# Smart Connected Bicycles

## User Acceptance and Experience, Willingness to Pay and Road Safety Implications

**Georgios Kapousizis**

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## *User Acceptance and Experience, Willingness to Pay and Road Safety Implications*

**Georgios Kapousizis**

**University of Twente**

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“Cycling User Experience” of the University of Twente

Cover illustration by Vasiliki and Nikos Karagiannopoulos

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## *User Acceptance and Experience, Willingness to Pay and Road Safety Implications*

**DISSERTATION**

to obtain
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on the authority of the rector magnificus,
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on account of the decision of the Doctorate Board,
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*Dedicated to*
*my family*

*“Φτάσε όπου δεν μπορείς!”*
*“Reach where you cannot!”*

*Νίκος Καζαντζάκης*
*Nikos Kazantzakis*

# Preface

Cycling has almost always been my daily transportation mode, despite coming from Greece, for various reasons, even when I was in Thessaloniki. Cycling has fascinated me and is a big part of my life. In this thesis, I combined my great interests, cycling and Intelligent Transport Systems, the latter being the topic of my Master thesis.

First, I would like to express my appreciation and gratitude to my supervisors: Karst, Baran and Paul. Karst, it was my pleasure to conduct my PhD with you, thank you. It was always nice to discuss with you; I appreciate your feedback and value your honest approach. I am also grateful for giving me the room to freely pursue my research ideas. Baran, thank you for being there to discuss the big and small points during those years. I am grateful for your feedback and our discussions about research. I enjoyed the time we spent together in and outside work. Most of our monthly meetings exceeded their scheduled time, mostly with good takeaways and always with a great atmosphere, which finally outlined this thesis. Thank you both very much for this. I would also like to express my gratitude to Paul, who unfortunately suddenly passed away, for his feedback and insights. I also want to thank all the committee members who took the time to assess this dissertation. I appreciate your time.

Being part of the University of Twente and especially the Transport Planning group was a pleasure for me; thanks all for the nice lunches, cycling trips and outings. Teun, thank you for the discussions we had about data, modelling, and life (and kebab). Dorette, thank you for all your help and the nice coffee breaks. Florian, thank you for helping me with the SEM, your input was insightful. The research work presented in this thesis is linked to the Smart Connected Bike project, and I would like to thank everyone who was working on this project. It was great working with you. I would also like to thank Accell group, for supporting this research project. I would also like to thank all the people who helped distribute the survey and all those who took the time to fill out the questionnaire and participate in the field trial.

I moved to Enschede at the end of August 2020, during the middle of the Covid-19 pandemic, with whatever this entails. Thankfully, Oskar was there at that time, and we started working the same days at the office and had a social life as well. Thank you for this. Later, Zakir joined our research group, and the three of us formed a great group. Without ever discussing anything, we had a kind of silent agreement, we never made noise and interrupted until the coffee breaks and lunches. Guys, I am grateful to have you, and these four years would not have been so great without you. Our moments within and outside of the UT will always be remarkable. Having drinks and food together with long discussions about everything is always great! A Guinness with you has a different taste.

I would also like to express my gratitude to Fransesco, for hosting me in his research group at ETH Zurich before my last sprint for my thesis. It has always been great discussing with you, and I appreciate your help. I spent two amazing months there and met great people. I mainly collaborated with David. David, working with you and writing a paper was really enjoyable, even though I was under pressure to finalize my PhD thesis. Thank you.

I never imagined working in academia nor conducting a PhD. This flame first came up during my first trip to Innsbruck, Austria, to visit a good friend, and later, during my master's studies, I found out I enjoyed doing research. Giorgo and Stella, I cannot thank you enough for all your support at the beginning of this journey! Sharing life with you and συγκάτοικο Anthi was amazing. My first step in academia was at the University of Innsbruck, where I met some amazing people. Thank you Prof. Mailer for giving me the opportunity to join your research group, it was a pleasure working with you. Also thank you Sabrina, for your help. Of course, I owe a huge thanks to Golam, who embraced me from the very beginning and has been a great friend since then. Rumana, thank you for all the nice moments in Innsbruck. It was nice to work with you and co-author a paper that is part of this thesis. Michele, thank you for everything! From having me during my first days in Innsbruck and speaking German to all our great moments together. It is great to have you as a friend. Pano going on cycling trips together has been absolutely incredible. I was back in the Netherlands, full of energy. Thank you (and be prepared)! I would also like to thank you, Rachel, it was absolutely nice to work with you at the University of Westminster, and it was an important step towards my PhD. I also thank the whole group of the 1055rock.gr, you were a great company during the long days and nights.

Of course, I would like to thank all of my friends back in Greece: Aleko, Karra, Moui, Patpat, Gianno, Tsimpleki, Tasouli, Voulgaraki and Antoni. We have become older and do not meet often, but catching up with you via phone and our amazing tele-taverna (τηλε-ταβέρνα) was a great strength. Thank you for being part of my life, guys; I would not be like I am today without you. Moui, thank you for always being the person I can turn to for advice, especially during these academic (four) years. Our discussions and your help have been invaluable.

Μαμά, μπαμπά σας είμαι ευγνώμων για την αγάπη και την υποστίριξη σας απο παιδί μέχρι και σήμερα, σας ευχαριστώ για όλα! Nasfika, Anastasi, and Stavro I am grateful to have you. Your innocence, smiles and happiness were priceless and a great support for me.

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Enschede, the Netherlands, October 2024

Giorgos Kapousizis

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# Chapter 1

# Introduction

Despite the rapid development of new technologies to increase road safety and mitigate human errors in motor vehicles (European Commission, 2018), such technologies have not yet been investigated extensively in cycling. Only the last decades has there been an increase in academic studies investigating “smart” e-bikes (Alam et al., 2018; Oliveira et al., 2021), and since 2016 “smart” e-bikes have been introduced to the market by bicycle manufacturers (Sparta, 2016; Stromer, 2017). Smart e-bikes can have a variety of functionalities, ranging from the Internet of Things (IoT) to more advanced technologies such as speed interventions. These bicycles can notify their owners when, for instance, the bicycle is moved (anti-theft) or remind the owners to charge the bike. More advanced smart e-bike technologies aim to automatically adjust the speed of smart e-bikes in critical locations to reduce crash risk, and governments, such as in the city of Amsterdam, are investigating these technologies (Tollenaar & Plazier, 2023). Besides, the digital revolution and the influx of new technologies will change the appearance, function, and role of bicycles and e-bikes. These allow researchers, governments, and bicycle manufacturers to further explore and develop systems that can decrease cyclists’ crash risk and improve cyclists’ comfort. Thus, the investigation of smart bicycle technologies is gaining attention, and research is needed for future deployment. This will take place by understanding cyclists’ preferences and attitudes towards smart bicycle technologies.

The rest of this chapter is organised into the following sections. Section 1.1 introduces the thesis background; Section 1.2 describes the research objectives; Section 1.3 identifies the research gaps that this thesis aims to cover; Section 1.4 describes the data collected and used for this thesis; Section 1.5 discusses the theoretical framework; Section 1.6 discusses the thesis contribution in regard to scientific, societal, and industry relevance; Section 1.7 concludes this chapter by proving the thesis outline.

## 1.1. Research Background

With the current trend of electrification all over the world to mitigate the negative transport externalities – such as emission and noise– the use of electric vehicles seems to be a one-way-street (Hamilton et al., 2020; International Energy Agency, 2022; McKinsey, 2018; Tamba et al., 2022). E-bikes also fall in the category of electric vehicles, and they are an emerging transport mode that can significantly contribute to the fight against emissions as well as congestion in cities (Behrendt, 2018; Bucher et al., 2019; European Commission, 2019;

Winslott Hiselius & Svensson, 2017). Although cycling is considered a green and sustainable transportation mode, there are growing concerns about the high number of e-bike user crashes and riding behaviour even in countries with dense cycling infrastructure and cycling culture, such as the Netherlands (European Commission, 2023a; ITF, 2023).

The number of people cycling is increasing year by year, and the COVID-19 pandemic has led to an even bigger increase (Buehler & Pucher, 2023; Nikiforiadis et al., 2020; Shimano, 2022). Cycling is a sustainable transport mode that contributes positively to society in various ways. It is associated with health benefits, contributes to the economy, increases the capacity of urban networks, and decreases carbon emissions and energy consumption (WHO, 2022; Wild & Woodward, 2019). The latter requires people to switch from cars to bicycles; however, the potential of replacing car trips is small since bicycle users need to produce power to cycle, which poses limitations for many people (e.g., commuters), especially over long distances. E-bikes can help to overcome this limitation, and studies show that e-bikes can reach a wider audience (Bike Europe, 2023; Fishman & Cherry, 2016; Van Cauwenberg et al., 2019). Van Cauwenberg et al. (2019) found that older people could cycle further and longer distances with e-bikes, and they continued using active travel mode. The use of the e-bike also has health benefits. A systematic literature review conducted by (Bourne et al., 2018) found that the use of e-bikes contributes to physical activity and can increase the fitness level of the users. Another study from the Netherlands found correlations between e-bike use and obesity (de Haas et al., 2021a). However, the direction of causality was unclear (obese people make more use of e-bike, or e-bike use contributes to higher weight). Overall, the use of e-bikes is also associated with a reduction in motorised vehicle use, which has potential positive impacts on the environment and the well-being of users (Bourne et al., 2020; Wild & Woodward, 2019).

Many governments worldwide promote e-bikes, since they have the potential to improve sustainability and replace car trips (Government of the Netherlands, 2018; Hiselius & Svensson, 2017; Philips et al., 2022). However, this depends on the transport mode e-bikes can replace. A study in Switzerland found that e-bikes have the potential to substitute car trips, public transport, walking and conventional cycling as well (Rérat et al., 2024). A study from the Netherlands conducted by de Haas et al. (2021b) found that e-bikes substitute commuting trips by cars, while many conventional bicycle users turned to e-bikes. Sun et al. (2020) also found that e-bikes significantly substitute conventional bicycles, and car usage reduction comes second. In addition, Sun et al. (2020) also found that people younger than 50 and older than 60 are more likely to reduce car usage after purchasing an e-bike. Generally, people turn to e-bikes since they can travel faster and cheaper (de Haas & Huang, 2022). In addition, the financial situation worldwide and in Europe in 2022 pushed more people to switch to alternative transport modes, such as e-bikes, to cope with high living costs and petrol prices (Shimano, 2022). As a consequence, the number of e-bike owners has increased in Europe in the last decades, and recent results show that the market share in Europe has increased by more than 10% on average, and more than 5 billion e-bikes were sold in 2023 (Statista, 2020, 2023). In particular, central and northern European countries keep a higher market share: 57% in the Netherlands, 49% in Austria, 48% in Germany, 47.1% in Belgium and 45.7% in Switzerland for 2022 (Bike Europe, 2023). Also, in the Netherlands, 4 out of 10 new bicycles sold are e-bikes, which is expected to be higher (Haas & Hamersma, 2020). The number of e-bikes sales will continue to increase in Europe, and current statistics show that e-bikes have a bright future ahead (Bike Europe, 2023; BOVAG en Vereniging, 2023; Deloitte, 2021).

Over the last decades, not only bicycle usage but also bicycle crashes have been increasing. Moreover, bicycle crashes are the only type of road crash in Europe that have had no decline since 2010 (European Commission, 2023a). One of the reasons for this trend is the increasing number of people using a bicycle and their exposure to motorised vehicles (Uijtdewilligen et al., 2022). In Europe, every year, around 2000 people die in road crashes using bicycles, which represents 10% of all road fatalities in Europe (European Commission, 2023a). Central and northern European countries, where cycling is popular, face more cycling fatalities. In the Netherlands, for instance, every year, there are more than 200 cycling fatalities since 2011, while 291 people using a bicycle died in road crashes in 2022, which represents 40% of all road fatalities (Statistics Netherlands (CBS), 2021, 2023). Also, neighbouring countries such as Belgium, Germany and Denmark have a high rate of cyclist fatalities per million inhabitants in Europe (European Commission, 2023a). In addition, it is observed that there is a steady increase in cycling fatality distribution among people aged 45 and older. In 2020, 47% of all bicycle fatalities were people older than 65, and 82% were men (European Commission, 2023a).

Bringing e-bikes into focus, literature shows that e-bike users have an increased risk of crashes; however, there is no clear indicator of whether the high speed of the e-bikes and/or the increased rates and exposure lead to these results (Haustein & Møller, 2016; Schepers et al., 2020; Schleinitz & Petzoldt, 2023). The number of e-bike user fatalities has also increased in European countries with more than 55% of all cycling fatalities in Switzerland were e-bike users, 44% in Germany, 38% in Belgium and 34% in the Netherlands. In addition, 40% of all road fatalities in the Netherlands were cyclists in 2022 (ITF, 2023). Besides, the number of cycling fatalities in people over 70 is high; this is due to the reason that people can cycle more and keep in the loop of active transport, while this was not the case previously with conventional bicycles. Most of the e-bike crashes occur due to high speed and unfamiliarity (Panwinkler & Holz-Rau, 2021; Schleinitz & Petzoldt, 2023). Thus, many countries with low cycling infrastructures are investing in building new ones. However, countries with dense cycling infrastructure and cycling culture are also confronted with a high number of e-bike crashes. This shows that cycling infrastructure alone cannot tackle this issue.

The Institute for Road Safety in the Netherlands recently published a report on improving cycling safety, in which intelligent bicycles instrumented with new technology are proposed as a measure to mitigate e-bike crashes (SWOV, 2023). New bicycle technologies have already been introduced to the market by bicycle manufacturers, such as Accell Group, which since 2016 has released a smart e-bike named Sparta. Sparta e-bike is connected to a smartphone via an application that can notify its owner when, for instance, the bicycle is being moved (e.g., anti-theft system) or remind the owner to charge the bike. In addition, over the last decades, new bicycle technologies have evolved and integrated into bicycles, focusing on cyclist safety (Nikolaeva et al., 2019; Oliveira et al., 2021). The industry aims to develop new types of e-bikes, such as smart e-bikes, that can increase cyclists' safety. In this sense, there is an increasing interest in new technologies in bicycling, and numerous studies, not limited to academics, have been published. These technologies vary from functionalities embedded in the helmet, such as blinkers and alcohol detection, and other systems installed in the frame of the bicycle, such as pothole alerts, blind spot detection and Bicycle to Everything communication (Boronat et al., 2021; Nikolaeva et al., 2019; Oliveira et al., 2021). Even though the investigation and development of bicycle technologies are still limited, it seems that they can contribute to decreasing bicycle crashes (Boronat et al., 2021; Soro et al., 2024), and there is a high potential for their deployment in the future of bicycling.

Considering the constantly evolving landscape of e-bike adoption and the constant development of bicycle technologies, this thesis presents a topology for new bicycle technologies and smartness bicycle levels; examines the factors influencing users' acceptance and willingness to pay for smart bicycle technologies; and investigates the effects of smart bicycle technologies on users behaviour and safety. It also examines users' perceived safety, trust and perceptions through a field test. In addition, it links the users' preferences with safety-related factors and cycling culture among different countries. Thus, individual-related and societal-related characteristics and road safety are some of the key aspects that are being examined in this thesis.

## 1.2. Research objective

### Research aim

This research investigates the impact of the Smart Connected Bicycles on user acceptance and willingness to pay, and their implication on road safety. A smart connected bicycle is an e-bike integrated with sensors and various systems, such as telecommunication technologies, and is connected to the urban infrastructure through wireless technologies to increase cyclist's safety and comfort. Therefore, user preferences and intention to use smart bicycle technologies are the main factors affecting their deployment. Individual and societal characteristics and road safety-related factors are key variables influencing users' acceptance and willingness to pay for smart bicycle technologies. This thesis consists of three main parts and five research questions (Chapters 2–6) (see Figure 1.1), which seek to assess the impact of smart bicycle technologies as mentioned above.

A systematic understanding of how and what type of bicycle technologies affect cycling safety is missing; we cover this gap by performing an in-depth literature review. This part makes an important contribution by reviewing the state-of-the-art bicycle technologies implemented to improve cyclists' safety and proposes a topology for different bicycle smartness levels and establishes a common terminology.

To date, no large-scale studies have been performed to investigate users' acceptance and willingness to pay (WTP) for smart bicycle technologies. This part is composed of three themed chapters and is based on an ex-ante European-based survey examining user acceptance, user preferences, and WTP for smart bicycle technologies. It describes the experimental approach and findings, which give multiple insights and help us better understand individuals' preferences for smart bicycle technologies.

Despite the importance of ex-ante surveys in understanding individuals' behaviour, there remains a paucity of evidence on users' preferences when interacting with a system. Thus, the third part focuses on the ex-post evaluation of smart bicycle technologies in field experiments. This important step helps to understand users' perceived safety, trust, performance and behavioural changes using a context-aware warning system prototype.

