies that **interior configuration** (e.g., seat, interior properties) influences passengers' perception of physical comfort, and that **stature** has a moderate influence on preferred recline angles**.** It further describes that **external context** (type of road, e.g., city vs. motorway) may influences passengers' perception of psychological comfort (e.g., perceived control). Lastly, it describes that the possibility to engage in activities, such as **observing surroundings** and **intervening** (e.g., accessing controls to assist the driving), influences functional comfort, and further shapes psychological comfort (e.g., perceived control).

Paper D: Passenger Ride Comfort and Influencing Factors

Paper D, based on the Web Survey Study, explored passengers' perceptions of comfort through a large-scale web survey. The aim was to further extend the understanding of passengers' perception of overall comfort across physical, psychological and functional dimensions, and to examine factors influencing comfort preferences in the broader population, with a particular focus on individual characteristics.

Informed by insights from the previous vehicle-based studies in this thesis, passenger ride comfort was operationalised into three dimensions; physical, psychological, and functional, capturing both physical sensations, emotional states and activity engagement. A total of 1,115 Swedish respondents completed the web survey, which combined multiple-choice questions about comfort preferences with optional free-text responses to capture perceptions of ride comfort and underlying reasons for preferences. Quantitative data were analysed using statistical modelling to explore associations between comfort items and individual characteristics such as age, stature, and BMI, while qualitative free-text responses were analysed thematically to identify patterns and subthemes within the three comfort dimensions. The thematic analysis was conducted by two of the authors, who iteratively reviewed emerging themes to ensure that findings reflected consistent patterns across respondents. Disagreements were discussed and the coding scheme was iteratively redefined until full consensus was achieved. By integrating statistical modelling with thematic analysis, this study deepened the understanding of how a broader population perceives and prioritizes different aspects of comfort, complementing the experimental insights gained from vehicle-based studies.

The findings of Paper D showed that while physical comfort appeared essential, psychological comfort - particularly feeling safe and in control - was the most prominent and foundational comfort dimension. Relationships between comfort dimensions were captured, describing how insufficient psychological comfort (e.g, lack perceived safety) could trigger physiological tension and reduce enjoyment of activities, while physical factors such as seat belt fit influenced both physical and psychological comfort. Physical comfort was described as avoiding physical discomforts, such as fatigue, stiffness, numbness and chafing, as well as physiological discomforts, i.e., the body's internal regulations such as thermoregulatory responses, motion sickness and tension. Further, statistical modelling identified associations between comfort preferences and individual characteristics (stature, BMI, and age), whereas thematic analysis provided explanatory depth, showing that ride comfort perceptions were often shaped by prior experiences and contextual influences rather than physical characteristics alone.

Overall, Paper D illustrates how comfort dimensions are related and that comfort perceptions are more comprehensively understood when the dimensions are considered in combination. The thematic analysis provided depth by exploring why passengers hold certain comfort preferences, highlighting the influence of prior experiences in shaping expectations, rather than physical characteristics alone. Findings related to driving behaviour show that how a car is driven can strongly influence passengers perceived safety and ride comfort, offering guidance for the development of future AVs where driving styles can be designed to align with passengers' comfort needs to shape trust and acceptance.

In conclusion, Paper D demonstrates that ride comfort is multidimensional, dynamic, and interconnected. The relationships between comfort dimensions highlight that car comfort cannot be fully understood when examined in isolation, as psychological, physical, and functional dimensions of comfort together shape passengers' perceptions of overall comfort. Moreover, physical characteristics cannot fully explain passengers' comfort preferences. Instead, perceptions of overall comfort are shaped by a combination of individual factors (e.g., individual conditions and prior experiences), artefactual factors (e.g., climate and driver behaviour) and contextual factors (e.g., trip duration and traffic).

Paper D contributions to RQs	
RQ1: *What constitutes passengers´ perceptions of ride comfort?*	Paper D shows that passengers' perceptions of ride comfort consist of **physical comfort**, such as the absence of numbness, stiffness, fatigue and chafing; **psychological comfort**, involving a sense ease, perceived safety, security and control; and **functional comfort**, relating to the possibility to engage in activities during a ride, such as observing surroundings and assisting the driver.
RQ2: *Which factors influence passengers´ perceptions of ride comfort?*	Paper D shows that **individual factors** - including anthropometrics as stature, BMI, age, and individual condition (e.g., sensitiveness to motion sickness, climate or cramped spaces) - influence passengers' perceptions of ride comfort. It also highlights the influence of **artefactual factors**, such as seat belt fit, climate, and the way the car is driven, as well as **contextual factors**, including traffic conditions and social context. The thematic analysis further describes that comfort perceptions are shaped not only by current sensations but also by **prior experiences.**

RQ3: *What relationships exist between passengers′ perceptions of ride comfort and the influencing factors?*	Paper D illustrates how the physical, psychological and functional dimensions of ride comfort are closely connected, with variations in one dimension affecting the others. For example, participants described that insufficient perceived safety led to bodily tension or limited engagement in activities.

Paper E: Effects of Smartphone Use on Passenger Ride Comfort

Paper E, based on the *Front Passenger Activity Study*, investigated how two common passenger activities - using a smart and gazing out the window – influence passengers' perceptions of ride comfort. The aim of Paper E was to provide a deeper understanding of activity-related ride comfort in everyday travel and to inform the design of vehicle interiors, by examining smartphone use in comparison with the reference activity of solely window gazing.

Thirty front-seat passengers seated on the right side, completed two 10-minute rides, one with smartphone-use and one while solely window-gazing, in counterbalanced order, such that half of the participants started with smartphone-use and half with window-gazing. For the window-gazing activity, participants were instructed to ride as they normally would as a passenger. For the smartphone-use activity, participants were instructed to use their own smartphone for light, non-demanding activities such as reading or scrolling. Perceived overall comfort was assessed using a questionnaire, with items developed based on findings from the free-text responses in the web-survey study reported in Paper D. In addition, localised physical discomfort was evaluated using a Body Part Discomfort Scale (BPDS), while semi-structured interviews were conducted to explore passengers' perceptions of ride comfort. Posture and seat belt fit were recorded on video using two cameras mounted on the ceiling and windshield, capturing side and front views of the participant. The analysis included statistical tests of questionnaire data to identify differences in ratings of perceived comfort between activity conditions, while a thematical analysis was applied to the interview data. The observations were then considered in relation to the participants' questionnaire ratings and interview statements, allowing identification of consistencies or contradictions (e.g., high ratings of seat belt comfort despite observations of belt chafing).

The findings of paper E showed that overall, participants perceived low physical discomfort in both conditions, with no statistically significant differences in perceived discomfort in the BPDS ratings. Yet, in the interviews, about one third of the participants described lower perceived comfort during smartphone use, and video observations showed almost all participants adopted bent-neck postures during smartphone use, with some adopting asymmetric postures leaning to the sides. The questionnaire item for seat belt comfort showed no significant difference between activities, although videos showed that belt fit differed. Specifically, during smartphone use, the shoulder belt was positioned further away from the neck and closer to the edge of the shoulder, compared to window gazing. Findings further showed significant differences in perceived awareness of surroundings, with lower awareness during smartphone use. The interviews confirmed this, with several participants describing that smartphone use distracted them from awareness of their surroundings. Participants described that one negative consequence was the difficulty of preparing for vehicle motions during smartphone use, and the risk of motion sickness. The interviews analysis further showed that many participants generally wanted to be aware of surroundings, to actively observe and increase their perceived control.

Although questionnaire results alone could not reveal whether reduced awareness contributed to participants' perceived ride comfort, interviews provided complementary insights, showing that one-third of the participants described a preference for observing surroundings. This suggests that awareness of surroundings may increase perceived control which may have positive influence on psychological comfort, particularly for individuals who prefer greater control. Observing the surroundings may therefore be associated with increased ride comfort, though this effect appears to be influenced by factors such as driving style, external context and individual preferences for perceived control. Furthermore, interview findings suggest that smartphone use may slightly reduce physical comfort indirectly by preventing preparedness for vehicle dynamics and behavioural adjustments that could help mitigate physical discomfort. When it comes to activity-related postures and comfort, the video observations revealed frequent forward-flexed neck postures and asymmetric leaning during smartphone use patterns, often without corresponding perceptions of perceived discomfort in the interviews and questionnaires. One explanation for this may be that the smartphone activity distracts from noticing discomfort or that participants accepted poor posture to gain the pleasure from engaging in the activity. However, the observed postural patterns may lead to physical discomfort during longer journeys, as discomfort often develops over time. Finally, although no significant differences in reported seat belt comfort were found between activities, smartphone use was associated with less symmetric postures, which influenced the shoulder-belt fit, which may have implications on kinematics in dynamic events.

In conclusion, Paper E investigated how two in-vehicle passenger activities - smartphone use and window gazing - influence front-seat passengers' perceptions of ride comfort. Findings indicate that smartphone use did not appear to reduce physical comfort directly, although postural changes associated with smartphone use may affect physical comfort over longer ride durations. However, looking down at a smartphone instead of out of the window, reduced awareness of the surroundings and influenced both psychological comfort by diminishing perceived control, as well as physical comfort indirectly, by preventing preparedness that could help mitigate physical discomfort. Furthermore, posture during smartphone use influenced shoulder-belt fit, which influence kinematics in dynamic events. Overall, the findings suggest that the activity performed by front-seat passengers affects ride comfort, and that passenger activities should be considered when developing future car interiors and restraint systems.