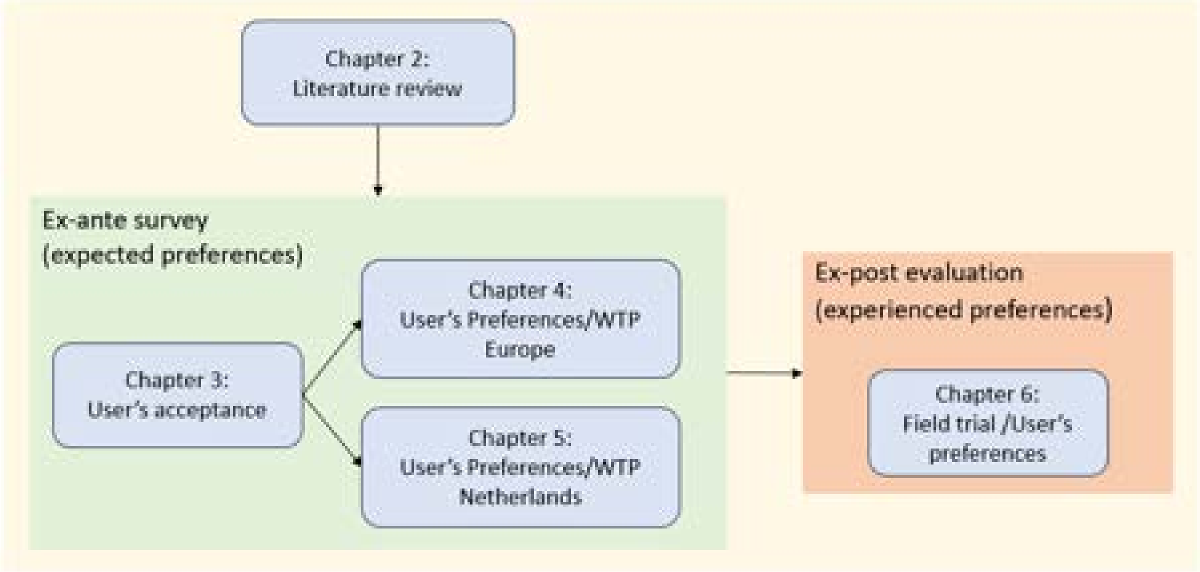

**Figure 1.1 PhD thesis overview with connections between main research parts**

The research of this thesis is the result of a collaboration between the University of Twente and Accell Group, and is conducted with the NWO-funded research project named Smart Connected Bikes. The aim of this NWO project is to design, develop and test a smart cycling eco-system where bicycles communicate in real-time with each other and with the urban transport infrastructure (e.g., traffic lights) to optimise the use and improve traffic safety, economic value, and efficiency. In total, there were six PhD students involved. The outcome from each part of this research project were used as input by other PhD candidates collaborating on the smart connected project to better develop the smart connected platform.

## 1.3. Research questions

We addressed the following five research questions for the smart connected bike project.

**Research question 1:** What bicycle technologies can be implemented on smart connected bicycles to enhance cycling safety?

Potential technologies that can be implemented on e-bikes, such as sensors and telecommunication technologies, which are already or are about to be on the market and affect cycling safety, are being investigated through a comprehensive literature review. Despite the high interest from researchers and bicycle manufacturers in smart bicycle technologies, there is no available research yet to investigate smart technologies implemented in bicycles to improve cyclists' safety, and classify them based on their use. Therefore, it is essential to study the feasibility of existing and potential technological features and to what extent they can improve e-bike users' safety and travel experience. While some researchers (Gupta & Kumar, 2020; Jenkins et al., 2017; Kiefer & Behrendt, 2016; Piramuthu, 2017; Wu & Lin, 2020) have recently studied the technologies that can potentially be implemented on bikes, we are still missing a clear view of how these technologies can improve cycling safety and what the users' perspectives are (Andres et al., 2019; Behrendt, 2016).

**Research question 2:** What are the factors affecting user acceptance of the Smart e-bike? The impact of respondents from different European countries.

While the previous chapter focused on scoping potential technologies, this chapter generates fresh insight into user acceptance for a specific set of smart bicycle technologies. Factors affecting user acceptance were examined based on data collected from a European survey. Different theories and methods derived from psychological, economic, and safety research fields were considered to investigate user acceptance of smart bicycle technologies. The comprehensive theory Unified Theory of Acceptance and Use of Technology 2 (UTAUT2) was applied. UTAUT2 explains user acceptance and uptake of new technologies and is derived based on different psychological theories, such as the theory of planned behaviour and the technology acceptance model. The UTAUT2 was proposed by (Venkatesh et al., 2012) and is an extension of the already comprehensive version of the UTAUT (Venkatesh et al., 2003). Many researchers have used the UTAUT and UTAUT2 in different domains, including cycling acceptance of shared bike systems, e-bikes, autonomous delivery systems, conditionally automated vehicles and shared information systems for public transport (Jahanshahi et al., 2020; Nordhoff et al., 2019; Sarker et al., 2019; Simsekoglu & Klöckner, 2019a; Wolf & Seebauer, 2014). Results are useful to develop the smart connected bike prototypes such as the one in Chapter 6 of this thesis. We investigate which road safety-related factors influence people's decision to accept smart bicycle technologies enhancing cycling safety. Data from a cross-country survey in five European countries- Austria, Belgium, Germany, Greece, and the Netherlands- differed in population, cycling culture, and e-bike market sizes investigated. We conduct a multi-country analysis to investigate the psychological factors affecting participants' acceptance levels living in different countries. In addition, we examine the differences between Pedelec and Speed-Pedelec users towards a smart e-bike.

**Research question 3:** Which variables influence potential users' preferences and willingness to pay for smart bicycle technologies across European countries? Providing a classification of individuals according to their choices.

This chapter investigates user preferences and willingness to pay for smart bicycle technologies in European countries. Discrete choice (DC) analysis was used to answer the above research question. DC models have been used for years to predict people's choices based on stated choice experiments. Especially in the transportation domain, many studies focus on using stated choice analysis to explain who and why people make specific choices and, for instance, the trade-off between travel time and cost as well as the willingness to pay (Ben-Akiva & Lerman, 1985; Hess & Daly, 2014). Choice analysis is divided into the discrete and continuous analysis; in this study, due to the nature of the collected data, heterogeneity is expected across five countries. A Latent Class Choice Model (LCCM) is used to shed light on the expected heterogeneity. This helps to capture heterogeneity among people's choices and classify them into groups with homogeneous choice characteristics (Ferguson et al., 2018; Hess, 2014; Molin et al., 2016). We apply a LCCM to examine users' preferences and willingness to pay for smart bicycle technologies. This approach allows us to capture unobserved heterogeneity in participants' choices and classify the sample based on similarities of participants' preferences. Thus, we link participants' choices with various variables, such as sociodemographic characteristics, available cycling infrastructure, and population density, to explain heterogeneity in users' preferences.

**Research question 4:** What are the preferences of Dutch e-bike users regarding smart bicycle technologies and to what extend are they willing to pay for such technologies? Shedding light and explaining the existing heterogeneity in preferences and WTP.

In this chapter, we examine users' willingness to pay and potential uptake of smart bicycle technologies in the Netherlands by using a mixed logit model and applying different distributions for the cost variable. This allows us to draw solid results about the willingness to pay. The Netherlands is the leading country in Europe and the second, after China, in the worldwide e-bike market. In addition, since 2017, more e-bikes have been sold than conventional bicycles every year, and it is estimated that in 2022, around 486,000 e-bikes were sold (BOVAG en Vereniging, 2023). The e-bike share increased from 5% to 37% of the total cycling kilometres in the past ten years (2012–2022). In addition, in the Netherlands, e-bikes are a common mode of transport with a large variety of users, including commuters, young and older adults, hence allowing an analysis of heterogeneity in preferences (de Haas et al., 2021; Sun et al., 2023).

**Research question 5:** What are the effects of a safety support system on cyclist's riding behaviour and perceived safety?

In the evaluation and feedback phase, a safety support system was developed and used in field trials to warn e-bike users of potential high-risk locations and school zone areas to investigate their perceived safety and riding behaviour changes. The field trial is a common method used in order to test a product, especially in the transportation domain where nowadays researchers and manufacturers are investigating, for instance, the loyalty of technology such as ADAS or partly automated vehicles (Piao & McDonald, 2008), user behaviour (Andres et al., 2019; Várhelyi et al., 2006), societal relevance (Berrada et al., 2020; Chee et al., 2020) and safety (Jeon & Rajamani, 2019; Kourtellis et al., 2019). Initially, the bicycle crash report (BRON) from the Netherlands was used to map bicycle crashes and identify hotspot locations. In the literature, the network Kernel Density Estimation (KDE) method has been widely used to identify crash density for vehicles and bicycles (Abdulhafedh, 2017; Ulak et al., 2017; Vandenbulcke et al., 2014; Xie & Yan, 2008). The KDE method estimates the density of crash points on a network. Then, the safety model will be used to feed a smartphone application, which will communicate the warnings to the users. Statistical methods, such as t-tests and multinomial logit models, will be used to link sociodemographic characteristics and examine users' perceived safety, trust, performance, and riding behaviour changes.

As such, we explore users' perceptions and perceived safety of the safety support system in real traffic conditions. Also, we study how the notifications that users receive from the safety support system concerning critical locations and other relevant information can help improve road safety by reducing bicycle crashes. Hence, we aim to evaluate the perceived safety of e-bike users while they use this system and their potential behavioural changes.

## 1.4. Research data

The data used in this study is mainly empirical data, and self-collected for the purpose of this PhD research. Data was collected in two phases: 1) during November 2022 and January 2023 for the user acceptance and stated choice experiment (research questions 2–4), and 2) during April and May 2024 for the field trials (research question 5).

The primary scope of this survey was to collect data from countries that vary in quality of cycling infrastructure and cycling culture to understand people's perceived safety and perception towards smart bicycle technologies. Hence, we focused on collecting data from different European countries. Our initial aim was to focus on the following countries: Austria, Belgium, Germany, Greece, France, the Netherlands, Switzerland and the UK. All these countries have fundamental differences in cycling infrastructure, size and topology. Thus, once the questionnaire was ready and tested within the research group, it was translated into five languages (Dutch, English, German, Greek, and French). Note that some countries have two or more official languages, e.g., Belgium and Switzerland. Then, a small pilot took place by distributing the survey among experts who natively speak one of the above languages. Once the experts' comments were implemented, the survey was distributed among the five countries to twenty random respondents per country to ensure the layman's translation of the survey and content. Later, we fully distributed the survey in the countries mentioned above. In total of 2364 people filled out our survey. After cleaning and focusing only on responses from participants who owned or were willing to buy an e-bike, we ended up with 1,625 respondents from five countries: Austria, Belgium, Germany, Greece, and the Netherlands.

In the second part of the data collection, for Research Question 5, a field trial study with a before and after survey was conducted in Enschede, Netherlands, between April and May 2024. The scope of this survey was to capture participants' perceptions, perceived safety and behavioural changes during a ride with an instrumented e-bike with a safety support system. The questionnaire focused on participant interaction with the safety support system, perceived safety and perception of this specific smart bicycle technology. In addition, GPS data was collected to analyse participants' speeds and riding behaviour changes. The field trial was constructed based on three rides in a predefined route. After each ride, participants were requested to fill out the questionnaire. In total, we collected responses from 46 participants.

## 1.5. Conceptual framework

This part introduces the conceptual framework (Figure 1.2) of this research and its effects on cycling safety and user acceptance. To better explain the theoretical framework and its use in the current study, we aim to answer how smart bicycle technologies can affect cycling safety and at what level users are willing to accept and pay.

While there is a constant increase in research on new bicycle technologies, the literature on smart bicycle technology is spread and scattered in regard to cycling safety. Thus, the first component of the theoretical framework for this study is to clarify how smart bicycle technologies can be used on bicycles. We conduct a literature review and follow a specific methodology and search strategy in order to ensure reproducibility and transparency. This will allow us to learn and create a technology base for the following research parts of the thesis. Once we introduce specific bicycle technologies, we investigate the impact of smart bicycle technologies on safety and user acceptance. We use one of the most well-established behavioural frameworks for assessing users' acceptance of new technologies, the Unified Theory of Acceptance and Use of Technology 2 (UTAUT2) (Venkatesh et al., 2012). The

UTAUT2 framework incorporates different factors in order to determine the user's acceptance of technology, which is the case for this thesis on smart bicycle technologies. In addition, we control our model for different sociodemographic characteristics, safety-related factors and countries' impact.

Furthermore, this thesis investigates users' preferences for smart bicycle technologies. In the literature, a common approach to analyse individuals' preferences and to predict their behaviour is the discrete choice model (DCM) (Train, 2009). DCM has been used for decades to predict individuals' choices based on choice experiments (CE), where individuals can make trade-offs between a set of alternative discrete choices (Train, 2009). The choice experiments consist of a finite number of alternatives, usually developed based on hypothetical scenarios, and are categorised by attributes and attribute levels. Once data is collected based on a CE, different type of models can be estimated, with the multinomial logit model (MNL) usually being the base model, assuming that individuals made a choice based on the best alternative for them. Hence, it is common to use the random utility maximization theory as described by (McFadden, 1973). There are more advanced choice models, such as the LCCM model, mixed logit model, and hybrid choice models, which allow the researcher to incorporate heterogeneity among respondents' choices, latent variables (based on attitudinal questions) and account for panel effect (Hess, 2014).

Finally, we use behavioural theories for perceived safety, trust and user experience, as well as methods for crash modelling in this study. The reason for this is twofold: 1) to identify crash risk locations in a network by developing a safety model that can be used to notify e-bike users of locations with high crash risk probability, and 2) to investigate users' perceived safety and riding behaviour changes in field trials. Field trial experiments are commonly used in research to investigate and test new systems and examine users' experiences and behaviour. Field trial experiments use some controlled elements that usually allow comparison before and after introducing a system or transport mode.

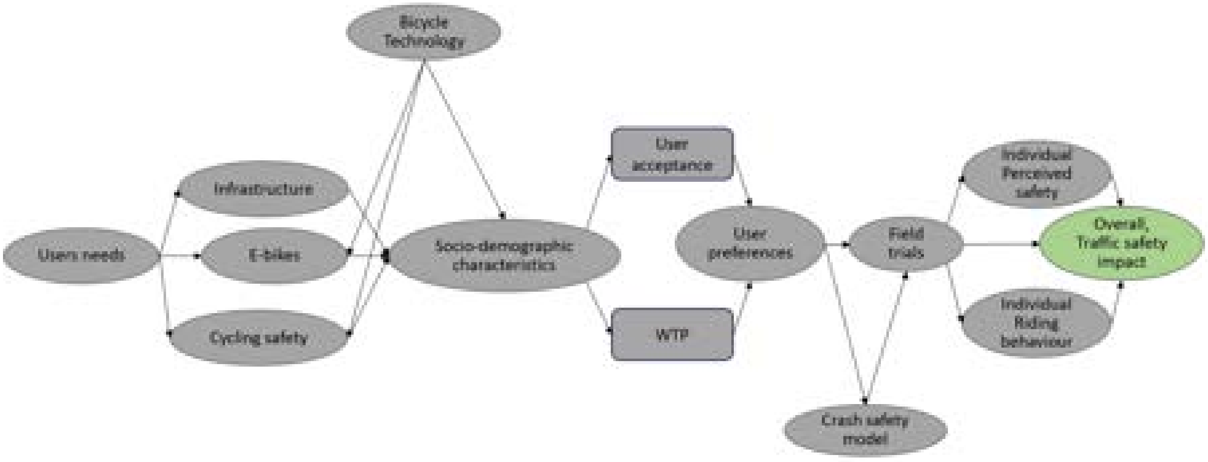

**Figure 1.2 Theoretical Framework**

## 1.6. Thesis contribution

This thesis contributes to the literature and practice in various ways. In this section, we discuss the theoretical and practical contributions.

### 1.6.1. Scientific relevance

The thesis is composed of five different chapters, so in the following section, we discuss the theoretical contributions of each chapter.

**Chapter 2.** Despite the high attention paid to new bicycle technologies on cycling safety and comfort by researchers and the industry, no study focuses on what type of technologies can be implemented on bicycles affecting cyclists' safety.

This is the first study to undertake a systematic literature review of emerging bicycle technologies that can be embedded into bicycles, affecting cyclists' safety. It proposes a classification for the definition and topology of different "smart bikes" levels based on their technology readiness level and assistance to the cyclists. This allows us to learn and create a technology base for the following research questions. We expect to develop a topology of technologies based on different criteria such as safety features, technology readiness levels and feasibility. We account for different maturity levels of technologies and the assistance they can provide cyclists. Hence, this can be used in the future development of smart bicycle technologies and serve as a consensus about their characteristics under the umbrella of "smart bikes". This way, we create the foundations of not only this research project but also future studies focusing on the implementation of new technologies for bikes.

**Chapter 3.** While there is a high interest in smart bicycle technologies, it is still unknown to what extent e-bike users' and potential e-bike users are willing to accept such technologies on their bicycles and what factors influence their acceptance level towards a smart e-bike.

While the UTAUT has been applied primarily to user acceptance of new technologies, this is the first study that adjusts it to fit the scope of this research better and examines the users' acceptance of the smart e-bike. Thus, this study provides an important opportunity to advance the understanding of user acceptance of the smart e-bike based on a specific set of smart bicycle technologies on Level 3 "active assistance" as defined in Chapter 2. We use this level due to the highest technology readiness level of the technologies included at this level. We analyse and compare data from different countries due to the increased sales and high penetration of e-bikes across European countries, which vary in cycling infrastructure and cycling culture. In addition, in our approach, we modify the model to better fit the scope of this research by adding two additional factors, perceived safety and social status and use safety-related factors to control the model to capture differences among countries. This cross-country comparison allows us to investigate users' acceptance of smart bicycle technologies in countries with fundamental differences in cycling and draw insights for stakeholders and bicycle manufacturers. To ensure the validity of our questionnaire among participants from different cultures, we established the measurement invariance, which is usually missing in such studies, to determine whether participants from different backgrounds equivalently interpreted the questions.

**Chapter 4.** In the previous Chapter 3, we analyse users' acceptance of a specific set of smart bicycle technologies. In this chapter, we study users' preferences and willingness to pay for different smart bicycle technologies in European countries.

The importance and originality of this study is that it explores a LCCM approach to investigate users' preferences for smart bicycle technologies, as well as WTP. This approach allows us to 1) comprehensively analyse differences in users' preferences living in different countries with different cycling infrastructures and their attitudes regarding smart bicycle technologies, 2) identify the sociodemographic variables that explain the differences among users, and 3) estimate the willingness to pay different groups of potential users towards smart bicycle technologies enhancing cycling safety. Also, no previous study has incorporated different levels of cycling infrastructure and other safety-related factors on their impact on users' perception of smart bicycle technologies. Thus, this study determines and incorporates different variables, such as cycling infrastructures and cycling cultures among countries, influencing users' perceptions and WTP towards different types of smart bicycle technologies. We estimate a LCCM to account for the random heterogeneity of the participants' choices and to link these preferences with variables such as safety-related factors and geographic areas.

**Chapter 5.** While Chapter 4 investigates users' preferences among countries, now we study the willingness to pay and the uptake of smart bicycle technologies in the Netherlands using a mixed logit model.

The importance and originality of this study is that it explores users' preferences by demonstrating that different segments of respondents show huge differences in WTP for smart bicycle technologies in the Netherlands. We estimate a mixed logit model with random parameters to account for heterogeneity, but we also seek deterministic heterogeneity among respondents' choices. By conducting such an analysis, we can provide solid results about Dutch preferences and willingness to pay using a specific model. Furthermore, we investigate to what extent potential users will accept different smart bicycle functionalities, advanced systems such as an automatic speed adaptation system, or whether they prefer only to receive notifications to adapt their speed (less advanced smart bicycle technologies) and link these sociodemographic and other related factors. These provide, for the first time, new insights into respondents' preferences and WTP for smart bicycle technologies.

**Chapter 6.** This chapter introduces a context-aware warning system for e-bike users, which warns e-bike users in high crash risk locations.

This study makes an original contribution and generates fresh insight by allowing us to examine, on the one hand, how bicycle crash data can be used to improve cycling safety; and, on the other hand, to examine users' perceived safety and behavioural changes when receiving notifications under specific circumstances. We utilise bicycle crash data to first feed a smartphone application with critical locations and then warn users when they approach an area with a high crash risk or school zones to reduce their speed or pay more attention during field trials. This can shed light on users' perceptions of smart bicycle technologies in a field experiment. In addition, we quantify the impact of smart bicycle technologies on road safety by collecting GPS data during the rides.

### 1.6.2. Societal relevance

The findings of this PhD thesis can assist policymakers, governments, and society overall in various ways. The findings are directly related to e-bike users and individuals willing to buy an e-bike, and their behaviour concerning smart bicycle technologies influencing cyclist safety.

Stimulating green transportation modes is key to many governments' action plans worldwide. E-bikes are one of the modes that can contribute to reducing transport emissions and improving sustainability. Bicycle technologies can help increase the adoption of e-bikes due to diminishing safety concerns. Additionally, individuals can cycle safer and more comfortably, especially those prone to bicycle crashes.

#### ❖ Relevance for policymakers and governments

In addition, findings from this PhD thesis can assist in better implementing new policy programmes promoting road safety for cyclists. Thus, policymakers can benefit from this study and develop regulations and legislation before a technology is introduced in the market.

- More and more people are considering purchasing e-bikes, and the sales of e-bikes are rapidly growing globally. At the same time, new bicycle technologies and “smart bicycles” overwhelm the market without a consensus on what can be labelled as “smart” and what the differences are. This thesis provides a common terminology for smart bicycle technologies that can help potential buyers, society, and policymakers towards the deployment of smart bicycles.

- Data analysed in this thesis was collected from a cross-country survey in five European countries. Hence, the findings of this thesis are relevant not only to a specific country, as usually happens, but to governments and policymakers in all these countries. Also, the findings can be used by high-level policymakers, such as the European level, to consider and create legislation and regulations at the Union level. Users’ preferences derived from the analyses conducted based on this data can help policymakers draw future plans for integrating smart bicycle technologies on e-bikes and prioritise different technologies in specific areas or countries. The WTP can provide insights not only to bicycle manufacturers but also to governments and policymakers in case they want to subsidise these technologies if they see safety implications.

- Users’ preferences of smart bicycle technologies and WTP in the Netherlands can show whether heterogeneity exists among individuals from the same area. Preferences of different smart bicycle technologies can show that individuals may find different systems more useful or do not want such systems to intervene in their bicycles. Thus, policymakers can incentivise advanced technologies and smart bicycles with high societal benefits. The market segmentation approach also provides useful insight since it will show whether individuals have differences in WTP for smart bicycle technologies. Policymakers and local authorities can use these results and create reward discounts for those willing to buy smart bicycle technologies.

- The ex-post evaluation of a specific set of smart bicycle technologies, among other things, provides relevant information about users’ performance and perceptions of a context-aware warning system and its safety implications. Governments can reflect on the effectiveness of this system since such a system could influence e-bike users' safety.

Overall, e-bikes can reach up to 25km/h while fast e-bikes, namely speed-Pedelecs, can reach up to 45km/h, making them a proper transportation mode, especially for commuters. In addition, the emerging fast-delivery companies that promise ten-minute delivery also use e-bikes. Thus, another group of fast e-bikes run around the cities. However, this leads to a high risk of crashes among cyclists and other motor vehicles due to the high speed of the e-bikes. As noted, the number of e-bike crashes and fatalities increased in European countries. Considering the rapid evolution of technologies in this field, the use and the status of bicycles will change, especially for e-bikes. Smart connected bicycles could be the next revolution in the urban road transport field since they could offer users an alternative transportation mode that brings all the positive characteristics of a bicycle, like easy accessibility to the city and increased safety.

### 1.6.3. Industry relevance

#### ❖ Relevance for bicycle manufacturers

From an industry point of view, bicycle manufacturers and system designers can gain insights from this thesis since it examines users' preferences for different possible bicycle technologies as well as technology acceptance and willingness to pay, which influences the deployment of such technologies.

In detail, bicycle manufacturers can use this thesis results to prioritise the development of specific smart bicycle technologies on which individuals have a higher preference. In addition, bicycle manufacturers should promote specific smart bicycle technologies in different areas and countries. This should be in line with the cycling infrastructure in the focus area since we found that individuals living in areas with low cycling infrastructure, such as Greece, are more likely to use advanced bicycle technologies. The above will help them to deploy such technologies and influence the penetration rate of smart bicycle technologies in the market. Another point of interest for bicycle manufacturers and system designers is the price potential users are willing to pay for a specific bicycle technology. Hence, they could develop systems that fall in price values similar to those in this thesis. This information can easily be extracted from the work in this thesis.

#### ❖ Relevance for insurance companies

Insurance companies can also benefit from the findings of this thesis. While insurance for e-bikes is not yet required, many e-bike owners usually insure their bicycles due to the high purchase cost. Insurance companies might consider giving discounts to individuals who own smart bicycle technologies if they see the potential benefits of reducing bicycle crashes. This will be used as a pull measurement, so e-bike owners might be willing to use smart bicycle technologies. Hence, the benefits will be twofold: on the one hand, they will potentially increase their safety, and on the other hand, they will have a discount on the insurance. This could be a way for policymakers and governments to substitute the cost for smart bicycle technologies.

## 1.7. Thesis outline

The overall structure of this thesis takes the form of six chapters, and Figure 1.3 illustrates the thesis outline. The first part introduces the research objective, establishes the fundament, and sheds light on the existing and future bicycle technologies affecting cyclists' safety. **Chapter 2** is being used as a base for the next chapters and introduces the context of smart bicycle technologies and bicycle smartness levels. **Chapters 3 to 4** address the theory-driven approach of investigating user acceptance and willingness to pay for smart bicycle technologies based on the European collected data. **Chapter 5** focuses on user perception and willingness to pay across the Netherlands, and **Chapter 6** provides users hands-on experience and behavioural changes using a specific smart bicycle technology, a safety support system. Finally, **Chapter 7** summarises each chapter's conclusions, synthesises the overall findings of this thesis, reflects upon them, and discusses implications and future research directions.

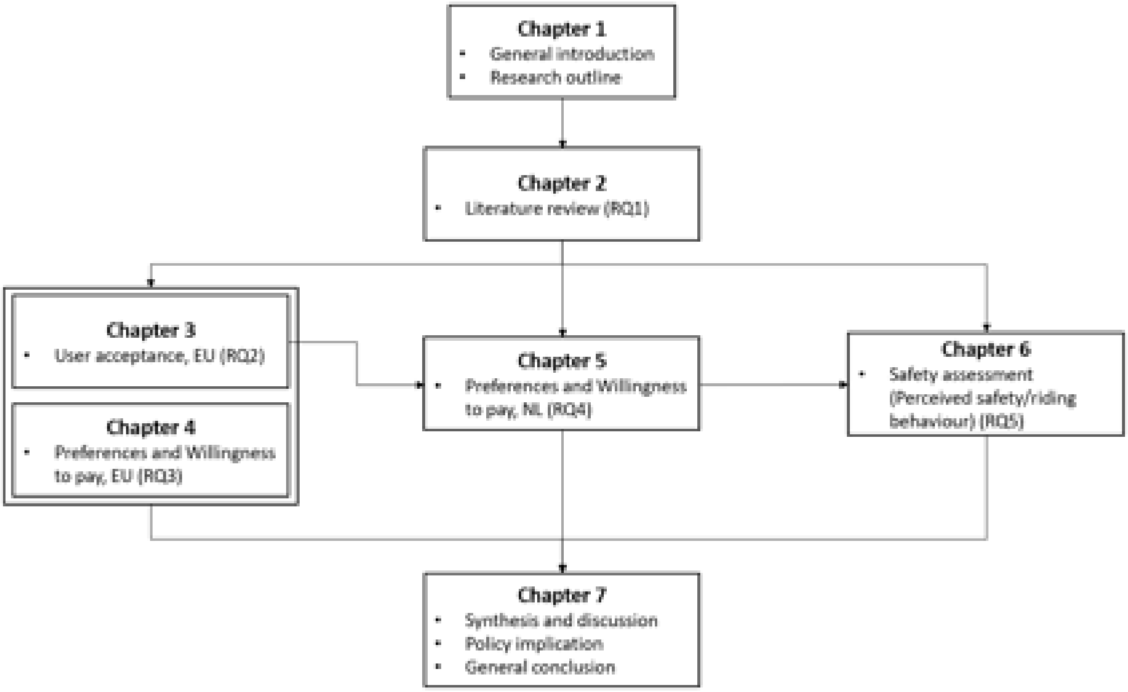

**Figure 1.3 Thesis outline**

# Chapter 2

# A review of state-of-the-art bicycle technologies affecting cycling safety: level of smartness and technology readiness

This chapter is based on: Georgios Kapousizis, Mehmet Baran Ulak, Karst Geurs & Paul J. M. Havinga (2022): A review of state-of-the-art bicycle technologies affecting cycling safety: level of smartness and technology readiness, Transport Reviews, DOI: 10.1080/01441647.2022.2122625

## 2.1. Introduction

The new era of mobility employs new technologies such as sensors and wireless communication to achieve a more sustainable, reliable, and safer environment for road users (Storme et al., 2021). Numerous studies have been published concerning relevant new technologies and systems like Cooperative Intelligent Transport Systems (C-ITS) and Connected Autonomous Vehicles (CAVs) (Milakis et al., 2017; van der Pas et al., 2012) as well as electronic vehicle systems such as Advanced Driving Assistance Systems (ADAS). For instance, ADAS assist drivers by warning them when the vehicle fails to keep within the road lanes (European Commission, 2018; Piao & McDonald, 2008), or the Intelligent Speed Adaptation (ISA) system which adjusts the speed of the vehicle (van der Pas et al., 2012). These systems aim to minimise human error, which accounts for more than 90% of all road injuries, according to the European Commission (2018).

Unlike motor-vehicle transport, the implementation of Information and Communications Technologies (ICT) and C-ITS in cycling has not been comprehensively investigated (Gadsby & Watkins, 2020), even though cycling offers several benefits both to society and the environment (WHO, 2022). Cycling is one of the most sustainable and green transportation modes. These advantages include the relief of congestion, the reduction in Greenhouse Gas emissions (Bucher et al., 2019), and improvements in the well-being of cyclists (Useche et al., 2019; Whitaker, 2005). Many people worldwide have been switching to bicycles, especially to e-bikes, and cycling has increased even more due to the Covid pandemic (Buehler & Pucher, 2021; Nikitas et al., 2021). In the Netherlands, the distance covered by e-bikes increased by 13% between 2019 and 2020, whereas the risk of deaths per e-bike kilometre cycled increased by more than one-third for the same years (KiM, 2021; SWOV, 2022a). 31% of all road fatalities in 2019 were cyclists (203 fatalities), while in 2020, this percentage was 37% (229 fatalities). 32% (74 fatalities) of these fatalities were e-bike users (Statistics Netherlands (CBS), 2021). It is noteworthy that in 2020, the number of cyclists' fatalities was higher than that of vehicle drivers (Statistics Netherlands (CBS), 2021). In spite of the constantly evolving landscape of cycling and electric bike adoption, applications of new bicycle technologies are still immature.

In recent years, academic research on new technologies related to cyclists' comfort and safety is growing. These studies have mainly focused on shared bicycle technologies such as locking and unlocking systems based on mobile applications, air pollution detection, and systems that track physiological factors like heart rate (Boularas et al., 2021; Muhamad et al., 2020; Nikolaeva et al., 2019; Shen et al., 2018). Furthermore, a considerable number of studies focuses on technologies affecting cyclists' road safety; however, it is unclear what type of technologies are implemented for bicycles. To the best of the authors' knowledge, a comprehensive review of such studies is lacking. Additionally, a clear definition of a "smart bike"- a concept gaining popularity nowadays, is missing in the literature.

To address this gap, this paper aims to conduct a literature review –to develop a topology of smart cycling technologies that affect cyclists' road safety for utilitarian trips, to facilitate a comparison of different technologies and understand potential impacts.

This review is organised in the following sections: Section 2.2 describes the methodology; Section 2.3 defines the levels of smartness on bicycles and assesses the current technologies on bicycles based on the Technology Readiness Levels (TRLs); Section 2.4 reports the findings of the review categories based on the purpose of each system; Section 2.5 discusses the findings and considers future research insights; and Section 2.6 presents the conclusion.

## 2.2. Methodology - Search strategy

The search and selection process of this literature review follows the framework of the systematic literature review methodology (Page et al., 2021) to ensure reproducibility, transparency, and an extended reach in the literature. However, the theoretical impossibility to achieve saturation (Durand et al., 2021, p. 38) still remains. Literature reviews, generally, omit to explicitly state and present the methodology used (van Wee & Banister, 2015). To address this, in our case the following section explicitly describes it in three stages: 1) search query, 2) databases, and 3) selection criteria.

### 2.2.1. Search query

The search query included 29 keywords in total and in some cases, generic terms avoiding the risk of excluding potentially relevant results. It consists of two parts; the first part referred to the type of bicycles and the second part referred to the new technologies associated with safety and user behaviour. Note that each database operates with a different query structure; therefore, the search query was adjusted accordingly. Only documents in English were included in the review, and no geographical restrictions were applied.

### 2.2.2. Employed search query:

“smart bike” or “connected bike” or “intelligent bike” or “smart cycling” or “smart bicycle” or “connected bicycle” or “intelligent bicycle” or “Internet of Bicycle” or “smart e-bike” or “connected e-bike” or “electrically-assisted bicycle” or “pedelec” AND “safety” or “monitoring system” or “user experience” or “behaviour” or “acceptance” or “smart velomobility” or “smart mobility” or “smart cities” or “intelligent transport” or “internet of things” or “control system” or “GPS” or “injury” or “accident” or “collision” or “incident” or “crash”.

### 2.2.3. Selection criteria

In addition to the search query mentioned above, we included studies that satisfied the following criteria:

- Only studies examining technologies implemented on conventional bicycles, e-bikes and speed-pedelecs were included.
- Only studies focusing on the general population were included.
- Only studies examining advanced technologies (sensors, IoT, wireless communication) directly implemented on bicycles that affect cycling safety were included.
- All academic publications, conference papers, books, reports and technical reports were included.
- Studies examining motorcycles, mopeds, and scooters were excluded.
- Studies focusing on exercise-related aims and physiological factors (i.e., heart rate) were excluded.

- Studies examining bicycle systems for specific populations, and populations with disabilities were excluded.
- Studies examining technologies implemented on cyclists (smart helmets/jackets) were excluded.

### 2.2.4. Databases

This review employed the two major and most comprehensive academic databases (Pranckutė, 2021) –Scopus and Web of Science– and the Google Scholar engine for grey literature (Haddaway et al., 2015). This choice conforms with a recent scoping review in the transport field by Tafidis et al. (2022). The screening tool Rayyan which helps users categorise and screen documents to efficiently perform the review process (Ouzzani et al., 2016) was used. First step was to import the hits from Scopus and Web of Science into the Rayyan and remove duplicates. The remaining hits were screened for eligibility based on the selection criteria listed above. The first screening was based on title and abstract, and for the second, the full text of the potentially relevant documents was reviewed. Note that the selection criteria were developed in advance before the screening process commenced.