Paper E contributions to RQs	
RQ1: *What constitutes passengers′ perceptions of ride comfort?*	Paper E expands the view on **psychological comfort** by describing feelings of awareness and perceived control when following what is happening in the surrounding traffic. In addition, it links the awareness of surroundings and perceived control to participants' preparedness to changes in vehicle dynamics, to be able to adjust posture.
RQ2: *Which factors influence passengers′ perceptions of ride comfort?*	Paper E shows that participants adjusted their posture, leaning to the side, or adopted tucked-in postures which they described suited the activity, demonstrating that **activity engagement** can influence postures and influence ride comfort. It also shows that participants describe that **artefactual factors** (such as driving style), **contextual factors** (such as traffic situation) and **individual factors** (preference for perceived control) influence their perceptions of ride comfort.
RQ3: *What relationships exist between passengers′ perceptions of ride comfort and the influencing factors?*	Paper E extends the view of functional comfort. It shows that participants describe how they activities they want to engage in during a ride are shaped by **motivations** to regulate psychological comfort and physical comfort. For instance, participants wanted to view surroundings for different reasons - to actively observe traffic and maintain aware of the traffic situation to feel in control (**psychological comfort**) or avoid motion sickness **(physical comfort)**, or to window gaze out of curiosity, for visual rest or for a pleasant experience, rather than a need for perceived control.

Chapter 5: Findings

This chapter synthesises the findings from the studies described in the appended Papers A to E and the expert workshop to answer the research questions posed in the thesis. Based on the cross-paper analysis of the appended papers, the chapter first presents the answers to **RQ1**: *What constitutes passengers′ perceptions of ride comfort?* and **RQ2:** *Which factors influence passengers′ perceptions of ride comfort?* The chapter then synthesises empirical insights across papers A to E and the expert workshop, answering **RQ3:** *What relationships exist between passengers′ perceptions of ride comfort and the influencing factors?* Finally, the chapter presents the proposed *Passenger Ride Comfort Framework*, representing an integration of the synthesised findings from the empirical studies described in the appended papers and the expert workshop, advancing the understanding of car ride comfort from a passenger perspective.

5.1 Comfort Dimensions Constituting Passengers' Perceptions of Ride Comfort

Passengers' perceptions of ride comfort are conceptualised as a multidimensional construct constituting three **comfort dimensions**: physical, psychological, and functional comfort. These dimensions together constitute how passengers perceive overall ride comfort. Findings from the appended papers show that ride comfort is not determined solely by bodily sensations, but also by passengers' emotional state, including perceived safety and perceived control, as well as the possibility to engage in activities during ride.

5.1.1 Physical Comfort

Physical comfort involves the bodily sensations and regulations that participants described in the studies. It includes (1) bodily sensations of **physical discomfort**, involving the absence of <u>fatigue,</u> <u>stiffness</u>, <u>numbness</u> and <u>chafing</u>, and (2) and **physiological discomfort**, involving the absence of <u>motion sickness</u>, temperature <u>regulation</u>, <u>tension</u> and <u>tiredness</u>.

Physical discomfort involves bodily sensations, with participants describing perceived <u>fatigue</u> and <u>numbness</u>, which they associated with reduced circulation and a need to stretch (Paper B). These perceptions were confirmed in Paper D, where participants also described the importance of avoiding <u>stiffness</u> and <u>chafing</u> to feel comfortable. The participants explained that these physical discomforts were typically perceived locally in body regions and tended to develop over time. For instance, they expressed that fatigue increased in body regions including back, buttocks, and legs during prolonged sitting (Paper B, D). Participants further emphasised that avoidance of physical discomfort is particularly important during longer journeys (Paper D). Together, these empirical findings emphasise the local characteristic of physical discomfort in extended periods of car riding, further reflecting the influence of exposure duration.

Physiological discomfort involves internal regulatory responses of the body rather than localized bodily sensations. For example, participants perceived reduced circulation, which reflects emergence of <u>internal regulations</u> (Paper B). In addition, participants expressed that they wanted to avoid bodily reactions such as perceived <u>motion sickness,</u> <u>tension</u> and <u>feeling too warm or too cold,</u> in order to feel comfortable as passengers

(Paper D). Overall, participants expressed these bodily regulations as responses to conditions such as in-car climate, car motion, as well as psychological unease such as anxiety during ride. They described that some reactions may interact, for example feeling too warm or sweating was described to increase the sensitivity to motion sickness. Lastly, tiredness - distinguished from fatigue which referred to muscular exhaustion - was expressed in response to sensory input and stimulation. For instance, participants described tiredness due to lack of stimuli (Paper B), and in response to excessive sensory input (e.g., from noise) that was described to cause overstimulation (Paper D).

5.1.2 Psychological Comfort

Psychological comfort involves emotional states that shape a sense of ease, calmness and the absence of anxiety that participants described in the studies. It includes **perceived safety**, a **sense of security**, and **perceived control**.

Perceived safety was reflected in participants' descriptions of feeling protected from physical harm (Paper D). In their elaborations, they typically referred to the protective capacity of the car and its safety systems that acts as a barrier keeping them safe in case of an unexpected event on the road, such as encounters with other road users or animals.

A sense of security rather reflects a psychological reassurance and trust, which were described as important for avoiding anxiety while riding as a front seat passenger. Participants expressed a sense of security in terms of reassurance with the driver. This was considered as essential by the participants, who related a sense of security and reassurance with the driver's skill and trust in their way of driving. (Paper D). Similarly, participants in reclined positions during AD emphasised the importance of trust in the driving style and system behaviour (Paper C).

Perceived control reflects a sense of predictability of how the ride will continue and readiness to intervene. For instance, predictability is reflected in participants' expressions of wanting to know how the car will behave while riding in a reclined position in AD (Paper C). Typically, participants associated this with the possibility to follow the situation by observing surroundings or having the possibility to intervene. Closely related to this, readiness refers to being ready to intervene, for example by sitting in a posture that allows for quickly reaching controls such as the steering wheel to take over the driving task if needed. This description was not limited to the AD context but was also reflected when riding in conventional cars with human drivers, where participants described the desire to observe surroundings to anticipate potential risks and intervene by alerting the driver (Paper D). Participants further associated awareness of surroundings with preparedness for changes in car dynamics. Such preparedness was described to make it easier to adjust their posture in response to car movements (Paper E).

5.1.3 Functional Comfort

Finally, functional comfort is characterised as the **possibility to engage in activities** during the ride. It therefore reflects the extent to which the ride environment provides the prerequisites for activity engagement. Participants described this possibility as characterised by ease of engagement and the absence of disruptions or disturbances that may hinder activity performance, for example due to noise, driving style, lack of perceived security, or anthropometric characteristics influencing interaction with the interior.

Activities that passengers engage in during a ride are considered within the dimension of functional comfort, categorized into two types: interactive and passive. **Passive activities** are characterized by low effort engagements, typically including calm activities such as resting, reading, listening to audio, adjusting posture and window gazing. Participants expressed that perceived safety, and security was a prerequisite for engaging in calm, passive activities, such as sleeping during a ride (Paper D). **Interactive activities** involve short-term engagement that require more attention to or interaction with the interior or other occupants, such as socializing, assisting driver, adjusting settings, and reaching storage. Participants typically linked the possibility to engage in these activities to the in-car environment. For instance, low noise levels were described to enable social interactions during ride (Paper D). Similarly, when riding in a reclined position in AD, participants linked their possibility to engage in observing the surroundings or reach controls (e.g., steering wheel) to the interior configuration (e.g., seat back angle) (Paper C). Easy access to settings and storage was also emphasized in conventional cars, where participants described that the way interactions could be performed influenced their sense of safety. For example, participants expressed that being able to reach items without leaning forward contributed to perceived safety (Paper D).

Expanding on the description of functional comfort, **comfort motivators** illustrate the motivations for engaging in an activity to regulate comfort. For instance, participants expressed that some activities during a ride are motivated by the need to regulate comfort. For example, for some, the desire to window gaze was related to the need to observe surroundings to support perceived control (i.e., psychological comfort) while others wanted to avoid motion sickness (i.e., physical comfort) (Paper E). Similarly, observing the surroundings or alerting the driver to potential hazards was motivated by the need for perceived control (i.e., psychological comfort) Paper D. At the same time, activity engagement was also driven by **other motivators**, such as curiosity or the desire to enjoy the scenery, reflecting a need for enjoyable in-car experiences (Papers B, E). Enjoyment was typically associated with engagement in activities perceived as pleasant during the ride, such as window-gazing. Such positive states were often reflected in the ride being perceived to pass quickly (Papers B, E). Together, these findings illustrate that participants' activity choices were influenced both by the regulation of physical and psychological comfort and by broader motivations for positive, enjoyable experiences during the ride.

5.2 Factors Influencing Passengers' Perceptions of Ride Comfort

Influencing factors that affect the three comfort dimensions were also identified in the appended papers in this thesis. The influencing factors include **individual factors** (anthropometrics, individual conditions, and personality), **artefactual factors** (in-car environment, interior configuration, driving style, and car model), and **contextual factors** (internal and external context).