Subsequently, the Google Scholar engine was employed to search for grey literature. Given that the use of the relevant search query was not possible, four keywords were used individually instead, namely “smart bike”, “connected bike”, “intelligent bike”, and “smart cycling”. The retrieved hits were also screened first based on title and abstract, and second on their full text against the same eligibility criteria.

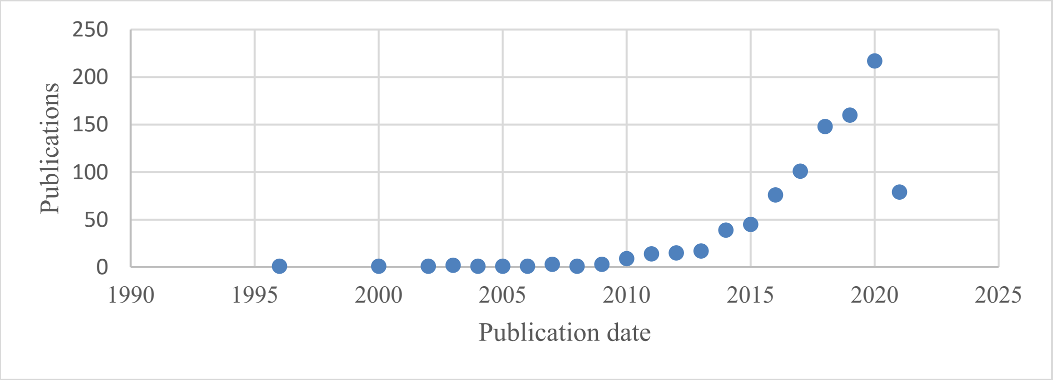

**Figure: 2.1 Distribution of publications through the years**

### 2.2.5. Results

The databases search resulted in 1035 hits up to May 2021; 946 were from Scopus and 89 were from Web of Science. This difference in the number of results is due to the relevance of the topic that each database welcomes most (Bosman et al., 2006; Pranckutė, 2021). The chronological distribution of these hits is presented in Figure 2.1. After deduplication, 939 hits were screened in title and abstract, and 82 of these hits were considered potentially relevant to examine full texts. Overall, 34 documents were finally included in the review following the second –full text– screening.

For the Google Scholar search, there were no relevant hits after the fifth page of the results. However, the first ten pages of each of the four keywords were still searched to ensure that no relevant hits were left out. Since each page included 10 articles, 400 hits were screened. Six articles remained after the first title and abstract– screening and two were finally included in this review after full text screening.

In total, 36 documents that explicitly considered road safety impacts or implications were included in this review. All of them have been published within the last six years, as no studies were retrieved on this topic before 2015. Concerning the types of the included publications, most of them are divided into two categories, specifically journal papers (15) and conference papers (14). While the rest are book sections (5) and reports (2). Figure 2.2 illustrates the selection process using the PRISMA 2020 (Page et al., 2021) flow diagram.

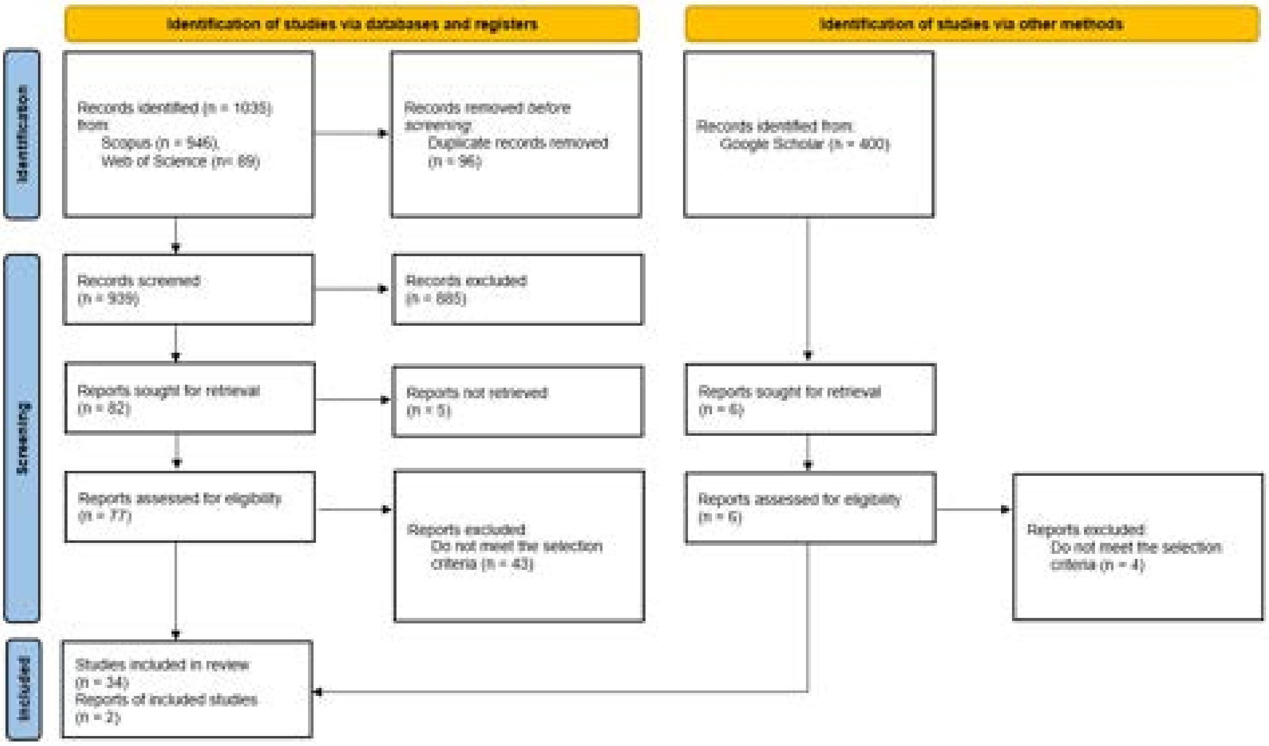

**Figure: 2.2 PRISMA flow diagram**

## 2.3. Evolution of new technologies on bicycles

New technologies have become an integral part of cycling in recent years, impacting cyclist safety as an additional means and/or as part of the bicycle itself. The most prevalent technologies found in this review are networking technologies, GPS, and accelerometers/gyroscopes. Table 2.1 lists them in detail. Application examples of such technologies in bicycles are met under the characterisation “smart cycling” (Nikolaeva et al., 2019); and “connected bikes” (Piramuthu, 2017), and they consist of blinkers, anti-theft systems, pothole alerts, and blind-spot detection using geofencing services. Bicycle manufacturers like Sparta (2016) and Stromer (2017) have already introduced different versions of a “smart e-bike” to the market, including anti-theft systems. Although there are bicycles designated as “smart” in the market, there is no consensus on what can be labelled as “smart” or what the levels of smartness are, unlike the J3016 standard of automated vehicles, which defined automated driving (SAE, 2019). Defining the smartness of a bicycle is a gap which this paper tries to fill. However, how can we classify a bicycle as smart? Alter (2019) described the context of smart devices and systems, not limited to transportation, as something that cannot be binary (yes/no) and proceeded to classify the smartness of the system. In the first level of this classification, a system does not process information or perform any actions. In contrast, on the highest (fifth) level, a system designs and executes unscripted or partially scripted actions based on the received information (Alter, 2019). Furthermore, connected vehicles are equipped with advanced ICT, allowing them to receive and share information in a connected environment (i.e., Vehicle to Everything communication) in order to perform actions (Coppola & Silvestri, 2019). To sum up, the capability of a system to execute actions and the use of ICTs are considered crucial parameters when defining the smartness of a bicycle.

### 2.3.1. Topology of smart bicycle technologies

In this section, we propose a topology for the Bicycle Smartness Level (BSL), considering dimensions of smartness defined by Alter (2019) and the automation levels of driving according to SAE (2019). With this topology (Figure 2.3), we wish to bridge the gap between the clear picture existing for automated vehicles and the less defined one in the more recently developed domain of smart bikes. Ideally, in this way, we can provide a foundation for a common language to be developed and used in future research to avoid confusion between the different capabilities and levels of smart bicycles. By doing so, the functionalities of smart bicycles addressing cyclist safety can be clarified through an escalation procedure. Moreover, this effort contributes to the literature by drawing a clear landscape of levels of smartness regarding the incorporated technology.

To clarify, Table 2.2 presents the BSLs based on the degree of assistance of these systems and their characteristics as follows:

- Level 0 contains the traditional bicycles, which cyclists pedal to use, and e-bikes with an electric motor and battery.
- Level 1 embodies systems that detect accidents and send emergency alerts as well as navigation systems.
- Level 2 consists of bicycles equipped with systems that can detect obstacles and warn cyclists to avoid a collision and cyclist monitoring system.
- Level 3 includes bicycles with cyclist assistance, including cruise control and automatic speed adjustment, to comply for instance, with the speed limits and reduce speed in critical locations. At this level Bike to Infrastructure (B2I) communication will be employed.
- Level 4 consists of systems that allow cyclists to receive notification of dangerous conditions through a connected environment where Bikes communicate with other

Bikes (B2B), and Vehicles (B2V), achieving Bike to Everything (B2X) communication as well as braking assistance.

- Level 5 comprises an intervention ecosystem where, based on real-time data, governments or traffic authorities are able to influence user's behaviour, e.g., interventions in the operation of smart bicycles. C-ITS and advanced technologies are used as behavioural change instruments to achieve specific societal goals.

With the development of new technologies and the deployment of higher levels of smartness becoming a reality, bicycles and their systems are able to sense, process and act, providing advanced assistance to cyclists. Each level includes and builds on the features of the preceding levels. Note that the use of an electric motor is mandatory for speed interventions.

Based on the above classification, it is important to clarify that the current state of technologies implemented falls within Level 2, where a bicycle can process some information and warn cyclists. In order for bicycles to reach a higher BSL, different factors have to be considered. Infrastructure, society, policy and governance are factors also implicated in the development of automated vehicles (Milakis et al., 2017) and could also be applied to bicycles.

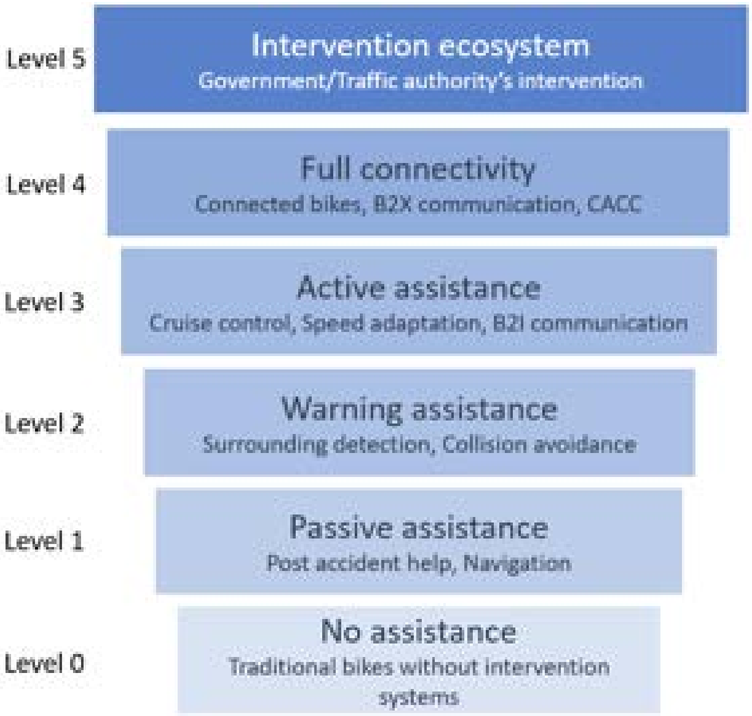

**Figure 2.3 The proposed topology of the level of smartness on bike**

### 2.3.2. Technology readiness levels of bicycles

National Aeronautics and Space Administration (NASA) has defined and uses TRLs to systematically measure the maturity of a technology and compare different types of technologies (Mankins, 1995). Even though the TRLs were developed for technologies and systems regarding space, today they are broadly used in multiple domains ranging from commercial use to research, i.e., European Commission Horizon 2020 (Bruno et al., 2020).

**Table 2.1 Technologies used**

| Technologies/Sensor* | Number of studies | Area of use |
|---|---|---|
| Networking technologies | 33 | Monitoring systems, connected bicycles, navigation, accident detection |
| GPS | 22 | Accident detection, monitoring system, connected bicycles, assistance systems |
| Accelerometer/gyroscope | 16 | Accident detection, assistance systems, autonomous bicycles, road quality, driver behaviour |
| LIDAR | 8 | Collision avoidance, rear detection, obstacle detection |
| Speed and Pedal sensors | 4 | Accident detection, assistance systems, connected bicycles |
| Radar, Ultrasonic sensors | 4 | Accident detection, assistance systems, Collision avoidance, obstacle detection |
| Camera | 3 | Assistance systems, obstacle detection |

*Microcontrollers (i.e., Arduino Uno) fall into multiple Areas of use, and for this we did not classify them in this table.

The TRLs are divided into nine different levels describing the maturity of a technology or system. The first level includes the principle idea of technology and the central concept, while the last (9) level consists of the full development and the release of the technology into the market (please refer to Mankins (1995) for a comprehensive review of these levels). The central use of the TRL framework falls into two parts: first to bring a specific technology into focus and examine its uses, and second, to assess the level of maturity of this technology within the TRL framework.

To assess the readiness level, we focused on deploying such technologies in the BSL - Level 5, since this is the level of interest for the future. In order to interpret the TRL for this level, we examined the existing technologies as applied to bicycles. As a result, we conclude that bicycle technologies currently fall into TRL 1 “Basic principles observed and reported” considering the maturity of technologies and lack of testing for the proposed systems. Nevertheless, since most of these technologies have already been implemented in motor vehicles, bicycles may adopt them effortlessly and reach the launch stage faster. Our assessment of the TRLs for each of the five BSLs is given in Table 2.2.

**Table 2.2 Extended topology and summary of the literature finding**

| Bicycle Smartness Level | Functions | Operation | Characteristics | Technologies | TRLs* | Number of papers | Source |
|---|---|---|---|---|---|---|---|
| 0 | - | Traditional bicycles and e-bikes where a cyclist' performs all the riding actions | No assistance | - | 9 | - | - |
| 1 | Accident notification,<br>Navigation system | Cyclists perform all riding actions – the system automatically sends an SMS to emergency units in the case of an accident (post-crash care). Also, the system can provide safe routes | Passive assistance | Accident detection and alerting systems,<br>Route planner/ Navigation | 8 | 6 | (Alam et al., 2018; Dutta & Dontiboyina, 2016; He et al., 2019; Islam et al., 2020; Oliveira et al., 2021; Rajarapollu et al., 2016) |
| 2 | Collision warning,<br>Surroundings detection,<br>Cyclist monitoring,<br>Braking system | Cyclists perform all riding actions – but the bicycle is aware of the surroundings, can sense obstacles and can warn and monitor cyclists | Warning assistance | Collision avoidance,<br>Monitoring system,<br>Human-machine interface, and User's behaviour | 6 | 15 | (Aguiari et al., 2018b; Amin et al., 2019; Andres et al., 2019; Behrendt, 2016; Degen et al., 2019; Felix et al., 2018; Gadsby & Watkins, 2020; Hagelen et al., 2019; Husges & |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | Degen, 2021; Jeon & Rajamani, 2019; Kiefer & Behrendt, 2016; Lee & Jeong, 2018; Maier et al., 2016; Piramuthu, 2017; Xie et al., 2021) |
| 3 | Cruise control, B2I communication, *Speed adaptation system* | Cyclists perform most of the riding actions, the bicycle is able to assist cyclists in sensing the need for acceleration/deceleration and implementing it, as well as collecting and sharing information | Active assistance | Smart assistance systems | 4 | 7 | (Aguiari et al., 2018a; Lee & Jiang, 2019; Lin et al., 2015; Makarova et al., 2018; Nikolaeva et al., 2019; Padmagirisan et al., 2019; Wu & Lin, 2020) |
| 4 | Connected bicycles, *B2X communication*, *Braking assistance*, Cooperative Adaptive Cruise Control | Cyclists perform some of the riding actions, the bicycle is connected with other bicycles, vehicles, and people to predict other users' trajectories/movements. The bicycle is able to enable the brakes itself in critical situations | Full connectivity | Connected and Cooperative bicycles, Unmanned bicycles | 3 | 9 | (Boronat et al., 2021; Céspedes et al., 2016; He et al., 2020; Jenkins et al., 2017; Kourtellis et al., 2019; MacArthur et al., 2019; Oliveira et al., 2021; Terashima et al., 2020; Zhang et al., 2021) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 5 | *Fully connected bicycles enabling government to intervene* | Cyclists perform some of the riding actions while traffic authorities are able to intervene i.e., to limit bicycle speed, through a connected ecosystem | Intervention ecosystem | Ubiquitous advanced computing systems, C-ITS | 1 | - | - |

*This is based on the average technology readiness of the level rather than that of individual technologies. Systems in italics are systems that we propose but were unable to find in the literature

## 2.4. Results of the review

The documents included were classified into the 6 levels of smartness set out above and also grouped based on the technologies they used (see Table 2.2 for an extended summary of the review results). These are presented in this section alongside a discussion of the use of each system and its limitations.

### 2.4.1. Level 0

Level 0 includes all bicycles, conventional and e-bikes, that do not employ any technology aiming to affect cyclists' safety described in upper levels.

### 2.4.2. Level 1

A level 1 smart bicycle is equipped with navigation systems and technologies to detect accidents and send emergency alerts.

#### Accident detection and alerting systems

Islam et al. (2020) mentioned that in many cases, it takes more than 15 minutes for bystanders around a crash to notify the emergency unit. This delay may cost the injured person vital time (Rajarapollu et al., 2016), so the contribution of telecommunication technologies in resolving this issue is crucial. To this end, numerous studies have focused on accident detection and emergency notification in the case of an accident.

Dutta and Dontiboyina (2016) developed an application using accelerometer and sensors to receive information about the bicycle's axes X, Y, and Z. The application uses this information to detect if an accident has occurred by measuring any alteration in the axes or a decrease in speed greater than 3g (gravitational acceleration). Similarly, Islam et al. (2020) created an application that uses accelerometer/gyroscopes and controllers to detect crashes and send alerts. Another study, by Rajarapollu et al. (2016) used accelerometers, sensors and microcontrollers to measure the bicycle's angle and vibration level to detect an accident. Alam et al. (2018) also developed an application that recognises vibrations representing a crash using microcontrollers. The role of these applications is twofold, to detect an accident and send an emergency notification. GPS was used to retrieve the location of the bicycle, and telecommunications technologies to share the crash location with the emergency units and/or with the predefined contacts. However, while these applications are functional, they have not been tested in a real environment. Therefore, the efficiency of these systems depends on the adoption of such technologies by the emergency units.

#### Route planning services (navigation)

Route planning guides people to reach a destination. There are numerous applications that users can access through their smartphones, such as Google Maps; however, the majority of them fails to provide traffic safety-related information, which is a crucial functionality.

He et al. (2019) developed an intelligent safety system connected with the cyclist's smartphone. The cyclist is guided by a device that uses a green to red hue and is embedded in the bicycle's handlebar. Furthermore, Oliveira et al. (2021) surveyed the use of new technologies on bicycles. They listed numerous navigation applications aiming to provide safer routes which is a crucial characteristic to make cycling safer.

These studies aim to increase cyclists' safety using route planning systems; however, a combination of these systems may satisfy cyclists' needs better since that will allow them to ride without looking at their smartphones for directions. These systems are mainly smartphone-based, which means that they are dependent on mobile connection and battery.

### 2.4.3. Level 2

A level 2 smart bicycle is equipped with sensors, cameras, LIDAR (Light Detection and Ranging), and other technologies that allow to detect surroundings –obstacles– and warn cyclists to avoid an imminent collision as well as to monitor cyclists.

#### Collision avoidance

Collision avoidance systems for vehicles and motorcycles have been widely researched for many years and their results on safety are well-known. Applications of such systems are the lane support systems and anti-locking systems (European Commission, 2018; Savino et al., 2020). The purpose of these systems is to warn and assist drivers in mitigating the risk of contingent collisions, and they have recently started being applied to bicycles.

Xie et al. (2021) created a system aiming to sense the vehicle trajectory within a specific range near the bicycle. If the system detects a vehicle in the proximity of the bicycle, it creates a sound to notify the cyclist and the driver of the vehicle to avoid a collision. They embedded a LIDAR sensor below the bicycle's handlebar to scan a wider area in front of the bicycle, aiming to detect more obstacles. In addition, they used an accelerometer, gyroscope and microelectromechanical systems to detect the bicycle's movement for the automatic activation of the sensors. They conducted simulations and experiments to test the system's validity by tracking obstacles in a range of 20 meters. Similarly, Amin et al. (2019) developed a prototype that estimates the distance between the bicycle and other vehicles through sonars and notifies cyclists by displaying the distance in a monitor placed on the bicycle's handlebar. Husges and Degen (2021) developed an algorithm to track objects in urban areas using radar, calculating the object's distance and velocity and warning cyclists about them. Jeon and Rajamani (2019) developed a system to track vehicles in the rear using a laser sensor. The system tracks vehicles in the same lane and/or in the adjacent lane of the bicycle. They conducted experiments, and the system was able to recognise and track the movements of the vehicles successfully. However, one limitation is that there are difficulties in accurately measuring the longitudinal and lateral distances simultaneously. Degen et al. (2019) developed a system that provides critical information to cyclists. The information can be transmitted to cyclists using a sound, or red signal or vibration on the handlebar. The authors suggested two modes of object detections, based on energy consumption, a) high performance detection for critical situations, i.e., when approaching an intersection, and b) low performance detection for non-critical situations. Hagelen et al. (2019) developed a radar with a 24 GHz frequency modulation continuous wave that aims to increase cyclist safety and reduce the accident risk by providing assistance to users in detecting obstacles. They proposed two different types of radars, one for rural and one for urban areas with different ranges of 30o and 70o degrees, respectively. The higher angle is proportional to the increased possibility of coming across an obstacle within a city area. Felix et al. (2018) examined different sensors requirements for creating an e-bike assistance system. They used different sensors and applied them on different parts of the e-bike such as fork, handlebar stem, down tube, seat tube, chain stay, to conduct experiments investigating the most suitable position. For testing they set up different scenarios of the e-bike and stated that the fork and the handlebar stem are the least efficient among the options to mount angular sensors. Furthermore, authors concluded that the squealing of the disk brake could affect the quality of a sensor up to the 19kHz range. Maier et al. (2016) developed and tested a braking system to avoid critical front wheel lockup and nose-over accidents. They embedded the system into an e-bike with disk brakes and conducted two experiments, manned and unmanned. The results showed the bicycle was safer when using the system and gained more trust from the users.

Piramuthu (2017) examined connectivity systems for bicycles either already available on the market or close to this stage. Some of the features of these bicycles/systems include a potholes alert and blind-spot detection using GPS, IoT, and smartphones. Finally, in their review, Gadsby and Watkins (2020) mentioned studies about an effective positioning system for bicycles, and a study with a detection system of approaching vehicles. They concluded that obstacle detection could improve cyclist safety and could be installed on e-bikes since they already have power that could be made available to operate the system.

Obstacle detection for bicycles aims to warn cyclists to avoid a collision. Most studies implemented and used the Kalman filtering algorithm, increasing the quality of detecting objectives and reducing the errors, and focusing on low-density LIDAR since it is inexpensive and lighter than high-density ones. Furthermore, several sensors have been used to detect obstacles including LIDAR, cameras, longitudinal and lateral sensors, radar rather than GPS, which is widely used in other studies. These systems could reduce cycling injuries and their adoption in bicycles is possible in the near future as communication protocols are not required and they can be applied independently. Additionally, the energy demands of such systems is low, but this can vary depending on their level of accuracy.

### Monitoring systems

Monitoring systems use multiple sensors, and GPS to collect real-time data to monitor and to analyse cyclists' riding behaviour. Such a system creates a network where cyclists share and save data to a cloud using wireless communication and IoT.

Aguiari et al. (2018b) designed a smart e-bike ecosystem prototype in which bicycles collect traffic data and pollution levels on the streets using GPS and vehicular network sensors. The application gathers and shares data with other users and road operators to improve cyclists' safety. Kiefer and Behrendt (2016) developed a smart e-bike monitoring system that applies the IoT into cycling and records location, level of assistance and other data. This system consists of a smartphone with GPS and 3G connectivity and sensors collecting all the e-bike's relevant information. The data is available to researchers and users by logging in to a specific website. Similarly, Lee and Jeong (2018) developed a monitoring system using microcontrollers, sensors, and GPS to monitor and share data within a group of cyclists. This system uploads and saves all the data to a cloud, and the application uses an open-source data tool analyst called Goldencheetah, through which users can access their data (speed, route, riding information).

The above studies used multiple sensors for collecting data and the internet to upload the data to a cloud and share it within a group. The most comprehensive field trial was Kiefer and Behrendt (2016), with 30 e-bikes and 80 participants. Moreover, these studies designed and implemented systems that can be used to develop a connected environment. However, smartphones are necessary to operate these systems, affecting their reliability due to the shortage of battery and GPS accuracy.

### Human-computer interaction and User behaviour

Human-Computer Interaction (HCI) and user behaviour are two of the main aspects of the adoption of new technologies and systems. Users typically adopt these systems in their driving experience, overestimate the potentials of these systems, and are then disappointed when their expectation as not met. This change in user behaviour is called behavioural adaptation (Eskandarian, 2012). Therefore, users need to be aware of the limitations of those systems to avoid unrealistic expectations (Sullivan et al., 2016).

Behrendt (2016) proposed a so-called smart velomobility concept that merges sensor technologies with the users' experience by combining IoT, ITS, velomobility and smart cities. Behrendt (2016) investigated collected data such as route, speed, riding behaviour and level of assistance from field trials with 80 participants (Kiefer & Behrendt, 2016). The results of this study highlight different perspectives of Human-Machine Interfaces (HMI). More specifically, the positive characteristics that could occur in a networked environment such as feeling rewarded and being able to share the data in contrast to the unpleasant feeling of invasion of privacy. This feeling of being tracked in some cases affects cyclists' riding behaviour and causes them to ride more carefully, i.e., not running red lights. Andres et al. (2019) developed a prototype named "ARI" using iOS aiming to help cyclists reach green lights (green wave). They used a smartphone's GPS and Bluetooth to track the bicycle's position and send its speed to a microcontroller connected to the bicycle's engine, so that the latter could adapt the bicycle's speed. In order to test ARI, they recruited 20 participants to examine HCI. Some of the significant findings are that participants were satisfied by using ARI since it assisted them in getting green lights. During the first rides, participants were worried about their safety since the bicycle adapted the speed on its own, and it was stated that they preferred to be notified prior to a speed adaption.

One of the observed weaknesses is that Andres et al. (2019) studied HCI for only a specific function, so it is unknown how users' experience could be affected if multiple systems were embedded to a bicycle simultaneously. In addition, Behrendt (2016) studied user interaction once they had completed a ride rather than in real-time. These limitations and the few numbers of studies indicate that there is still room for further research on HCI in bicycles, and future studies should focus on filling this gap.

### 2.4.4. Level 3

A smart bicycle at level 3 includes systems that assist cyclists in providing specific power and complies with the speed limits in critical locations.

#### Smart assistance systems

E-bikes can make the cycling experience more desirable by demanding less pedalling effort. Smart assistance systems can consider specific factors such as hilly areas and different user needs in order to abet cyclists by providing personalised assistance: the needed power, gear and breaking for each occasion.

Lee and Jiang (2019) proposed a fuzzy-logic control assistance system that provides the required power to cyclists to ride an e-bike with less effort ensuring their safety and comfort. This system adapts to users' pedalling behaviour and provides power assistance according to each user's needs and the topography of the riding area. Similarly, Makarova et al. (2018) developed an assistance system which is able to identify cyclist's physical condition and provide the cyclist with the appropriate power based on environmental parameters and their abilities. This system uses a smartphone, GPS, sensors, microcontrollers, a gyroscope, and an electric motor. Padmagirisan et al. (2019) developed a power assistance system to help users pedal with more ease and cruise control to set and/or maintain the desired speed. Wu and Lin (2020) developed an intelligent bicycle, named IntelliBike, with an automatic gears system, consisting of a Raspberry Pi and Arduino and using Kalman filtering to improve the system's ability to analyse user riding conditions. Lasty, Lin et al. (2015) developed an automatic shift control system that consists of a microcontroller and sensors and is capable of self-learning to better adapt to user riding habits.

Nikolaeva et al. (2019) displayed the landscape about the future of smart cycling. They focused on innovative applications and technologies for bicycles using IoT and ICT by searching around 85 websites and listed the use and characteristics of these applications for bicycles. These features vary from blinkers indicating turns to smart applications that can reach the green wave, saving time and making cycling safer. This work provides a clear image of how the future of cycling is hand-in-hand with ICT. Finally, Aguiari et al. (2018a) created a system called Bike Information Gathering Architecture that collects data, such as riding distance and traffic, through sensors implemented on the bicycle, and shares them through a cloud. The collected data will be analysed to offer smart mobility solutions i.e., users to avoid dangerous roads (traffic-wise) through a Personal Urban Mobility Assistant.

These studies lack any field trials to ensure the reliability of their proposed systems. However, these smart assistance systems tend to be beneficial since they recognise and provide specific assistance to cyclists affecting their safety and comfort. Furthermore, only one study mentioned self-learning abilities for adapting to users' needs, and artificial intelligence (AI) is missing from all the rest. However, AI will be valuable for the further development of such assistance systems.

### 2.4.5. Level 4

In level 4 smart bicycle leverages the communication technologies that allow cyclists to receive notifications of dangerous conditions through a connected environment.

#### Connected and Cooperative bicycles

Communication technologies have positive effects on road safety and numerous studies (Li et al., 2017; Talebpour & Mahmassani, 2016) have been conducted on connected and C-ITS in vehicles. Nowadays, these technologies are gaining ground in cycling, aiming to achieve communication between bicycles and vehicles, creating a connected environment, and avoiding collisions.

Jenkins et al. (2017) proposed and developed a platform based on a smartphone where the bicycle is connected to vehicles and infrastructure. This platform is called Multimodal Alerting Interface with Networked Short-range Transmissions (MAIN-ST), and its purpose is to send and receive information through a network using the Dedicated Short-Range Communications radio (DSRC) and Arada system. The platform aims to provide users with notifications targeting a safe cycling experience by offering solutions to critical situations. Kourtellis et al. (2019) mentioned two main communication methods to develop a connected environment for bicycles, first a smartphone-based communication, and second the DSRC band protocol. The latter does require that the bicycle has a sufficient energy supply as the communication will demand a certain amount of energy. As such, e-bikes might support it more easily. The authors therefore suggested a smartphone-based system as it seems most feasible. Based on this decision, they developed a system that warns users to avoid an accident by using a smartphone-based application for three different types of users: cyclists, drivers, and pedestrians. Communication is only achieved within the application, and thus involvement by all types of users is necessary. Similarly, Boronat et al. (2021) developed a smartphone-based application named SafeCyclists to warn users when a vehicle or a bicycle is approaching them. Each user has to carry their smartphone to enable the application to warn them about critical situations. They used the mobile 4G network and GPS from the smartphone to share the position of each more frequently and allow communication between the SafeCyclists users.

Increasing cycling flows on bicycle lanes in European cities inspired Céspedes et al. (2016) to develop a prototype Cooperative Adaptive Cruise Control (CACC) for bicycles. The aim is to achieve the platoon-based system in which cyclists respond to a CACC delivered through specific HMI. This system contains GPS, an accelerometer, and an Arduino microcontroller to receive and send information from other bicycles. Piramuthu (2017) mentioned that a B2B communication could be valuable for cyclists since they can share information on a connected environment concerning the road condition using geofence applications.

Oliveira et al. (2021) described the key characteristics that a bicycle in the new era of IoT would have. Some of these characteristics are GPS, sensors, accelerometer/gyroscope, and network communication. Furthermore, the authors mentioned that new technologies on bicycles under a bicycle platform using IoT could improve sustainable mobility under communication and connected environments. Such environments consist of communication among bicycles, Low Power Area Networking as well as IoT. Another study focusing on the effect of new technologies on bicycles conducted by MacArthur et al. (2019) described the available systems for making cycling safer. In parallel, the authors stated that there are multiple limitations concerning the reliability of new systems, which may affect their quality and their adoption by users. Some of the limitations are cybersecurity since it is poorly investigated in the cycling domain and the quality of DSRC. The feasibility of some applications could also be an issue since some of them require a high number of users to operate with high quality data shared on a cloud platform.

Most of the studies describe smartphones-based applications to develop a connected environment and mention GPS accuracy as a limitation in their results. An improvement of the DSRC technologies and cellular networks may overcome this issue. A connected environment for bicycles can have positive aspects in cyclists' safety, at least in a rural environment where most field trials took place. However, since urban environments host the majority of bicycles, it would also be important to test these systems there.

#### Unmanned bicycles systems

Fully automated vehicles are being widely investigated and tested in the field and are expected to be released onto the market by 2030 (Coppola & Silvestri, 2019). However, there is still a long way to go before fully automated bicycles are available on the market. Nevertheless, unmanned bicycles systems could affect cyclists' safety since they can balance themselves and move around.

He et al. (2020) developed and implemented a control strategy based on deep learning consisting of the Deep Deterministic Policy Gradient (DDPG) algorithm and the Active Disturbance Rejection Control (ADRC) to stabilise a bicycle (self-balance) and follow a specific trajectory. The authors managed to autonomously run a bicycle under specific circumstances in a simulation environment. Similarly, Terashima et al. (2020) developed an autonomous control system that enables e-bikes to run and turn autonomously by using equilibrium points. Additionally, Zhang et al. (2021) developed and implemented a system for an unmanned bicycle and conducted experimental short trips in a lab allowing the bike to run autonomously.

Unmanned bicycles are in an early stage, and none of these studies can integrate these systems on a bicycle today apart from in simulation and experiments. While there is some research about automation systems in bicycles more needs to be investigated in this field, before they will become available to the general population.

### 2.4.6. Level 5

A level 5 bicycle will operate as part of an intervention ecosystem with the employment of C-ITS and advanced technologies.