5.2.1 Individual

Individual factors involve passenger characteristics that influence perceptions of ride comfort, including **anthropometrics**, **condition** and **personality**. Anthropometrics includes body shape (e.g., chest size, abdominal shape, sitting height, BMI), which was associated with the development of localised physical discomfort that participants described in the rear seat (Paper B). Specifically, these anthropometric measures were associated with the seat belt movements during the ride (Paper A) and further associated with occasional seat belt discomfort (Paper B). Aligning with this, stature and BMI showed associations with front seat participants' perceptions of physical discomforts (Paper D). For instance, chafing from the seat belt was described by participants of shorter stature or higher BMI, while taller or high-BMI participants emphasised the importance of adequate interior space, which they associated with the possibility to stretch to avoid stiffness (Paper D). In addition, stature had a moderate influence on preferred seat back angles in the reclined seat position (Paper C), while participants in conventional cars associated their stature with the possibility to reach controls or grab a snack during a ride (Paper D).

Individual **conditions** that influence passengers' perceptions of comfort were also described by participants (Paper D). For example, some participants noted that tendencies to sensitivities – such as motion sickness, climate conditions or cramped spaces - could heighten their sensitivity to discomfort. Those participants described that avoiding physiological discomforts as motion sickness, feeling too cold or warm was particularly important.

Beyond anthropometrics and individual conditions, the papers described that **personality** could influence perceptions of ride comfort, shaped by prior experiences and preferences. The role of prior experiences was emphasised when participants elaborated on factors influencing a sense of reassurance and predictability (Paper E). Participants described that prior experience, e.g., of the driver or familiarity with traffic context, influenced their sense of reassurance and predictability of how the ride would proceed (psychological comfort). Similarly, participants riding in a reclined position in AD expressed that more experience would increase the knowledge about how the car handles different traffic situations, reflecting that experience influences perceived control and a sense of security (Paper E). Furhtermore, the findings indicated age-related differences in comfort preferences. These differences were not primarily related to physcial charecteristics associated with age, but rather associated with prior expereinces. For example, age influenced participants' preference for car models perceived as safe. When reasoning about this preference, participants described that past accidents increased their recognition of safety systems. Additionally, participants described personality traits, such as having a sense of responsibility to be ready to assist the driver as a passenger, a personality trait associated with increased need for perceived control, (Papers D, E). Although individual differences such as the need for control may not directly affect passengers' perceived control in a ride, they may influence how strongly activities such as observing the surroundings or having the possibility to intervene contribute to perceived control.

5.2.2 Artefact

Artefactual factors that influence passengers' perceptions of car ride comfort include **driving style**, **car model**, **interior configuration**, and the **in-car environment.** Across participants' descriptions, **driving style** was characterised by vehicle dynamics and behaviour under human or automated driving. **Car model** captured aspects such as, condition, quality and brand. Interior configuration is shaped by the seat, seat belt, and interior space while the **in-car environment** was characterised by climate, noise, and vibrations.

Interior configuration includes the elements of the seat, seat belt and interior space. When it comes to the seat, participants typically described attributes as seat softness, seat settings and adequate physical support of body regions (e.g., head support from head restraint), as artefacts influencing their physical comfort (Paper B, C, D). The seat belt was expressed to cause physical discomfort as chafing during ride (Paper B, D), while the fit of the seat belt was associated with protection from physical harm and further described to influence participants' perceptions of safety (Paper D). Further, participants described the interior space linked to their possibility to stretch or move the legs and feet, which they associated with physical discomfort as stiffness (Paper B, D). Interiors space was also associated with the protective capacity of the car, with participants describing that spaciousness has a positive influence on their perception of safety (Paper D).

The **in-car environment** involves the climate, noise and vibrations in the car. Participants described these elements as factors that influence their perceptions of physical and physiological discomforts. For instance, participants described that a climate that was perceived as unpleasant could cause sweating, which could in turn lead to additional physiological responses such as motion sickness. The in-car environment could further disturb or hinder a passenger's engagement in activities during a ride. On the other hand, participants described that low noise levels could enable listening to music, having conversations or entertaining children during a ride (Paper D).

Driving style, i.e., the car dynamics and behaviour of the car when driven either by a human driver or an automated driving system, is also associated with passengers' perceptions of ride comfort. In particular, participants associated the driver's behaviour and driving style with a sense of security (Paper D), while the way that the AD system handled situations was described to influence perceived safety (Paper C). Furthermore, participants associated the driving style with motion sickness (Paper D).

Finally, the **car model** influenced perceived safety, with participants describing elements as brand, quality and condition and further elaborating on inspection status, service, and tire quality (Paper D). Participants related these elements to perceived protective capability of the car, such as the protection to external risks as other road users or animals.

5.2.3 Context

Contextual factors involve elements of the surrounding environment and refer to dynamic conditions that can change throughout a journey and influence perceived ride comfort, including **external** and **internal context**.

The **external context** includes elements such as traffic situation, type of road, weather conditions and surrounding scenery, with participants describing how these elements influenced their perceptions of ride comfort. For instance, participants perceived some contexts as unpredictable, such as roads with potential animal hazards, influencing their perceived safety and increasing their need for perceived control. A dynamic surrounding scenery could also influence psychological comfort, with participants describing that surrounding scenery could contribute to a pleasant state when participants engaged in window-gazing (Papers B, D and E).

The **internal context** includes situational conditions within the car environment that may vary during a journey, such as the social context and the presence of carried items such as luggage and personal belongings. For instance, participants described that having a large amount of luggage in the car influenced perceived safety (Paper D).

Internal context could influence the activities participants engaged in. For example, participants described that travelling with children shaped activity choices, such as listening to audio to entertain the children (Paper D). However, activities were treated separately from contextual factors, as they represent passenger engagements within the ride rather than conditions of the car environment. Therefore, activities were considered within the functional dimension of comfort rather than within the internal context.

5.3 Relationships Between Passengers' Perceptions of Ride Comfort and Influencing Factors

While the cross-paper analysis described comfort dimensions that constitute passengers' perceptions of ride comfort (physical, psychological and functional), and influencing factors (individual, artefactual and contextual), this subsection synthesises the findings, resulting in the presented Passenger Ride Comfort Framework (Figure 8). Furthermore, the findings also revealed relationships both between comfort dimensions and between the influencing factors themselves. These relationships are also presented in this section.

5.3.1 Relationships Between Comfort Dimensions

Overall, psychological comfort emerged as a prominent component of passengers' ride comfort across the papers. Unlike drivers, passengers lack direct control over vehicle manoeuvres, making them more reliant on the driver's (or AV's) behaviour and the surrounding traffic environment to handle potential risks. As a result, psychological comfort may become foundational. Even when physical comfort was adequate, concerns related to driving style or traffic situations reduced ride comfort, highlighting the central role of the psychological dimension in passengers' perception of ride comfort.

The findings further illustrate that the comfort dimensions are not independent, but dynamically interrelated. Two types of relationships can be identified between dimensions. One relationship is characterised by sequential influences, where perceptions of comfort in one dimension influence perceptions in another. For example, safety concerns (i.e., psychological comfort) could trigger physiological responses such as tension (i.e., physical comfort), which in turn could disrupt the possibility for activities such as sleeping (i.e., functional comfort), ultimately influencing passengers' perceptions of overall car ride comfort.

In contrast the other type of relationship appeared activity mediated, characterized by participants' engagement that influences perceptions of comfort across dimensions. For instance, observing surrounding traffic allows participants to maintain awareness of the traffic situation, supporting perceived control (i.e., psychological comfort), while also helping prevent motion sickness (i.e., physical comfort). At the same time, looking down at a smartphone instead of out of the window reduced awareness of the surroundings, diminished perceived control (psychological comfort), and indirectly prevented preparedness that could help avoid bodily discomfort (physical comfort). These examples demonstrate that participants can actively regulate their perceptions of comfort through their chosen activities. In some cases, activity engagement appeared to be intentional, driven by a **comfort motivator**, i.e., chosen to regulate psychological and physical comfort. For instance, participants wanted to actively observe traffic to maintain awareness of the traffic situation to increase perceived control (psychological comfort) or avoid motion sickness (physical comfort). This illustrates that the activity can be intentionally chosen to regulate ride comfort between dimensions.

Furthermore, sufficient levels of physical and psychological comfort emerged as a prerequisite for functional comfort. For instance, the absence of chafing or stiffness together with a sense of safety or trust in the driver appeared to enable engagement in activities, such as sleeping or enjoying music. This highlights how sufficient levels of physical and psychological comfort can serve as prerequisites that enable engagement in passenger activities. In this sense, physical and psychological comfort form a foundational basis that allows passengers to engage in activities of their choice during the ride.

Exposure duration reflected the length of time passengers are exposed to a given situation, which may shape ride comfort in different ways across dimensions. For example, physical discomfort was described to emerge progressively over time, recognised through bodily sensations such as fatigue and numbness. The progression of physical discomfort was particularly emphasised for longer journeys. In contrast, perceptions of psychological comfort were characterised by continuous reassessments as participants interpret the traffic situation and driving style throughout a ride. Unlike physical discomfort, which tended to accumulate over time, perceptions of psychological comfort could fluctuate in response to changes in the surrounding context or shifts in attentional focus. For instance, attention to the surroundings enhanced perceived control, while attention directed inwards was described to influence the perception physical discomforts. Lastly, functional comfort was often described in relation to short-term, intermittent activities, and became noticeable when participants attempted to perform activities during the ride, particularly when such engagement was disrupted. Overall, exposure duration influenced the dimensions of comfort in different ways during a ride, depending on the length of time participants were exposed to a given situation or interaction.