Smart bicycles will interact with government/traffic authorities allowing the latter to intervene in their operation to influence cyclist behaviour. This level represents an integration of societal goals, similar to level 4 in the Mobility-as-a-Service topology developed by Sochor et al. (2018). By using real-time data collected from bicycles, vehicles, and infrastructure, traffic authorities will be able to intervene by influencing the level of pedal-assistance of e-bikes or enforcing speed limits on the road network. The functionalities of such systems could mitigate the injury risk for cyclists and make cycling safer. While we did not find published papers in the academic literature on this level related to traffic safety, such possibilities on how speed limit enforcement can be valuable in preventing road crashes can be drawn from research in this field for vehicles (Ammar et al., 2021; Soole et al., 2013). Furthermore, research is ongoing on the potential of geofencing for traffic management, see Hansen et al. (2021) for an overview. Nevertheless, in grey literature, we can find some research and pilots on the use of access and speed control (based on geofencing) to improve traffic safety of e-bike use. For example, the California Department of Transportation (Caltrans) is investigating whether geofencing could be used to prevent e-bikes and e-scooters from entering access-controlled highways and other specified locations and limit the maximum speed in certain areas, allowing access to some bike paths where they typically would not be allowed (DRISI, 2020).

## 2.5. Discussion and direction for future research

The purpose of the study is to provide an in-depth review of emerging technologies and propose a topology for the BSLs, establishing a common terminology for future studies focusing on emerging technologies affecting cycling road safety.

This literature review follows a specific methodology described in Section 2.2, to investigate this subject. This is scientifically correct, yet also limits the scope somewhat to research-oriented papers. Thus, we suggest future research to include commercial products and websites searches since they could add to the universal investigation of the topic.

Furthermore, there are still some critical knowledge gaps that must be filled to figure out the safety impact of new technologies. Some possible directions for future research arose when discussing the findings of this review. Most of the systems analysed in this review have been tested through simulations and have not yet been tested extensively in field trials. Additionally, the few existing field trials were carried out in rural environment. Hence, some of these systems have not demonstrated clear evidence of safety benefits. Thus, extended field trials are necessary to investigate the effectiveness of the embedded systems and identify the thresholds required for them to act successfully (e.g., send out a warning) at different road types. For this, we suggest that future field trials should target urban environments since they host the majority of cyclists and come with high risk. To this end, some ongoing studies are currently applying new smart technologies to bicycles. An example in the Netherlands is a bicycle safety pilot project (mid 2021-2022) using IoT technology that automatically modulates the power and speed of fast e-bikes in dangerous traffic conditions (Townmaking Institute, 2021). This pilot aims to reduce cycling accidents with the use of intelligent infrastructure as well as using 4G and 5G networks to achieve a connected environment. Furthermore, such a study evidently fills the gap of the insufficient number of field trials and identifies the required need to implement these systems in the current infrastructure. However, this study targets a rural area, too.

Additionally, a critical gap lies in the indirect effect of these systems due to the possible users' behavioural changes (i.e., overestimating the systems' capabilities), resulting in unsafe riding while the BSLs go up. Therefore, the actual and perceived safety benefits need to be investigated as well as users' reactions when they receive critical notifications. HMI is an important area for further research in these emerging bicycle technologies, as well.

Furthermore, since people tend to enjoy the feeling of freedom that comes with a bicycle, connectivity and intervention on bicycles may make cyclists feel restricted and reduce their willingness to use these technologies.

In addition, currently, studies only investigate one system at a time, such as obstacle or accident detection. Future research could address this and provide knowledge on how the simultaneous operation of multiple sensors and systems on a bicycle could affect a system's efficiency concerning in terms of safety and power consumption.

These safety enabling systems require energy to operate, and several studies (Flüchter & Wortmann, 2014; Kourtellis et al., 2019; MacArthur et al., 2019) observed numerous challenges, such as battery performance issues due to continuous data transmission in a connected bicycle environment. This affects the range of the travel distance of these bicycles and, therefore, user intention to adopt them. However, large batteries and communication through cellular connectivity (5G) appear to be promising solutions to enable bicycles' integration into a connected environment (Flüchter & Wortmann, 2014; MacArthur et al., 2019; Oliveira et al., 2021).

It is evident that further investigation is needed to better understand the advantages/disadvantages of using smartphone-based systems to promote cycling safety and develop an entire ecosystem for bicycles, at different BSLs. Smartphones are becoming an essential object in everyday life, –in Europe 80% of the population uses them– and their penetration rate is increasing (Statista, 2021). Currently, the B2B, B2V and B2X communications are mainly based on smartphones. However, even though smartphone-based systems might help promote cycling safety, they are still far from ideal. This is since, for instance, they may struggle to identify the exact transport mode of the user, such as cycling, walking or driving. Also, the use of smartphones for other functionalities that they were designed for during the day may increase the possibility of them running out of battery. Thus, an important question arises for future research, is it appropriate and effective to use smartphone-based systems as the primary and only means to influence cyclists' safety?

So far, in this review, we have discussed new technologies that can make cycling safer concurrent to preserving its active way of mobility. Thus, considering the use of unmanned bicycle systems, we think of setting some boundaries on the use of such systems so that cycling will not be losing its advantages. Such systems could be employed in critical situations to retain, for example, balance control in case of an imminent fall rather than replacing the need for steering by a cyclist.

Finally, cybersecurity is another topic that needs investigation. While the smart bicycles reach higher BSLs, new issues arise. Such issues are privacy aspects and the reliability of the systems against hacking. Additionally, the complexity of multiple actors raises the questions of who will be responsible for the collected data, with whom this data will be shared, and what the future of road safety governance will be (Hysing, 2021).

To sum up, the proposed BSL topology aims to clarify the concept of "smart" bikes, which was yet undefined. Thus, this review can benefit all actors involved in the cycling field, ranging from researchers and manufacturers to users, by providing a common language. In addition, it offers directions for future work that could assist the deployment of these emerging technologies on bicycling, making the only green and sustainable transport mode–the bicycle–safer.

## 2.6. Conclusion

This study presents the current landscape of new technologies implemented on bicycles by reviewing studies focusing on applications and systems affecting cycling safety. While there is a huge portion of recent literature concerning new technologies on bicycles, only a few focus on such technologies for safety purposes. The number of studies examining new technologies for cyclists' safety has increased steeply after 2015, confirming the growing interest in cycling safety in research and policymaking and growth in the development of bicycle-related technologies.

This paper aims to develop a topology of Bicycle Smartness Level (BSLs) and thereby provide a common language for future development and discussion around smart bicycles. The proposed topology consists of 6 levels: from BSL 0, which contains the traditional bicycles, to BSL 5, which consists of an intervention ecosystem. It is noteworthy that while research and prototypes reach up to BSL 4, the current state of the practice falls into BSL 2. As evident in Section 4, BSL 5 is still theoretical and was not found in the literature. This level will require the cooperation of various stakeholders, digital ecosystem and infrastructure.

To better understand the deployment of different emerging technologies and systems on bicycles we assessed their TRLs which vary. From the findings of this literature review, it is evident that the TRLs of the relevant technologies are inversely proportional to BSLs, since the higher the BSLs the lower the TLRs and more immature the technologies.

This review also demonstrated that the majority of academic studies investigated systems that mainly focused on warning systems for avoiding a collision, more commonly by using accelerometers/gyroscopes, LIDAR, sensors, and microcontrollers. These systems track obstacles such as vehicles and are limited to warning cyclists when they approach them. Although more than 50% of the studies included in this review employed e-bikes which could enable the implementation of speed intervention systems, the adoption of such systems was not investigated, which demonstrates the lack of advanced technologies implemented in bicycles.

To conclude, among the reviewed studies, only a few academic studies collected and shared data through IoT based platforms, which illustrates that the level of communication technologies on bicycles is still underdeveloped. For the promotion of safe bicycle environments, more research is needed to examine the safety impacts of advanced IoT based cycling platforms and safety enhancing features.

# Chapter 3

# User acceptance of Smart e-bikes: What are the influential factors? A cross-country comparison of five European countries

This chapter is based on: Georgios Kapousizis, Rumana Sarker, Mehmet Baran Ulak, Karst Geurs (2024): User acceptance of smart e-bikes: What are the influential factors? A cross-country comparison of five European countries, Transportation Research Part A: Policy and Practice, DOI: 10.1016/j.tra.2024.104106

## 3.1. Introduction

Electric bicycles (e-bikes), an emerging transport mode gaining popularity in recent years (Shimano, 2022), can contribute to reducing emissions and congestion in cities, peri-urban as well as rural areas by replacing motor vehicles (Bucher et al., 2019; European Commission, 2019; Fishman & Cherry, 2016; Philips et al., 2022). The recent Covid-19 pandemic and the energy crisis have led to a significant number of people switching to more active transport modes, such as cycling (Buehler & Pucher, 2021, 2023; Nikitas et al., 2021; Shimano, 2022). Shimano (2022) surveyed 12 European countries with over 15,500 participants and found that the high cost of living and higher fuel prices are two leading factors for individuals to buy an e-bike. Additionally, within the last two years, several European research projects have been announced investigating and promoting e-bikes (ETH zürich, 2022; Salzburgresearch, 2022), supporting the assumption of the potential increase in e-bike users. Also, many European countries subsidise purchasing e-bikes or e-cargo bikes. For instance, the Greek government subsidises up to €800, the Austrian government up to €1000, while countries with an already high number of cyclists, such as the Netherlands and Belgium, offer a tax reduction (ECF, 2023). This has resulted in a high number of e-bikes sold in Europe in recent years. In 2021, around five million new e-bikes were sold in Europe (Sutton, 2022), while in 2009, this number was only half a million (Statista, 2020). Note that e-bikes include two categories: Pedelecs (e-bike with pedal assistance up to 25 km/h) and Speed-Pedelec (e-bike with pedal assistance up to 45 km/h) (ECF, 2017). Thereafter, under the term e-bikes we are referring to both, Pedelecs and Speed-Pedelecs.

With the increasing use of e-bikes, there are also increasing concerns about crash risks and the severity of crashes among e-bike users. In the literature, many studies have been conducted to examine safety-related aspects of e-bike use (Haustein & Møller, 2016; Schepers et al., 2020; Vlakveld et al., 2021), in particular, if there are more safety risks using e-bikes and if injuries are more severe, compared to conventional bikes. A recent literature review also showed that the share of single-bicycle crashes among injured cyclists is about 70% (Utriainen et al., 2022); and e-bike users are prone to such crashes (Panwinkler & Holz-Rau, 2021). In the Netherlands, 2 out of 3 seriously injured people treated at emergency units are cyclists, and the increasing use of e-bikes is seen as a leading cause of the increase in the number of seriously injured cyclists is growing over time (40% increase between 2013-2022). In particular, among older cyclists, one-third of this growth is attributed to e-bike use, and among younger cyclists, about 50% (VeiligheidNL, 2023). Some studies also indicate that crash severity for e-bike users is higher than for conventional cyclists (Panwinkler & Holz-Rau, 2021; Schleinitz & Petzoldt, 2023), although other studies did not find clear differences (Dozza et al., 2016; Schepers et al., 2014). In the literature, speed is found to be one of the leading causes of the high number of e-bike crashes (Haustein & Møller, 2016; Schepers et al., 2014; Stelling et al., 2021), as higher cycling speed influences riding behaviour and the ability to predict movements while in traffic (Huertas-Leyva et al., 2018). Furthermore, many European countries lack sufficient cycling infrastructure, and even countries with well-designed bicycle networks cycling infrastructure are not always designed to cater for the cycling speeds of e-bikes (Statistics Netherlands (CBS), 2021). Moreover, e-bike users' interactions with other non-motorists and safety risks associated with single-bicycle crashes raise concerns. However, this does not imply that the responsibility for reducing these crashes lies with the cyclist. According to traffic rules and road safety hierarchy, the responsibility lies on motor drivers to ensure vulnerable road users' safety, such as cyclists and pedestrians (ETSC, 2023; Mullen et al., 2014; Safedrivingforlife, 2023).

In the recent literature, there is an increasing emphasis on preventing e-bike crashes using smart bicycle technologies (Boronat et al., 2021; Oliveira et al., 2021). Such technologies can alleviate cycling safety issues and positively influence cyclists' riding behaviour (Kiefer & Behrendt, 2016). Many studies have been published investigating the development of new smart bicycle features to improve safety and comfort (Boronat et al., 2021; Nikolaeva et al., 2019; Oliveira et al., 2021). Also, an increased feeling of safety is associated with increased comfort (Lu et al., 2018; McNeil et al., 2019; Mekuria & Nixon, 2012). In addition, some cities in the Netherlands have also started exploring the role of technology on bicycles to decrease the high risk of bicycle crashes (Tollenaar & Plazier, 2023). Kapousizis et al. (2022) proposed a "Bicycle Smartness Levels" (BSLs) classification for these new technologies focusing on cycling safety, which consists of 6 levels with different safety-enhancing functionalities. These technologies may improve cyclists' safety and comfort in addition to other measures, such as improving the quality of cycling infrastructure, lowering car traffic speeds, etc. (SWOV, 2023). Moreover, some cyclists may feel the need or desire to use smart bicycle technologies. This study aims to investigate the factors influencing users' acceptance of smart bicycle technologies on e-bikes by collecting data and comparing factors across five European countries (Austria, Belgium, Germany, Greece, and the Netherlands). Note that examining the user acceptance of smart bicycle technologies does not imply shifting responsibility for avoiding crashes completely to cyclists, as this also lies with other road users and road authorities. To the author's knowledge, no previous study has investigated user acceptance of Smart e-bikes nor the role of differences in cycling culture and cycling infrastructure across countries. In addition, we established the measurement invariance to draw valid conclusions regarding the comparison among groups.

The cross-country comparison allowed us to examine the acceptance of smart bicycle technologies in countries with fundamental differences in cycling culture and draw insights for policymakers and industry. To do this, we focused on Level 3 "Active assistance" according to the classification of Kapousizis et al. (2022) considering that this level has the highest technology readiness level and does not employ any communication with other vehicles that needs specific infrastructure. Level 3 consists of the following functionalities: surrounding detection, collision avoidance, speed warnings, post-crash notifications, safer routes and bike-to-infrastructure communication (B2I).

This paper is organised as follows: Section 3.2 presents the theoretical background, including the conceptual model and hypotheses; Section 3.3 describes the methodology, survey setup, sample composition, and data; Section 3.4 reports the research approach and the results; Section 3.5 discusses the research findings, their implication, future research, and Section 3.6 closes this work with the conclusions.

## 3.2. Theoretical framework

Although extensive research has been carried out on user acceptance in transportation, no single study has investigated the Unified Theory of Acceptance and Use of Technology 2 (UTAUT2) on e-bike technology (Venkatesh et al., 2012). The UTAUT and UTAUT2 were extensively used for automated vehicles (AV) use, and even though the proposed Smart e-bike is not automated in nature, one common factor between AV and Smart e-bike is the introduction of new technologies. Thus, the following section describes the UTAUT2 framework and its applications so far, as well as its implementation in Smart e-bikes.

### 3.2.1. User acceptance of new technologies in transport

Several studies conducted surveys to investigate public opinion and acceptance of new systems and technologies. Some of those studies focus on user acceptance of AVs (Adnan et al., 2018; Kenesei et al., 2022), automated shuttles (Nordhoff et al., 2020b), autonomous car-sharing services (Curtale et al., 2021), and last-mile delivery using autonomous vehicles (Kapser et al., 2021). These prove that investigating the public acceptance of new applications in transportation-related studies is important to examine users' intentions and help researchers and manufacturers optimally design new systems. The above studies used a wide range of methods spanning from descriptive statistics to advanced theoretical models to examine users' acceptance. The present study utilises one of the most well-known behavioural frameworks for assessing users' acceptance to use new technologies, the UTAUT2 and applies it to bicycle technologies (Venkatesh et al., 2012).

### 3.2.2. Adjusting the UTAUT2 model

This study adopted the framework of the Unified Theory of Acceptance and Use of Technology 2 (UTAUT2) (Venkatesh et al., 2012). Previously, the Unified Theory of Acceptance and Use of Technology (UTAUT) was proposed by (Venkatesh et al., 2003), focusing on users' acceptance of new technologies in work environments. UTAUT was built based on other theoretical models, such as the technology acceptance model, theory of planned behaviour, motivational model, and innovation diffusion theory (Venkatesh et al., 2003). However, UTAUT does not consider consumers' technology acceptance (Venkatesh et al., 2012), while UTAUT2 was constructed especially to cover this gap. The UTAUT2 contains four constructs (Performance expectancy, effort expectancy, social influence and facilitating conditions) from the UTAUT model and builds up the rest (hedonic motivation, price value and habit) (Venkatesh et al., 2012). While, as we mentioned, the original UTAUT2 model specifies seven constructs (Venkatesh et al., 2012), we adjusted the model to fit this study's aim better. Since the initial UTAUT model was developed focusing on users' acceptance and use of technology in work environments (Venkatesh et al., 2003; Venkatesh et al., 2012), adjustments to the models are common in transport research. For instance, Kapser et al. (2021) studied the acceptance of autonomous delivery vehicles and adjusted the model by excluding the constructs habit and price value since autonomous delivery vehicles were not yet available. However, they added perceived risk and price sensitivity as constructs. Curtale et al. (2021) also excluded facilitating conditions, price value and habit since these constructs tend to predict the actual use rather than intention due to the lack of available automated electric car-sharing services. Finally, a study related to bicycle-sharing systems conducted by Jahanshahi et al. (2020) excluded habit and hedonic motivation and included perceived safety as a construct.

### 3.2.3. Conceptual model of Smart e-bikes

To develop a theoretical model that fits best in this study, we have adapted the UTAUT2 model. More specifically, following other studies (Jahanshahi et al., 2020; Kapser et al., 2021) we included perceived safety as a construct as well as social status since it has been proved that it plays a key role in people's psychological behaviour (Jahanshahi et al., 2020; Simsekoglu & Klöckner, 2019a). However, we excluded facilitating conditions, price value, and habit of the UTAUT2 model since the Smart e-bike is hypothetical and not commercially available yet. Figure 3.1 displays the conceptual model for this study.