5.3.2 Relationships between influencing factors

The synthesis analysis also suggests interrelationships among influencing factors, where individual factors interact with artefactual and contextual factors in shaping passengers' perceptions of ride comfort. For instance, individual factors such as anthropometrics (e.g., BMI) interact with artefactual factors such as interior configuration (seat, seat belt, and interior space), which together influence seat belt fit. In turn, seat belt fit may influence passengers' perceptions of discomfort, such as chafing when the belt is positioned close to the neck, and perceptions of safety, as participants associated the fit of the seat belt with protection from physical harm.

In addition, individual factors showed interactions with contextual factors, as passengers' prior experiences and expectations shaped their perceptions of the ride conditions. For example, passengers described that familiarity with the traffic context influenced how predictable they perceived the ride to be. In addition, familiarity with the driver – considered an artefactual factor related to the vehicle system - also influenced perceived predictability and whether participants felt the need to actively monitor the surroundings. Furthermore, contextual factors shaped the activities participants engaged in during the ride, as for example the social context influenced activity choices.

5.3.3 Relationships Between Comfort Dimensions and Influencing Factors

Across the papers, individual, artefactual, and contextual factors were found to shape all three comfort dimensions, with some factors influencing multiple dimensions simultaneously. For instance, an artefactual factor such as the in-car environment triggered bodily responses such as feeling too warm or cold (i.e., physical comfort), caused safety related concerns about the driver's ability to drive safely (i.e., psychological comfort), and disrupted the enjoyment of in-car activities such as listening to music (i.e., functional comfort). This illustrates the cross-dimensional character of influencing factors.

Furthermore, passengers' perceptions of comfort in each dimension may be shaped by several influencing factors simultaneously. For physical comfort, anthropometric characteristics together with the interior configuration of the seat and seat belt affected seat belt fit, contributing to discomfort such as chafing. For psychological comfort, prior experiences of the driver interacted with familiarity with the traffic context to influence perceived safety and control. For functional comfort, the combination of interior configuration and anthropometrics supported or hindered engagement in activities, such as looking out the window or reaching controls. These examples illustrate that individual, artefactual, and contextual factors can jointly influence perceptions of comfort across dimensions. However, the strength of these influences varies.

The synthesis further showed systematic patterns in how different types of factors relate to the comfort dimensions. Individual factors such as anthropometrics and individual condition were primarily associated with physical comfort, while personality traits were related to psychological comfort, particularly themes such as perceived control. Artefactual factors demonstrate a broader distribution of influence across all three ride comfort dimensions. For example, the interior configuration may influence physical comfort through chafing from the seat belt, psychological comfort through perceived safety when feeling protected from physical harm, and functional comfort through supporting or hindering in-car activities such as window gazing. In contrast, contextual factors appear to primarily influence the psychological dimension, spanning several themes within psychological comfort, such as perceived safety and perceived control. These relationships are illustrated in the Passenger Ride Comfort Framework, representing the synthesis of the empirical findings (Figure 8).

5.3.4 Insights From Expert Workshop

In the expert evaluation, the strength of the influences between influencing factors and comfort dimensions were mapped and discussed. Several challenges emerged regarding how strength should be interpreted. Experts discussed that the influence of factors over time could be considered in terms of frequency (how often the factor occurs) or intensity (how strongly it affects comfort when it occurs). For instance, interactive activities may be brief and infrequent but could be critically important during those specific moments, whereas passive activities tend to be continuous and therefore consistently influence ride comfort over the course of a ride. The experts further highlighted that individual, artefactual, contextual factors or exposure duration could strongly affect perceptions of comfort for some passengers or in certain situations, while having little effect for others. For instance, personality may influence the degree of perceived control which passengers desire, meaning that the perception of control may strongly affect ride comfort for some passengers while having weaker effect for others. Experts further noted that factors such as the purpose of the ride or awareness of how much travel time remains can amplify or diminish the importance of various influencing factors. Taken together, this expert evaluation indicated that the strength of influence of different factors on ride comfort is dynamic, shaped by variations in frequency and intensity, as well as by contextual and individual factors. Nevertheless, drawing on their domain-specific knowledge from industry and research, the experts evaluated the strengths of influence within their two groups, either by reaching consensus or by agreeing on an averaged judgement for each relationship based on the group discussions. The final strength of influence of each factor, reflecting both evidence from the papers and insights from the expert workshop, was then categorized as weak, moderate, or strong and is illustrated in Figure 8.

Hence, the Passenger Ride Comfort Framework is based on a synthesis of empirical findings from the included studies described in the appended papers, complemented by expert evaluations of the strengths of influence between influencing factors and comfort dimensions. It describes passenger ride comfort as a multidimensional phenomenon, involving physical, psychological and functional comfort dimensions, and influencing factors of the individual, artefact and context. It illustrates the relationships between and within them, as well as the assessed strengths of influence between comfort dimensions and influencing factors. These strengths should be interpreted as indicative rather than absolute, reflecting both the empirical findings and expert evaluations. The framework captures general patterns in how ride comfort is shaped, rather than specifying fixed relationships that apply in every individual situation. Instead, it provides an overview of how comfort dimensions and influencing factors may interact and vary over the course of a ride.

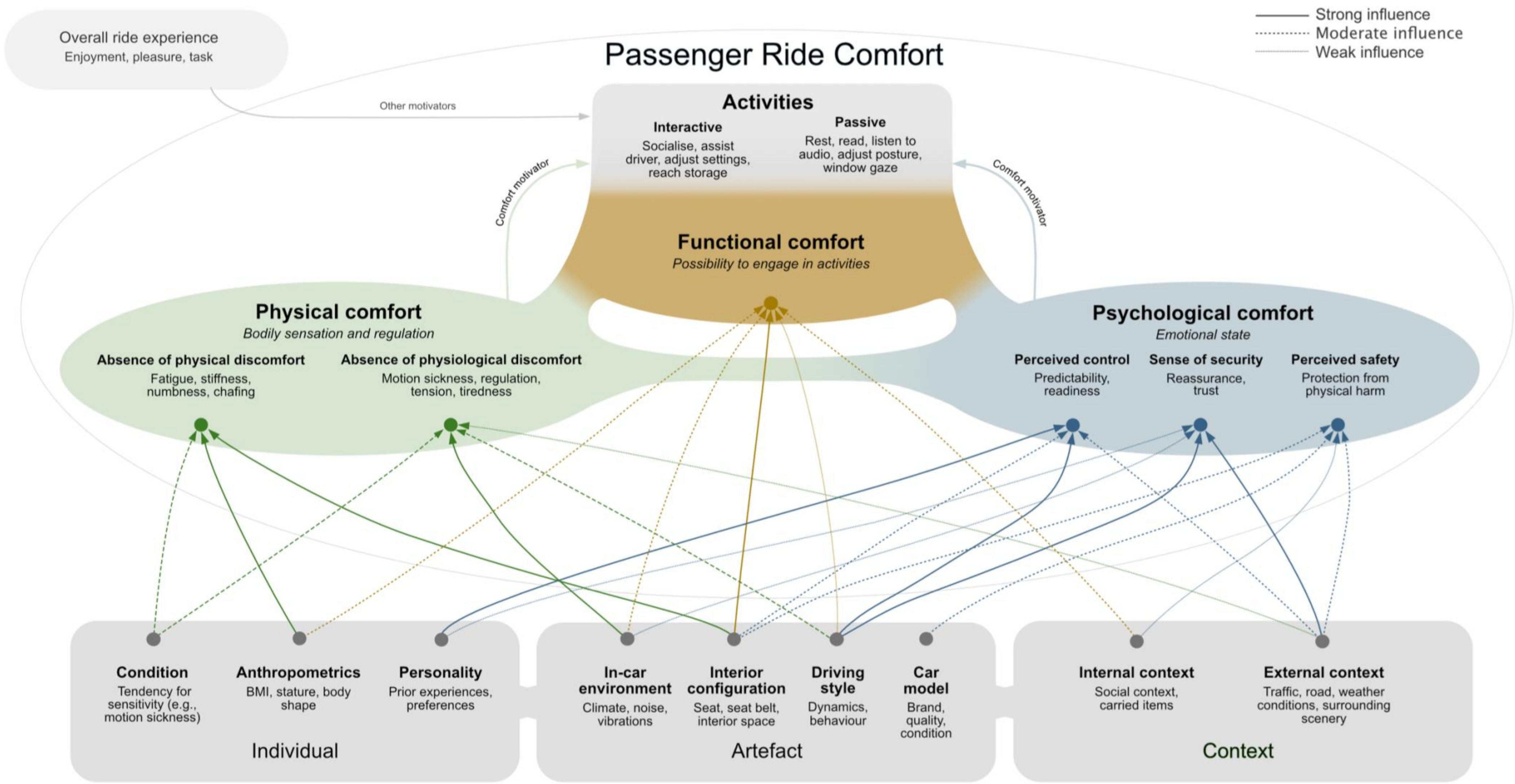


Figure 8. The Passenger Ride Comfort Framework, representing the synthesis of empirical insights across Papers A to E. It illustrates the elements involved in passengers' perceptions of ride comfort, including the relationships between and within comfort dimensions and influencing factors.

Chapter 6: Discussion

The aim of this thesis was to advance the understanding of passengers' perceptions of car ride comfort by exploring how passengers themselves perceive ride comfort and how these perceptions are shaped by influencing factors. While previous research has largely focused on physical discomfort and on drivers, less attention has been given to passengers' own perspectives and the interactions between factors influencing their perceptions of ride comfort. Following an iterative process, four studies were conducted, with each study building on insights from the previous ones, progressively expanding the understanding of passenger ride comfort by broadening the scope of the investigation. The findings are discussed in relation to the research questions and existing literature, with particular focus on the relationships between physical, psychological, and functional comfort and the interactions between factors influencing passengers' perceptions of ride comfort.

6.1 Research Findings

The findings of this thesis suggest that passengers' perceptions of ride comfort constitute three dimensions - physical, psychological and functional comfort - influenced by factors of the individual, artefact and context. When it comes to physical comfort, participants' descriptions of bodily sensations typically included terms such as fatigue, stiffness and numbness – terms associated with descriptors of physical discomfort (Zhang et al., 1996) – as sensations they wanted to avoid. Similarly, Peng et al. (2024) found that more terms were used to describe physical discomfort compared to physical comfort, suggesting that feeling uncomfortable is a tangible, conscious feeling. In contrast, psychological comfort tended to be expressed as emotional states that participants wanted to achieve, such as feeling safe or secure. While these descriptions may appear more subtle, participants often emphasized that perceptions related to psychological comfort, such as safety concerns, could shape ride comfort across dimensions. Taken together, these findings confirm that ride comfort is a multidimensional phenomenon, involving physical and psychological comfort dimensions.

Building on this, the thesis advances the understanding of passenger ride comfort by positioning functional comfort - conceptualised as the possibility to engage in activities – as a central part of passenger ride comfort. The findings suggest that functional comfort is interrelated with physical and psychological comfort, and that engagement in activities may shape both physical and psychological comfort. Aligning with this interpretation, studies have suggested that activities may influence perceptions of comfort (Vink et al., 2012; Domova et al., 2024). For instance, activity engagement can prompt postural movement (Groenesteijn et al., 2014; Hiemstra-Van Mastrigt et al., 2016), increasing motion sickness during a ride (Domova et al., 2024), or increasing passenger pleasure and enjoyment (Coelho and Dahlman, 2002). While these studies describe that activities can influence comfort, they typically describe distinct outcomes, often related to physical effects of the activities. Adding to this knowledge, the findings of this thesis illustrate how passengers' engagement in a single activity can simultaneously regulate both physical and psychological comfort. For example, participants described that the activity of observing the surroundings not only reduced the risk of motion sickness but also increased perceived control and predictability. Taken together, these findings suggest that functional comfort is a central part of passengers' ride comfort, that allows passengers themselves to actively regulate ride comfort across dimensions, despite their limited control over the car.

The findings further suggest that sufficient physical and psychological comfort form prerequisites for functional comfort. For instance, participants described that the absence of chafing or stiffness, together with a sense of safety or trust in the driver, enabled engagement in activities such as sleeping or enjoying music. Hence, activity choices appeared motivated not only by the regulation of physical and psychological comfort, but also by broader motivations, such as the pursuit of positive and enjoyable experiences. This aligns with previous work suggesting that comfort and pleasure may emerge from activities that a product enables or supports (Coelho and Dahlman, 2002), indicating that passenger activity engagement plays an active role in shaping the overall ride experience. However, while passengers may have the opportunity to shape their ride comfort and overall experience through activity engagement, their control over the ride itself remains limited. In situations where participants felt unsafe, concerns about bodily discomfort or engagement in activities became secondary. Similar patterns were observed by Bengler et al. (2014), who discussed that perceived safety and trust influence comfort more strongly than physical factors in complex driving contexts. Taken together, this suggests that passengers may actively shape their ride comfort and overall ride experience through activity engagement, although an enjoyable overall ride experience appears to be dependent on psychological comfort.

The findings also show an interplay between comfort dimensions, as comfort in one dimension was observed to influence others. For example, safety concerns could trigger physiological responses such as tension, which could influence functional comfort by limiting the possibility for activities like sleeping or resting, thereby and reducing overall ride comfort. Previous research has highlighted factors that support or disrupt activity engagement during rides, but these have primarily focused on physical conditions, such as unexpected vehicle behaviour, driving style, or seat design (Domova et al., 2024; Peng et al., 2024). The present findings suggest that perceived disruptors for engagement may also be associated with perceptions of safety. This thesis extends existing comfort conceptualisations by describing the relationships between and within physical, psychological, and functional comfort, where changes in one dimension affect the others - a level of interplay that rarely is described from passengers' own perspectives in research.

In addition to the relationships between ride comfort dimensions, the findings also illustrate that influencing factors are highly intertwined. While many studies have investigated the influence of factors such as anthropometrics, seat properties and restraint systems (Coelho and Dahlman, 2012; Osvalder et al., 2013; Bohman et al., 2019), these studies have often been conducted with the aim of comparing different seat or restraint designs, and have often focused on isolated factors rather than providing a broad overview of passengers' ride comfort. Some prior work has though indicated the importance of interactions between factors - for example, a study based on written scenarios showed that perceptions of comfort are influenced by a combination of individual characteristics and road conditions, while also highlighting the need for user studies on road to study these effects under real conditions (Delmas et al., 2022). This thesis deepens the knowledge by capturing a complexity of how the influencing factors are intertwined. For instance, participants described that chafing from the seat belt was associated with a shorter stature and not only caused physical discomfort but also triggered anxiety due to safety concerns, which in turn could trigger physiological responses such as tension. These findings illustrate that anthropometric characteristics interact with interior configuration to influence seat belt fit, which in turn may influence both physical comfort and perceived safety. Furthermore, participants described that low noise levels enabled both having conversations and enjoying music, while contextual factors such as other occupants influenced the activities passengers choose to engage in during a ride. Taken together, these findings illustrate the complex interplay of multiple influencing factors of the individual, artefact, and context during a ride, and how they, in combination, influence ride comfort across dimensions.

Although exposure duration is not explicitly illustrated in the proposed Passenger Ride Comfort Framework, it emerges as a central factor shaping passengers' perceptions of ride comfort. Throughout the course of a ride, some influencing factors may be more static, such as anthropometrics, personality, interior configuration or the driving style, while others are more dynamic, including the external context and in-car environment, as well as the activities which passengers chose to engage in. These observations are consistent with previous literature that describe that some factors are stable whereas others change throughout a ride (Domova et al., 2024). The present findings extend this understanding by illustrating how these static and dynamic characteristics shape comfort dimensions differently throughout a ride. For example, participants' concerns about physical comfort were frequently linked to relatively static factors such as seat, interior space or anthropometrics, as well as to journeys of longer durations. In turn, physical comfort tended to decrease over time, consistent with previous research on sitting discomfort (Smulders et al., 2016). Unlike physical discomfort which appears to accumulate over the course of a ride, psychological comfort appears to be reassessed in response to dynamic, influencing factors. For instance, unpredictable road context, such as roads with potential animal hazards, may have a temporary influence on perceived safety. At the same time, concerns about safety from an unpleasant driving style can arise from the beginning of a ride and last for a whole journey. Taken together, the findings suggest that physical comfort tends to decrease over time is typically influenced by static factors, whereas psychological comfort varies in response to dynamic factors, although it may also be shaped by static factors, such as the driving style from the start of a ride. By highlighting how exposure duration influences perceptions of ride comfort differently across dimensions, this thesis illustrates how passengers' perceptions of ride comfort are continuously reassessed in response to the influence of static and dynamic influencing factors in combination.

Moreover, the focus of attention appears to influence participants' perceptions of ride comfort throughout the course of a ride, as it can fluctuate over time. For instance, participants described that a lack of surrounding stimuli directed their attention inward and increased their attention to bodily discomfort. This pattern aligns with the Gate Control Theory of Pain, which proposes that reduced competing stimuli can amplify attention to bodily sensations (Melzack & Wall, 1965). Furthermore, engaging in activities may also serve as a way to shift the focus of attention, for shorter or longer periods of the ride, and thereby influence ride comfort. For example, attention to passive activities such as observing the surroundings, tend to be continuous and could therefore influence psychological comfort over the course of a ride, whereas attention to brief, interactive activities could be short-term or infrequent, yet important for functional comfort during those specific moments. On a similar note, previous research emphasises that comfort and discomfort emerge through the interaction between product and the user (Vink and Hallbeck, 2012), which may be comparable to passengers' engagement in activities that require interaction with the interior or other occupants. Furthermore, the experts in the workshop noted that awareness of how much travel time remains may amplify or diminish the importance of various influencing factors, implying that awareness of the journey duration and attention to the ride affect ride comfort. This interpretation is consistent with findings by Vink et al. (2017), who hypothesised that in situations where discomfort is present, it may decrease towards the end as the individual becomes aware that the situation is coming to an end. Taken together, while previous work has shown that duration of activities can influence comfort during a ride (Peng et al., 2024), this thesis illustrates that focus of attention and activities change over the course of a ride and together influence passengers' perceptions of ride comfort. This highlights the dynamic nature of ride comfort, where passengers' perceptions may fluctuate in different directions in response to influencing factors and the passengers' engagement and attention during the ride.