### 3.2.4. Research hypotheses

It is hypothesised that behavioural intention to use the Smart e-bike is related to performance and effort expectancy, social influences, hedonic motivation, social status and perceived safety. The elements in the conceptual model are as follows:

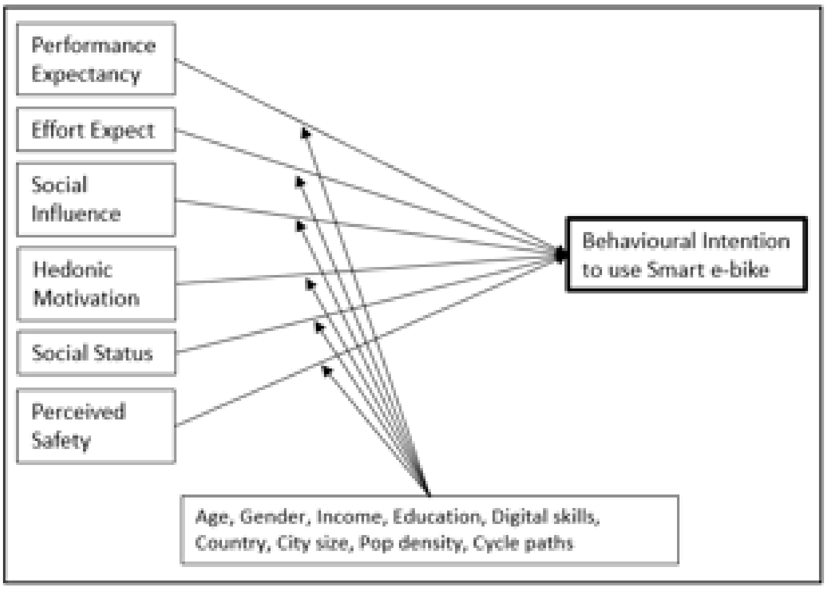

**Figure 3.1 Conceptual model for the user acceptance of Smart e-bikes**

**Performance expectancy** relates to the individual beliefs concerning a system and the help an individual gains when using it (Venkatesh et al., 2003). Having a closer look at the transportation domain, there are many studies which have investigated users' acceptance of AVs (Curtale et al., 2021; Nordhoff et al., 2020a). These studies have found that this construct has a positively strong impact on behavioural intention. In addition, performance expectancy has a positive and strong relationship in research studies investigating the intention to use e-bikes and shared e-bikes (Simsekoglu & Klöckner, 2019a; Yasir et al., 2022). In the context of this study regarding the Smart e-bike, we assume that the performance expectancy construct will also be a strong predictor since the Smart e-bike could improve user comfort and mobility. Also, since we perform a cross-country analysis, we believe that performance expectancy will be a strong predictor for all the countries.

**Effort expectancy** refers to the ease of use of a specific system (Venkatesh et al., 2003) and is also associated with the degree of consumer's ease of use (Venkatesh et al., 2012). Effort expectancy shows a positive influence in studies related to AV acceptance (Buckley et al., 2018; Golbabaei et al., 2020), while other studies have proved that the influence of effort expectancy is low but positive as well (Nordhoff et al., 2020a). Also, previous studies on bicycles found that effort expectancy has a frugal influence on behavioural intention (Jahanshahi et al., 2020; Wolf & Seebauer, 2014). Therefore, in the context of the Smart e-bike we believe that effort expectancy will have positive influence on behavioural intention.

**Social influence** is defined as an individual's perception of what others believe they should follow for a specific technology and to what extent others' opinion influences an individual to accept and use technology (Venkatesh et al., 2003). In the literature, social influence is a positive predictor of behavioural intention in many studies investigating the use of AVs (Kapser et al., 2021; Nordhoff et al., 2020a). However, Jahanshahi et al. (2020) could not support this hypothesis in a bicycle-sharing system study. With respect to the previous studies, it is hypothesised that social influence will positively influence behavioural intention to use Smart e-bikes.

**Hedonic motivation** proves the enjoyment an individual can sense using a technology (Venkatesh et al., 2012). This construct positively discloses users' intention to accept technology in transportation, especially in AVs (Kapser et al., 2021; Nordhoff et al., 2020a). Hence, it could conceivably be hypothesised that hedonic motivation will positively impact behavioural intention to use a Smart e-bike.

In addition to the main constructs of the UTAUT2, we extended the model by using two more constructs, namely **social status**, and **perceived safety**. Social status refers to practices that individuals do because they believe they belong to a specific social group and/or their beliefs about their status (Jahanshahi et al., 2020; Simsekoglu & Klöckner, 2019a). Perceived safety has been used by Jahanshahi et al. (2020); Kapser et al. (2021) as a construct to predict the intention to use shared bicycles and autonomous delivery vehicles. In this study, perceived safety predicts how the intention to use Smart e-bikes is influenced by an individual's belief that the Smart e-bike will improve their safety. The hypotheses derived from the behavioural framework are as follows:

> **H1:** Performance expectancy positively influences behavioural intention to use a Smart e-bike.
>
> **H2:** Effort expectancy positively influences behavioural intention to use a Smart e-bike.
>
> **H3:** Social influence positively influences behavioural intention to use a Smart e-bike.
>
> **H4:** Hedonic motivation positively influences behavioural intention to use a Smart e-bike.
>
> **H5:** Social status positively influences behavioural intention to use a Smart e-bike.
>
> **H6:** Perceived safety positively influences behavioural intention to use a Smart e-bike.

Furthermore, we also developed sixteen sub-hypotheses, presented in Table 3.1, together with the paths and the proposed effect of each variable. We hypothesise that socio-demographic characteristics, especially high-income and highly educated people as well as the elderly (considering the risk averseness), would positively impact the behavioural intention to use the Smart e-bike (H7a-H7d). Similarly, we hypothesise that males will have a positive behavioural intention as they tend to be open to new technologies compared to females (Curtale et al., 2021; Nordhoff et al., 2020a). People who are technology-friendly and aware of the benefits of new technologies, such as people with high digital skills and those who know about advanced driving assistance systems (ADAS) will also positively influence behavioural intention (H8a and H8b) (Wolff & Madlener, 2019). Traffic-related and safety-related characteristics, such as lack of cycling infrastructure, low perceived safety, and high traffic density, would also positively impact behavioural intention (H9a-H9d) due to the safety advantages the Smart e-bike can bring. Similarly, geographical characteristics such as population density, city size and availability of cycle paths would positively impact behavioural intention (H10a-H10d), since potential users living in such areas can benefit from the Smart e-bike characteristics such as B2I. We also hypothesise that the behavioural intention to use a Smart e-bike varies among countries, in addition to individual characteristics, due to the differences in cycling culture and levels of infrastructure; hence, we expect heterogeneity between countries towards behavioural intention (H11).

## 3.3. Methodology

### 3.3.1. Survey setup and recruitment

For this study, a tailor-made web-based survey using the Lighthouse Studio platform (Sawtooth Software, 2022) was developed. The survey was administered by fully complying with the General Data Protection Regulation (GDPR). In addition, the security issues for the survey were addressed. Lastly, Ethical approval for this survey was obtained by the Human Research Ethics Committee (HREC) at the University of Twente. The complete questionnaire can be found in Appendix E.

The survey was administered in four phases: three pilot test versions and the final distribution. The first phase falls into the survey distribution among the researcher group members to ensure the optimal structure and reliability of the survey. Afterwards, the survey was translated into five languages (Dutch, English, German, Greek, and French). In the second phase, we sent the translated version of the survey to fourteen experts across the selected countries; nine of them participated and sent their suggestions. Then, in the third phase, we distributed the survey to twenty random respondents per language/country to ensure the layman’s translation was clear. Lastly, we officially distributed the survey in a web-based online format among the target countries. The responses from the research group members and the experts were discarded, while the responses from random people were included in the analysis.

The online survey was conducted in Austria, Belgium, Germany, Greece and the Netherlands between November 2022 and January 2023, targeting both existing and potential e-bike users. The choice of these target groups derives from the perspective of collecting from people interested in cycling, especially on e-bikes. Note that the survey distinguished between Pedelecs (up to 25 km/h) and Speed-Pedelec (up to 45 km/h) (ECF, 2017).

**Table 3.1 Sub-hypotheses**

| Hypothesis | Path | Proposed effect |
|---|---|---|
| H7a | Gender (male) → BI | + |
| H7b | Age → BI | + |
| H7c | Age (older than 60) → BI | + |
| H7d | Education (high)→ BI | + |
| H7e | Income (high)→ BI | + |
| H8a | Digital skills (high) → BI | + |
| H8b | ADAS (yes)→ BI | + |
| H9a | Lack of infrastructure (high)→ BI | + |
| H9b | Perceived safety (high)→ BI | + |
| H9c | Traffic density (high)→ BI | + |
| H9d | Crash (yes)→ BI | + |
| H10a | Population density (high)→ BI | - |
| H10b | City size (< 50 k)→ BI | + |
| H10c | City size (> 500 k)→ BI | + |
| H10d | Cycle paths (few)→ BI | - |
| H11 | Countries are heterogenous → BI | ≠ |

BI: Behavioural intention

The survey was distributed through European Cyclists' Federation (ECF) members, cycling unions, and social media. In the Netherlands, we used a mixed-method approach by distributing the survey online and on-site. We visited a bicycle experience centre in Ede, the Netherlands for the on-site distribution. Ede is located in the middle of the Netherlands and welcomes visitors from all over the country to test different types of bicycles. The reason for this choice of the mixed-method was twofold, 1) to get as many participants as possible who are unfamiliar with the technologies (e.g. do not use smartphones or computers) and could not participate in the online survey, namely elderly and low-income people, and 2) to recruit people who are buying an e-bike. In addition, to ensure representative samples, a second group of respondents were recruited through panel market research, panelclix[1].

Furthermore, the countries were not selected randomly; on the contrary, we chose them due to the different quality of cycling infrastructure to understand people's perceived safety and cycling culture. These countries vary in size, cycling rate and cycling safety. While the Netherlands has a high-quality cycling infrastructure, a dense network, and high bicycle rate (Schepers et al., 2017), Belgium and Germany have medium cycling infrastructure and bicycle rates, while Austria has medium to low ones. On the other hand, Greece has a scarce and low quality infrastructure network and low cycling rate (European Commission, 2020).

### 3.3.2. Survey design

The survey consisted of three parts. Firstly, the participants were introduced to the survey concept, and screening questions such as mobility habits and familiarity with new technologies

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[1] https://www.panelclix.co.uk/

were asked. The second part refers to UTAUT2-related questions about psychological constructs affecting the use of a Smart e-bike. All the questions were designed based on a five-point Likert scale (Table 3.2) (Venkatesh et al., 2003; Venkatesh et al., 2012). To avoid bias in our data due to participants' unfamiliarity with the smart technologies on bicycles, participants received a description of the Smart e-bike in plain layperson language and a representation of a graphical scenario before entering the UTAUT2-related questions as follows (Kyriakidis et al., 2015):

In the following questions, you will be asked to give your opinion about a smart electric bicycle, the Smart e-bike.

- *The Smart e-bike is equipped with various systems to improve your comfort and safety while cycling. You always maintain the steering control of the bicycle.*
- *The Smart e-bike will warn you and/or automatically reduce its speed in order to avoid a collision with other bikes, vehicles, or pedestrians.*
- *The Smart e-bike will request green at traffic lights. You will need to stop fewer times, and your travel time can be shorter.*
- *The Smart e-bike will automatically send an SMS/call to emergency units in case you have involved in a severe crash.*
- *The Smart e-bike will recommend safer routes for you.*

Below you can see a representation of how a Smart e-bike would look like:

**Image 3.1 Graphical representation of a Smart e-bike.**

Thus, participants were able to understand better the features of the Smart e-bike and more details about their use. The third and last part refers to the socio-demographic characteristics of the participants.

While other alternatives exist assisting cyclists to get green traffic lights (green wave), such as the Green Waves for bicycles in Copenhagen (Centreforpublicimpact, 2016) and computer vision cameras identifying bicycles approaching (vivacitylabs.com, 2024), we focused on wireless technology since it can achieve communication between traffic lights and bicycles in a longer range and ensure the priority to the latter (Ben Fredj et al., 2023).

### 3.3.3. Sample description

In total, 1,625 people who own an e-bike or are interested in buying one completed the survey in the target countries. Responses with less than 5 minutes of completing time and no variation in the Likert scale questions were excluded from further analysis (a total of 36 respondents). Thus, after the data cleaning, 1589 responses remained. Table 3.3 shows the sample characteristics. In detail, 48% (762) of the total sample own an e-bike, while the rest, 52% (827), is willing to buy one. 45% (699) of the respondents live in a town smaller than 50,000 citizens, while 43% (638) and 12% (187) respondents live in a city size between 50,000-500,000 and higher than 500,000, respectively. The Netherlands' sample is representative according to the Mobility Panel Data (Kennisinstituut voor Mobiliteitsbeleid, 2021) for e-bike users. There is no available database for cyclists to compare our samples for the rest of the countries.

### 3.3.4. Geographical data

In the survey, we asked participants to provide their home postcodes. We obtained 1,524 correct postcodes out of 1,589. More specifically, we had the full postcodes for 79 respondents from Austria, 269 from Belgium, 90 from Germany, 212 from Greece, and 874 from the Netherlands. To identify the geographical home locations of the respondents, we used the Postal codes dataset provided by Eurostat (2022b) and merged it with the available 1524 postcodes. Table 3.3 shows the sample composition per country.

In addition, we used the home postcodes data to identify the city size, population density and the available cycling infrastructure for the respondents' home area. We used OpenStreetMap (2023) data to get the cycle infrastructure, the Nomenclature of Territorial Units for Statistics 3 (NUTS3), and Administrative Units from Eurostat to get the population density and city size. Using ArcGIS (ESRI, 2022), a buffer zone of 10 km was developed for each postcode centroid to identify the entire cycling infrastructure per postcode in each country. Appendix A shows the maps for each country.

### 3.3.5. Analysis approach

A variety of methods and steps were used to assess the Structural Equation Model (SEM). The analysis included exploratory factor analysis (EFA) followed by confirmatory factor analysis (CFA) and the SEM estimation. The EFA was conducted using the Principle Axis Factoring and Varimax rotation with the average sum of Cronbach's alpha = 0.926 and KMO (Kaiser-Meyer-Olkin) = 0.946, confirming its suitability for CFA and SEM estimation. EFA results can be found in Appendix B. The CFA and the SEM model were estimated using the SPSS-AMOS software (Arbuckle, 2022) employing the robust Maximum Likelihood estimator.

**Table 3.2 Constructs, statements, and sources**

| | ***Constructs*** | ***Main sources*** |
|---|---|---|
| Performance Expectancy (PE) | | |
| PE1 | I expect that a Smart e-bike would be useful for me | *(Simsekoglu & Klöckner, 2019b; Venkatesh et al., 2012)* |
| PE2 | Using a Smart Bike would help me reach my destination, within a city, more comfortably | |
| PE3 | I expect that a Smart e-bike would be useful for achieving my daily mobility needs | |
| Effort Expectancy (EE) | | |
| EE1 | It would be too much effort for me to pay attention to the systems of a Smart e-bike | *(Nordhoff et al., 2020a; Simsekoglu & Klöckner, 2019b; Venkatesh et al., 2012)* |
| EE2 | It would be too time consuming for me to learn how to use a Smart e-bike | |
| EE3 | I will ride with more stress using a Smart e-bike | |
| Social Influence (SI) | | |
| SI1 | I believe that people who are important to me think that I should use a Smart e-bike | *(Curtale et al., 2021; Jahanshahi et al., 2020; Venkatesh et al., 2012)* |
| SI2 | I expect that people who are important to me would encourage me to use a Smart e-bike | |
| SI3 | I expect that people whose opinions I value would prefer that I use a Smart e-bike | |
| Hedonic Motivation (HM) | | |
| HM1 | Riding a Smart e-bike would be enjoyable for me | *(Kapser et al., 2021; Nordhoff et al., 2020a; Venkatesh et al., 2012)* |
| HM2 | Riding a Smart e-bike would be much more enjoyable than a conventional bicycle for me | |
| HM3 | Riding a Smart e-bike would be cool | |
| Social Status (SS) | | |
| SS1 | I would feel part of a group/community using a Smart e-bike | *(Jahanshahi et al., 2020; Simsekoglu & Klöckner, 2019a)* |
| SS2 | Riding a Smart e-bike will be in line with my social class | |
| SS3 | I would be proud if people saw me owning a Smart e-bike | |
| Perceived Safety (PS) | | |
| PS1 | I believe that a Smart e-bike will increase my safety (when riding) compared to a conventional bicycle | *(Jahanshahi et al., 2020) and own investigation* |
| PS2 | I think that riding a Smart e-bike can reduce the risk of me getting involved in a crash/collision compared to a conventional bicycle | |
| PS2 | I think that there will be fewer severe crashes for the Smart e-bike users | |
| Behavioural Intention (BI) | | |
| BI1 | I would like to buy a Smart e-bike when it will be on the market in the future | *(Nordhoff et al., 2020a; Pan et al., 2022; Venkatesh et al., 2012)* |
| BI2 | I would like to choose a Smart e-bike even though it is more expensive | |

EE1 to EE3: Likert scale scoring has been reversed for the analysis.