6.2 Research Process

This thesis followed an iterative research process in which each study informed the subsequent one, using a mixed-methods approach to progressively advance the understanding of car passengers' perceptions of ride comfort. This iterative process enabled subsequent studies to build on emerging insights, allowing the investigation to gradually expand from physical comfort to include physiological and functional comfort dimensions. This development strengthened the empirical grounding of the measurement instruments and ensured that later studies were informed by passengers' own descriptions of comfort. At the same time, the approach required methodological trade-offs, as the evolving focus limited the possibility of maintaining identical measures across all studies. It also illustrates how activity-related aspects of comfort become noticeable primarily when passengers attempt to engage in activities during the ride. However, this flexibility also allowed the research approach to remain responsive to emerging findings, supporting a progressively more comprehensive and passenger-centred understanding of ride comfort.

Each study adopted a mixed methods approach in which objective and subjective, qualitative and quantitative data were collected in parallel and analysed in relation to each other to examine how different data sources converged, diverged, or complemented one another. While video analysis and questionnaire results enabled observations of behaviours and perceived ride comfort, they did not reveal the perspectives and rationale shaping participants' perceptions of ride comfort or behaviour. These deeper insights were more fully captured through interviews, as similarly noted by Osvalder et al. (2013) in studies combining these methods in in-car studies. In a similar way, free-text responses added complementary detail by revealing perspectives not captured by predefined questionnaire items. While earlier studies have conceptualised ride comfort through literature reviews and expert workshops (Peng et al., 2024; Domova et al., 2024), the methodological approach in this thesis complements by exploring car passengers' ride comfort empirically, directly through passengers' perceptions during actual car rides and through their own descriptions. Without these qualitative insights into passengers' own perspectives, the relationships between and within passengers' perceptions of ride comfort and the factors that influence them would remain underrepresented.

The strong engagement in the large-scale web survey further underscores the relevance of investigating passenger comfort from the users' own perspectives. Around half of parti provided detailed free-text descriptions of their comfort preferences, offering a large amount of rich data (cf. Given, 2008) that extended insights beyond predefined questionnaire items. This high level of participation reflects passengers' interest in passenger comfort and suggests that car ride comfort remains an underexplored area with significant potential to inform both research and car design. Nevertheless, while the large-scale web survey provided perspectives from a wide range of passengers, certain interactions between factors influencing comfort are difficult to capture through questionnaires alone. For example, Aggarwal et al. (2021) showed that light and sound can be perceived as separate influences on comfort, whereas sound and vibration interact and influence each other. Such interdependent effects may be challenging to distinguish by participants, highlighting the value of the experimental in-car studies where observations can reveal interactions between influencing factors that are not easily captured in retrospective elaborations. Taken together, the thesis highlights that capturing the complexity of passengers' perceptions of ride comfort requires empirically grounded mixed-methods approaches, in which objective and subjective measures are combined to provide a complementary basis for analysis, while interviews and free-text responses support the interpretation of questionnaires and video observations, advancing the understanding of passengers' perceptions of ride comfort.

6.3 Contributions

This section describes the contributions of the thesis, both to the research area of passenger ride comfort and methodological contributions to support future research and guiding the evaluation and development of car interior.

6.3.1 Contributions to the Research Area of Passenger Ride Comfort

The work presented in the thesis contributes to research area of passenger ride comfort in cars by providing empirical evidence from car passenger experiences, thereby grounding multidimensional comfort concepts in everyday ride contexts. By identifying physical, psychological, and functional comfort as interrelated dimensions, and by demonstrating how these are shaped through interactions between individual, artefactual, and contextual factors, the thesis extends existing comfort frameworks beyond predominantly physical and driver-focused perspectives. In particular, the thesis highlights psychological comfort – involving perceived control, safety and security - as foundational to passengers' perceptions of ride comfort. Further, it introduces functional comfort as a distinct dimension in passenger ride comfort, that allows passengers themselves to actively regulate ride comfort. Taken together, the thesis contributes to the research area of passenger ride comfort by clarifying and conceptualising the concept of passenger ride comfort, synthesising empirical insights to provide a multidimensional framework that captures how the relationships between physical, psychological, and functional comfort dimensions that together constitute passengers' perceptions of ride comfort.

A central contribution to the area of research on passenger ride comfort is the view of functional comfort as an integrated dimension of passengers' ride comfort, alongside physical and physiological comfort. Functional comfort, conceptualised as the possibility to engage in activities, is a central part of passenger ride comfort, as it allows passengers themselves to actively regulate comfort across dimensions during a ride, despite having limited control over the car. In turn, functional comfort is shaped by physical and psychological comfort, which appear to set the basis for perceiving the possibility to engage in activities. Activity engagement appeared to be driven by both comfort motivators - where passengers engage to regulate physical and psychological comfort - but also by broader motivations related to the overall ride experience, such as enjoyment or task performance. Enjoying the broader, overall ride experience appeared to become possible once sufficient ride comfort was perceived. For instance, participants noted that feeling secure and having enough space makes it possible to enjoy the ride. Taken together, this suggests that psychological and physical comfort form a basis for activity engagement, which not only supports comfort regulation but also enables enjoyable overall ride experiences. By highlighting the relationships between functional, physical, and psychological comfort, this thesis provides a way to understand passenger ride comfort from passengers' own perspectives, extending existing frameworks and offering a more nuanced view of passengers' perceptions of ride comfort.

Moreover, the findings of this thesis contribute to the understanding of how different comfort dimensions become noticeable over time during a ride. While conceptual frameworks such as those proposed by Peng et al. (2024) and Domova et al. (2024) provide comprehensive categorizations of factors influencing comfort and acknowledge that some factors are relatively stable while others may vary during a ride, they do not explicitly capture the temporal dynamics of perceived ride comfort. Adding to this knowledge, the empirical findings in this thesis suggest that within a ride, psychological comfort varies with activities and dynamic factors of the ride such as external context; physical discomfort tends to accumulate over time and become more noticeable in the absence of other stimuli; while functional comfort appears to become noticeable through participants' interactions with the factors of the artefact and internal context. These findings highlight the dynamic nature of passenger ride comfort, emphasizing the interplay between static and dynamic factors, passenger engagement in activities and focus of attention – aspects that have rarely been explored directly from car passengers' own perspectives. Overall, by providing empirical insight into how everyday car passengers experience, interpret, and regulate comfort during rides, especially in relation to activity engagement, the thesis contributes to the research on passenger ride comfort by advancing the understanding of car ride comfort from a passenger perspective.

6.3.2 Methodological Contributions

A central contribution of this thesis is the proposed Passenger Ride Comfort Framework, which serves as a representation of the empirical findings. By integrating physical, psychological, and functional comfort dimensions with influencing factors of the individual, artefact, and context, the findings illustrate how these elements interact in shaping passengers' perceptions of ride comfort. Synthesising empirical insights across studies described in the appended papers, the framework provides a structured overview of the complexity in passengers' perceptions of ride comfort. As ride comfort comprises interrelated dimensions and influencing factors, the framework highlights the need for cross-disciplinary collaboration in passenger car development, where comfort-related considerations are typically distributed across departments responsible for seating, restraint systems, interior design, climate, driving behaviour, and user experience. Although focusing on isolated factors, such as specific components or physical parameters is important, it is also necessary to understand how they interact with other factors and comfort dimensions to shape perceptions of ride comfort. In this context, the Passenger Ride Comfort Framework can be used as a mediating tool to support communication, planning, and decision-making by providing a shared reference for identifying relevant comfort dimensions, influencing factors, and their interrelationships from a passenger perspective. For passenger ride comfort research, the proposed framework offers an illustration for systematically structuring empirical investigations, supporting the design of studies that capture comfort as a multidimensional and dynamic experience rather than as an isolated outcome. Together, this positions the framework as a practical tool for both car development and future research on passenger ride comfort in conventional and emerging mobility contexts.

Another methodological contribution of this thesis lies in the iterative development of questionnaire items for capturing passengers' overall car ride comfort across physical, psychological, and functional dimensions. Designing comfort items that are perceived as both distinct and comparable constitutes a methodological challenge. In this thesis, questionnaire formulations were refined across successive studies based on passengers' own descriptions of their comfort experiences. By combining questionnaire items with opportunities for qualitative elaboration through interviews or free text responses, the approach enabled insights into how passengers interpret and articulate overall ride comfort beyond predefined item wordings. These qualitative inputs supported the interpretation of questionnaire results and mitigated limitations related to item uncertainty and variability in interpretation, thereby strengthening the validity of the comfort measures used. In doing so, the thesis contributes with empirically grounded questionnaire tools for assessing passenger ride comfort, supporting future research and guiding the evaluation and development of car interior.

Much of the earlier research has focused on conceptualising ride comfort within transportation contexts such as rail and air (Groenesteijn et al., 2014; Ahmadpour et al., 2016), or AVs, where conceptualisations have been developed through literature reviews and expert workshops (Peng et al., 2024; Domova et al., 2024). While such approaches have synthesised and structured existing knowledge on factors influencing perceived comfort, they rely on the aggregation of empirical findings rather than data grounded directly in passengers' perceptions. In contrast, this thesis synthesises empirical data grounded directly in passengers' own descriptions of actual cars rides on-road, enabling a holistic understanding based on passengers' perceptions of how influencing factors are intertwined and how they, in combination, shape ride comfort. Furthermore, combining multiple data collection methods can provide deeper insights (cf. Creswell, 2014) into passengers' perceptions of ride comfort. While video analysis and questionnaire results enable observations of behaviours and perceived ride comfort, they may not reveal the perspectives and rationale shaping participants' perceptions of ride comfort or behaviour. These can be more fully captured through interviews and free-text responses which can add complementary detail. Taken together, this thesis contributes methodologically by demonstrating how empirically grounded mixed-methods approaches can be used to capture the complexity of passengers' perceptions of ride comfort, while interviews and free-text responses support the interpretation of questionnaire and video data.

6.4 Limitations

While this thesis provides important insights for advancing the understanding of passengers' perceptions of ride comfort, several limitations should be acknowledged when interpreting the findings. As the in-car studies were conducted in passenger cars of recent model year, the generally low levels of reported physical discomfort may partly reflect the characteristic of these cars. Furthermore, all on-road studies were conducted in Sweden, and the results may not fully generalize to countries with different traffic conditions, road quality or traffic behaviours. Consequently, passengers' perceptions of ride comfort may differ in cars with harsher ride dynamics and more confined interiors, or in markets with different safety culture, traffic densities and traffic norms compared to the Swedish context. However, each in-car study had different focus; comparing comfort across study design contexts (stationary versus driving), seat positions (upright versus reclined), and activities (smartphone use versus window gazing), rather than examining effects of specific car models, traffic events or car dynamics. Overall, these methodological choices supported more controlled comparisons, providing a relatively consistent baseline for examining ride comfort, which aligns with the overall aim of the thesis, to increase understanding of passengers' perceptions of ride comfort, rather than car-specific features.

Another limitation is that only a single activity - smartphone use - was investigated, compared with the reference activity of window-gazing, and that each study included only one participant per car, limiting the investigation of interactions between multiple passengers and activities. Furthermore, the three in-car studies included 19–30 participants each. While this sample size allowed for detailed within-subject comparisons across contexts, seat positions, and activities, it may limit the generalizability of the findings to the broader population of car passengers. Nevertheless, the large-scale web survey complemented these insights, although it was based on passengers' retrospective accounts of ride comfort. As with qualitative analyses, these responses are subject to interpretive analysis. To ensure consistency, thematic analyses were conducted in teams of two researchers, who iteratively reviewed emerging themes and discussed disagreements until full consensus was achieved to minimise bias in interpretation. Overall, combining more controlled in-car studies with insights from the broader passenger population, the findings provide an empirically grounded understanding of how passengers perceive ride comfort across physical, psychological, and functional dimensions. The holistic Passenger Ride Comfort Framework and associated questionnaire items developed in this thesis are directly applicable for future research as well as evaluation and development of interiors in new passenger cars.

6.5 Future Work

This thesis provides a thorough basis for future research on passengers' perceptions of ride comfort. Future research could expand the understanding of passenger ride comfort by combining in-car investigations with broader population-based data drawn from passengers' own experiences. One approach would be to conduct a naturalistic diary study, in which participants travel in their own cars over a defined period and report their perceptions of ride comfort for each ride in a diary, combining predefined items with opportunities for qualitative elaboration through free-text responses. With cameras mounted inside the car capturing posture, belt fit and activity, this approach would enable exploration of engagement in multiple activities, interactions with other occupants, and how passengers' ride comfort evolves dynamically over time in each journey in response to both static and dynamic factors. Such an approach would capture ride comfort in real-world conditions and reflect the variability and complexity of everyday travel experiences, complementing insights of this thesis. In addition, as this thesis provides empirically informed questionnaire tools for assessing passenger ride comfort future research could further refine these tools. For example, an opportunity could be to evaluate and further improve its consistency by examining each item and the questionnaire, through statistical validation. Overall, future research may extend this work by exploring passengers' perceptions of ride comfort across more realistic conditions while continuing to refine methods for capturing the dynamic and complex multidimensionality of passenger ride comfort.

Chapter 7: Conclusion

By studying passengers' perceptions of ride comfort in cars, this thesis provides empirically grounded findings that advance the understanding of passenger ride comfort. Altogether, this thesis concludes that:

- Passengers' perceptions of ride comfort constitute physical, psychological, and functional comfort dimensions. These dimensions are interrelated, such that changes in one dimension may influence others to varying degrees of prominence.

- Functional comfort, conceptualised as the possibility to engage in activities, is a central part of passenger ride comfort, as activity engagement allows passengers themselves to actively regulate comfort across dimensions during a ride, despite having limited control over the car.

- Passengers' perceptions of ride comfort are affected by the interplay of individual, artefactual, and contextual factors that influence ride comfort in combination, rather than as isolated factors, over the course of a ride.

- Exposure duration influences ride comfort differently across dimensions, as passengers' perceptions of ride comfort are continuously reassessed in response to the interplay between static and dynamic influencing factors.

- Passengers' perceptions of ride comfort may fluctuate in different directions over the course of a ride, not only in response to influencing factors, but also due to passengers' focus of attention and activity engagement.

- Capturing the complexity of passengers' perceptions of ride comfort requires empirically grounded mixed-methods approaches, where interviews and free-text responses advance the understanding of passengers' perceptions of ride comfort by supporting interpretations of questionnaire ratings and video observations.

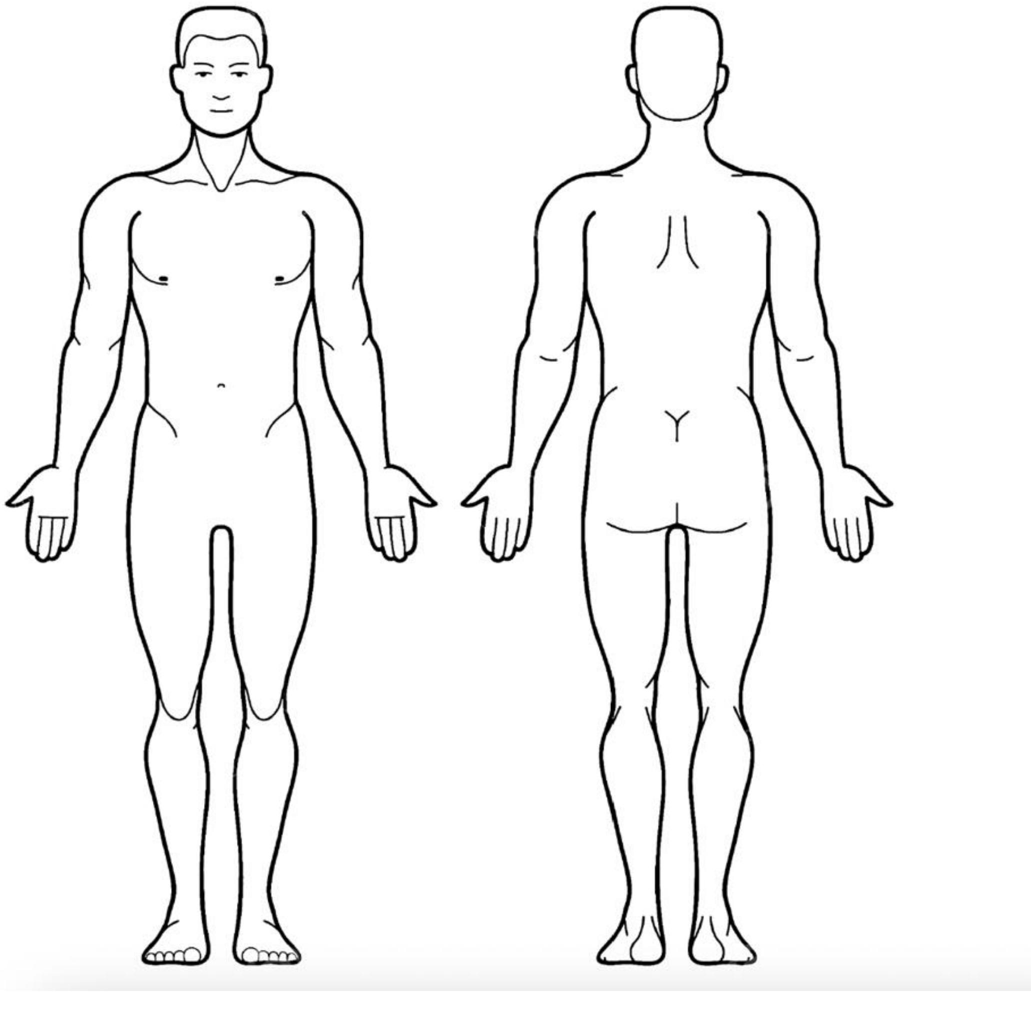
Appendix

Appendix A1: Rear seat study questionnaires

Body Part Discomfort Map

Are you experiencing discomfort in any part of your body?

- If yes, mark the location(s) on the figure by circling the area(s).
- If no, check the following box:
  - ☐ No, I do not experience any discomfort in any part of my body.

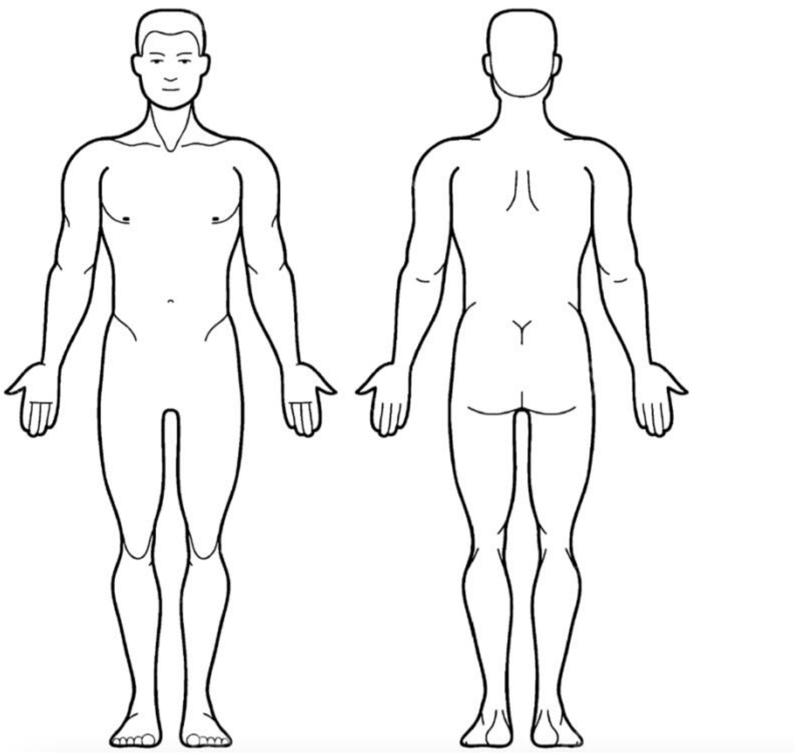


Sitting comfort questionnaires

	Strongly disagree						Strongly agree
	1	2	3	4	5	6	7
I sit comfortably in the car.							

	Strongly disagree						Strongly agree
	1	2	3	4	5	6	7
I sit comfortably with my head.							
I sit comfortably with my arms.							
I sit comfortably with my back.							
I sit comfortably with my buttocks and thigs.							
I sit comfortably with my legs.							
I sit comfortably with my feet.							

If you are currently experiencing any discomfort from sitting, mark the locations on the figure by circling the areas.



Seat belt discomfort questionnaires

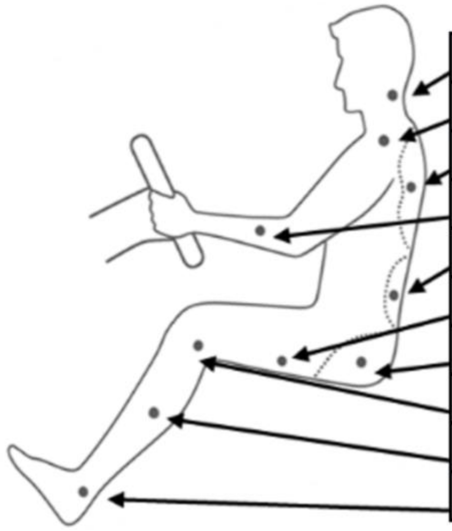
	Discomfort						No discomfort	
	1	2	3	4	5	6	7	
I experience…								…related to the seat belt.

	Discomfort						No discomfort	
	1	2	3	4	5	6	7	
I experience…								…related to the seat belt on my upper body.
I experience…								…related to the seat belt on my hips.
I experience…								…related to seat belt against my neck.

Appendix A2: Reclined seat study questionnaire

Perceived discomfort - upright position

Check the box that best represents your experience of discomfort during the ride you just completed, where 0 = no discomfort, 1 = very little discomfort, 2 = little discomfort, 3 = moderate discomfort, 4 = a lot of discomfort, and 5 = much discomfort.



	No discomfort	Very little discomfort	Little discomfort	Moderate discomfort	A lot of discomfort	Much discomfort
	0	1	2	3	4	5
Head						
Shoulders						
Upper back						
Arms						
Lower back						
Back of thighs						
Buttocks						
Knees						
Calves						
Feet						

How did you experience riding in the car while it was driving itself? Check the box that best represents your experience.

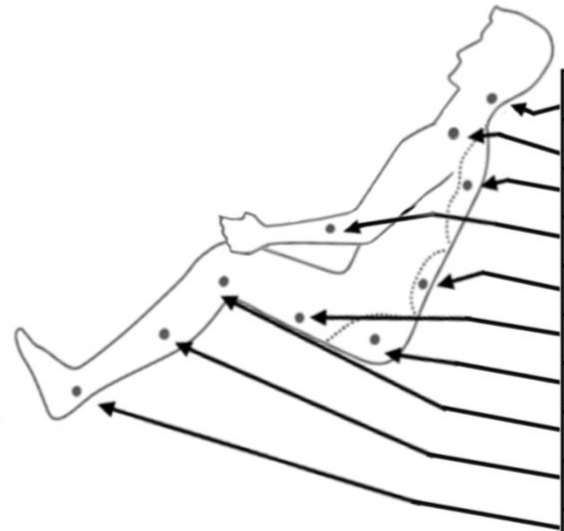
	1	2	3	4	5	
Safe						Unsafe
Reliable						Unreliable

How did you experience sitting upright while the car was driving itself? Check the box that best represents your experience.

	1	2	3	4	5	
Relaxed						Tense
Comfortable						Not comfortable
Natural						Unnatural
A sitting position I would like to use often						A sitting position I would like to use rarely

Perceived discomfort - reclined position

Check the box that best represents your experience of discomfort during the ride you just completed, where 0 = no discomfort, 1 = very little discomfort, 2 = little discomfort, 3 = moderate discomfort, 4 = a lot of discomfort, and 5 = much discomfort.



	No discomfort	Very little discomfort	Little discomfort	Moderate discomfort	A lot of discomfort	Much discomfort
	0	1	2	3	4	5
Head						
Shoulders						
Upper back						
Arms						
Lower back						
Back of thighs						
Buttocks						
Knees						
Calves						
Feet						

How did you experience riding in the car while it was driving itself? Check the box that best represents your experience.

	1	2	3	4	5	
Safe						Unsafe
Reliable						Unreliable

How did you experience sitting reclined while the car was driving itself? Check the box that best represents your experience.

	1	2	3	4	5	
Relaxed						Tense
Comfortable						Not comfortable
Natural						Unnatural
A sitting position I would like to use often						A sitting position I would like to use rarely

Appendix A3: Web survey study

What is the most important for you to feel **comfort**able **as a passenger in the front seat?** *Please select 2-3 items that you consider most important.*		
That I am sitting comfortably in the seat		
That the seat belt fits comfortably		
That I have good visibility through the windows		
That the cabin is functional so that I can perform the activity I want (e.g., reach controls and storage)		
That the noise level in the car is low		
That the climate in the car is pleasant		
That I feel secure with the driver		
That the car model feels safe		
That there are few disturbing vibrations		
That the cabin is spacious so that I have sufficient room		
Other:		

Why are these aspects the most important for you to experience comfort as a car passenger in the front seat? Please elaborate.

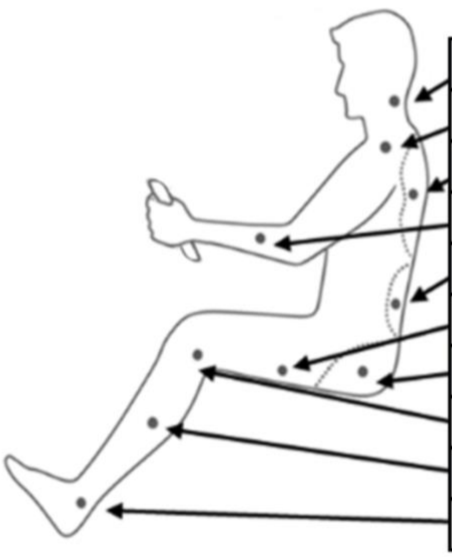
Appendix A4: Front passenger activity study

Check the box that best represents your experience during the ride.

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
I sat comfortably in the seat					
I had adequate space in the cabin					
The seatbelt fitted comfortably					
I felt secure					
I felt mentally relaxed					
I had good visibility through the windows					
I felt aware of the surrounding traffic situation					
I could perform the activity comfortably					
I experienced no disturbing noises					
I experienced no disturbing vibrations					
The climate in the car felt pleasant					

Body Part Discomfort Scale

Check the box that best represents your experience of discomfort for various body regions during the ride, where 0 = no discomfort, 1 = little discomfort, 2 = moderate discomfort, 3 = much discomfort, and 4 = very much discomfort.



	No discomfort 0	Little discomfort 1	Moderate discomfort 2	Much discomfort 3	Very much discomfort 4
Head					
Shoulders					
Upper back					
Arms					
Lower back					
Back of thighs					
Buttocks					
Knees					
Calves					
Feet					

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