### Table 3.3 Sample composition

| Variable | Austria | Belgium | Germany | Greece | Netherlands | Total |
|---|---|---|---|---|---|---|
| Number of respondents | 80 (5) | 271 (17) | 124 (8) | 231 (15) | 883 (55) | 1589 (100) |
| **Gender** | | | | | | |
| Male | 58 (73) | 169 (62) | 85 (69) | 171 (74) | 425 (48) | 908 (57) |
| Female | 18 (23) | 99 (37) | 37 (30) | 59 (26) | 444 (50) | 657 (42) |
| Non-binary | 3 (4) | 1 (0) | 0 | 0 | 4 | 8 (0) |
| Other/prefer not to answer | 1 (1) | 2 (1) | 2 (2) | 1 (0) | 10 (1) | 16 (1) |
| **Age** | | | | | | |
| 18-29 | 3 (4) | 15 (6) | 12 (10) | 27 (12) | 44 (5) | 101 (6) |
| 30-39 | 17 (21) | 37 (14) | 16 (13) | 61 (26) | 113 (13) | 244 (15) |
| 40-49 | 12 (15) | 51 (19) | 19 (15) | 70 (30) | 113 (13) | 265 (17) |
| 50-59 | 24 (30) | 54 (20) | 39 (31) | 51 (22) | 194 (22) | 362 (23) |
| 60-69 | 18 (23) | 78 (29) | 31 (25) | 22 (10) | 226 (10) | 375 (24) |
| >70 | 6 (8) | 36 (13) | 7 (6) | 0 | 193 (22) | 242 (15) |
| **Education** | | | | | | |
| Low (high school or lower) | 28 (35) | 72 (27) | 35 (28) | 60 (26) | 459 (52) | 654 (41) |
| High (univ. degree or higher) | 52 (65) | 199 (73) | 89 (72) | 171 (74) | 424 (48) | 935 (59) |
| **Net monthly income (€/month)** | | | | | | |
| Low (until 2000) | 23 (29) | 58 (21) | 34 (27) | 180 (78) | 285 (32) | 580 (37) |
| High (more than 2000) | 42 (53) | 175 (65) | 69 (56) | 32 (14) | 478 (54) | 796 (50) |
| Prefer not to answer | 15 (19) | 38 (14) | 21 (17) | 19 (8) | 120 (14) | 213 (13) |
| **E-bike ownership** | | | | | | |
| Pedelec | 35 (44) | 119 (44) | 62 (50) | 28 (12) | 429 (49) | 673 (42) |
| SPX | 0 | 48 (18) | 3 (2) | 6 (3) | 32 (4) | 89 (6) |
| **Willing to buy an e-bike within five years** | | | | | | |
| Pedelec | 42 (53) | 82 (30) | 55 (44) | 154 (67) | 388 (44) | 721 (45) |
| SPX | 3 (4) | 22 (8) | 4 (3) | 43 (19) | 34 (4) | 106 (7) |
| **City size** | | | | | | |
| Less than 50 k | 22 (28) | 183 (68) | 28 (23) | 93 (40) | 373 (42) | 699 (46) |
| 50-500 k | 17 (21) | 62 (23) | 25 (20) | 95 (41) | 439 (50) | 638 (42) |
| More than 500 k | 40 (50) | 24 (9) | 37 (30) | 24 (10) | 62 (7) | 187 (13) |
| **Population density*** | | | | | | |
| Low (0-462) | 39 (49) | 113 (42) | 55 (17) | 122 (53) | 399 (45) | 750 (47) |
| High (463-20.965) | 40 (50) | 156 (58) | 69 (56) | 90 (39) | 484 (55) | 839 (53) |

* Population density refers to people per km$^2$ by NUTS3; number in brackets indicate the percentage (%)

### 3.3.6. Multigroup analysis and measurement invariance

This study utilises multigroup analysis to examine differences between the acceptance of Pedelec and Speed-Pedelec and between respondents from five countries. Measurement invariance (MI) is the main method used to determine whether a construct is equivalently perceived across groups and whether the comparisons made are meaningful (Putnick & Bornstein, 2016). However, multigroup analysis in the transportation domain often lacks MI assessments. Based on the literature (Putnick & Bornstein, 2016; Vandenberg & Lance, 2000), we compared three models: configural (M1), metric (M2), and scalar invariance (M3) to test MI. Comparisons of the RMSEA and CFI fit indices are commonly used. The fit values are $<0.015$ and $\leq 0.01$ for the $\Delta$RMSEA and $\Delta$CFI, respectively (Chen, 2007; Cheung & Rensvold, 2002). However, the fit value for $\Delta$CFI varies among researchers and some use more liberal fit ($\Delta$CFI $\leq 0.02$) due to different model parameters such as sample size, number of groups, and number of factors (Cheung & Rensvold, 1999; Putnick & Bornstein, 2016).

## 3.4. Research approach and results

### 3.4.1. Structural Equation Model

The CFA contains seven constructs and 20 variables (Table 3.4). Hair et al. (2014, p. 618) put a threshold for the standardised loading above 0.5 and ideally above 0.7. In this study, standardised factor loading varies mainly from 0.703 to 0.947, except for one variable, EE1, which was 0.640, with the accepted threshold at 0.5 (Hair et al., 2014). Table 3.4 presents the factor loadings and the descriptive statistics, i.e., each variable's mean, standard deviation, skewness, and kurtosis.

The goodness of fit of the model was evaluated using the following measurements: chi-square test of model fit (CMIN/DF) = 3.878, Comparative Fit Index (CFI) = 0.982, Tucker-Lewis index (TLI) = 0.977, Root Mean Square of Approximation (RMSEA) = 0.043, Standardised Root Mean Square Residual (SRMR) = 0.0253 and Parsimony Fit Index (PNFI) = 0.761 (Hair et al., 2014; Schumacker & Lomax, 2010). Those indexes are also commonly used in many transportation studies (Curtale et al., 2021; Kapser et al., 2021; Nordhoff et al., 2020a; Sarker et al., 2019). As was expected, due to the large sample, the test of exact fit indicated not entirely adequate results, with $\chi 2$ = 573.926. Table 3.5 displays all the assessments with their cut-offs.

**Table 3.4 Results of factors loadings and descriptive statistics.**

| Construct | Item | Factor loading | M | SD | Skew | Kurt |
|---|---|---|---|---|---|---|
| **Performance Expectancy** | PE1 | 0.901*** | 3.36 | 1.10 | - 0.566 | - 0.333 |
| | PE2 | 0.877*** | 3.35 | 1.10 | - 0.597 | - 0.315 |
| | PE3 | 0.832*** | 3.14 | 1.14 | - 0.352 | - 0.665 |
| **Effort Expectancy** | EE1 | 0.640*** | 2.99 | 0.98 | 0.065 | - 0.503 |
| | EE2 | 0.703*** | 3.53 | 0.98 | - 0.371 | - 0.314 |
| | EE3 | 0.715*** | 3.39 | 1.04 | - 0.332 | - 0.493 |
| **Social Influence** | SI1 | 0.899*** | 2.83 | 1.08 | 0.070 | - 0.647 |
| | SI2 | 0.943*** | 2.83 | 1.08 | 0.101 | - 0.718 |
| | SI3 | 0.908*** | 2.82 | 1.07 | 0.361 | - 0.841 |
| **Hedonic Motivation** | HM1 | 0.881*** | 3.43 | 1.03 | - 0.766 | 0.213 |
| | HM2 | 0.826*** | 3.01 | 1.17 | - 0.152 | - 0.811 |
| | HM3 | 0.851*** | 3.05 | 1.16 | - 0.299 | - 0.713 |
| **Social Status** | SS1 | 0.748*** | 2.28 | 1.08 | 0.441 | - 0.716 |
| | SS2 | 0.725*** | 2.61 | 1.12 | 0.014 | - 0.791 |
| | SS3 | 0.856*** | 2.36 | 1.17 | 0.361 | - 0.841 |
| **Perceived Safety** | PS1 | 0.903*** | 3.45 | 1.00 | - 0.678 | 0.095 |
| | PS2 | 0.813*** | 3.29 | 1.01 | - 0.630 | - 0.195 |
| | PS3 | 0.750*** | 3.21 | 1.00 | - 0.483 | - 0.247 |
| **Behavioural Intention** | BI1 | 0.947*** | 3.00 | 1.09 | - 0.359 | - 0.676 |
| | BI2 | 0.848*** | 2.80 | 1.09 | - 0.118 | - 0.914 |

***: p-value < 0.001; M = mean; SD = standard deviation; Skew = skewness; Kurt = kurtosis

In addition to the above tests, we assessed the construct validity of our model. Construct validity refers to what extent the variables which comprise a construct are converged and to the degree these variables are not interrelating with other constructs. Various tests are available for construct validity, such as Nomological (Cronbach & Meehl, 1955) and Multitrait-Multimethod

Matrix (Campbell & Fiske, 1959). We assessed the model for convergent and discriminant validity, which are subtypes of construct validity and the most commonly used (Kapser et al., 2021; Nordhoff et al., 2020a). Cronbach's alpha and composite reliability (CR) were above the acceptance threshold of 0.7 for all constructs (Hair et al., 2014).

**Table 3.5 Model fit indices.**

| Model fit assessment | $\chi^2$* | CMIN/DF | CFI | TLI | RMSEA# | SRMR | PNFI |
|---|---|---|---|---|---|---|---|
| Cut-off | - | < 5.0 | ≥ 0.95 | ≥ 0.95 | ≤ 0.07 | < 0.05 | > 0.5 |
| Results | 573.926 | 3.878 | 0.982 | 0.977 | 0.043 | 0.0253 | 0.761 |

* (df= 148, p-value < 0.001); # with a 90% confidence interval of [0.039; 0.046]

The Average Variance Extracted (AVE) was above the cut-off criterion of 0.50 (Fornell & Larcker, 1981; Hair et al., 2014), 0.477 for effort expectancy, illustrating the convergent validity. Despite the AVE for effort expectancy being at the limit, we retained it since the AVE is often too strict, and reliability can be established through the CR only (Malhotra & Dash, 2011). Hence the assessment supports internal consistency. In addition, the Fornell-Larker criterion was assessed, which indicates discriminant validity; the square root of the AVE of each construct surpass all the correlation among the constructs (Fornell & Larcker, 1981). All those assessments are reported in Table 3.6. However, Franke and Sarstedt (2019) recently concluded that the Fornell-Larker criterion could not properly identify the discriminant validity. Hence, as an addition, we employed the Heterotrait-Monotrait ratio correlation (HTMT) (Henseler et al., 2014). The values of the HTMT were below the threshold of 0.85 and can be found in Appendix C.

**Table 3.6 Convergent validity, construct reliability, and Fornell–Larcker criterion.**

| | **α** | **CR** | **AVE** | **PE** | **EE** | **SI** | **ST** | **HM** | **PS** | **BI** |
|---|---|---|---|---|---|---|---|---|---|---|
| **PE** | 0.904 | 0.903 | 0.757 | **0.870** | | | | | | |
| **EE** | 0.728 | 0.728 | 0.477 | 0.458 | **0.687** | | | | | |
| **SI** | 0.940 | 0.941 | 0.841 | 0.697 | 0.281 | **0.917** | | | | |
| **ST** | 0.819 | 0.821 | 0.605 | 0.650 | 0.275 | 0.675 | **0.778** | | | |
| **HM** | 0.890 | 0.889 | 0.728 | 0.823 | 0.536 | 0.651 | 0.725 | **0.853** | | |
| **PS** | 0.885 | 0.865 | 0.680 | 0.737 | 0.515 | 0.618 | 0.594 | 0.772 | **0.825** | |
| **BI** | 0.891 | 0.894 | 0.808 | 0.844 | 0.492 | 0.685 | 0.671 | 0.842 | 0.758 | **0.899** |

α = Cronbach's alpha; CR = composite reliability; AVE = average variance extracted.

Bold elements on the diagonal of the construct correlation matrix represent the square roots of the AVE.

### 3.4.2. Measurement invariance

Table 3.7 presents the results of the MI-Pedelec and Speed-Pedelec and-MI Country, indicating that the behavioural intention to use Smart e-bikes across the five countries and among the two groups of e-bikes attained the scalar invariance. This means invariance among those groups (i.e. countries and e-bikes) reached, hence the comparison made is meaningful and the multigroup analysis can be conducted. Note that the ΔCFI in MI-Country M3 slightly exceeds the cut-off; however, we proceeded with the analysis since the ΔRMSEA is well below its cut-off and since it is not easy to achieve MI with many groups (Putnick & Bornstein, 2016). In addition, scalar invariance is rarely tested and established (Putnick & Bornstein, 2016; Vandenberg & Lance, 2000).

### 3.4.3. SEM results

A significant positive relationship was found between performance expectancy and behavioural intention, effort expectancy and behavioural intention, social influence and behavioural intention, hedonic motivation and behavioural intention, and perceived safety and behavioural intention. In contrast, there is no significant relationship between social status and behavioural intention. The hypotheses and their structural results are presented in Table 3.8. The variability of behavioural intention to use a Smart e-bike is explained by 80% of the proposed model.

**Table 3.7 Comparison of the nested models**

| Model | $\chi^2$ | df | $\chi^2_{diff}$ | Δdf | RMSEA [90% CI] | ΔRMSEA | CFI | ΔCFI |
|---|---|---|---|---|---|---|---|---|
| **MI-Pedelec and Speed-Pedelec** | | | | | | | | |
| M1 | 742.905 | 296 | - | - | 0.031 [0.028-0.034] | - | 0.981 | - |
| M2 | 753.47 | 309 | 10.565 | 13 | 0.030 [0.027-0.034] | 0.001 | 0.9982 | 0.001 |
| M3 | 784.987 | 322 | 31.517*** | 13 | 0.030 [0.027-0.034] | 0.000 | 0.981 | 0.001 |
| **MI-Country** | | | | | | | | |
| M1 | 1278.064 | 740 | - | - | 0.021 [0.019-0.023] | - | 0.977 | - |
| M2 | 1346.489 | 792 | 68.425* | 52 | 0.021 [0.019-0.023] | 0.000 | 0.976 | 0.001 |
| M3 | 1715.481 | 844 | 368.992*** | 52 | 0.026 [0.024-0.027] | 0.005 | 0.963 | 0.013 |

MI: Measurement invariance, MI-Country: Measurement invariance for the countries, MI-Pedelec and Speed-Pedelec: Measurement invariance for e-bike groups, M1: configural invariance, M2: metric invariance, M3: scalar invariance, ***: p-value < 0.001, *: p-value < 0.1

**Table 3.8 Results of structural relationships**

| Hypothesis | β | p-value | Results |
|---|---|---|---|
| H1 | 0.394 | < 0.001 | supported |
| H2 | 0.037 | 0.004 | supported |
| H3 | 0.080 | < 0.001 | supported |
| H4 | 0.356 | < 0.001 | supported |
| H5 | 0.027 | 0.132 | rejected |
| H6 | 0.112 | < 0.001 | supported |

### 3.4.4. Socio-demographic, geographic and safety-related effects on constructs

Socio-demographic characteristics affect all the UTAUT2 constructs (Table 3.9). All the variables for the following analysis are dummy-coded. Performance expectancy significantly increases for all the variables that were tested. Effort expectancy increases for males, people older than 60, high income, and areas lacking cycling infrastructure. Also, it increases significantly for people with high digital skills using a smartphone and in high-density areas. Social influence decreases in high-traffic density areas and increases with the increase in city size and people unfamiliar with ADAS. For the rest of the variables, it significantly increases. Hedonic motivation shows a significant effect across all the variables, while there is no educational impact on hedonic motivation. Social status increases with age, income, perceived safety and lack of cycling infrastructure, and there is no effect for the other variables. Perceived safety significantly increases with all the variables, while there is no effect with the technology and the cycle paths.

**Table 3.9 Regression results of socio-demographic effects on constructs**

| Variables | PE | EE | SI | HM | SS | PS |
|---|---|---|---|---|---|---|
| Gender (male) | 0.386*** | 0.036** | 0.080*** | 0.376*** | 0.031 | 0.106*** |
| Age (>60) | 0.435*** | 0.039** | 0.052** | 0.252*** | 0.079** | 0.120** |
| Education (high) | 0.366*** | 0.019** | 0.101*** | 0.425 | 0.003 | 0.080** |
| Income (high) | 0.384*** | 0.043** | 0.074*** | 0.350*** | 0.038 | 0.135*** |
| Digital skill (high) | 0.368*** | 0.076*** | 0.114*** | 0.369*** | 0.027 | 0.040 |
| ADAS (yes) | 0.435*** | 0.028 | 0.037 | 0.345*** | 0.030 | 0.120*** |
| Lack of infrastructure (high) | 0.435*** | 0.039** | 0.052** | 0.252*** | 0.079** | 0.121*** |
| Perceived safety infrastructure (high) | 0.386*** | 0.016** | 0.115*** | 0.365*** | 0.006 | 0.120*** |
| Traffic density (high) | 0.549*** | - 0.017 | - 0.090* | 0.397** | 0.015 | 0.127** |
| Crash (yes) | 0.388*** | 0.034** | 0.073*** | 0.361*** | 0.025 | 0.128*** |
| Population density (high) $^g$ | 0.428*** | 0.064*** | 0.068** | 0.346*** | 0.013 | 0.082** |
| City (< 50 k) $^g$ | 0.395*** | 0.022 | 0.034 | 0.318*** | 0.042 | 0.185*** |
| City (> 500 k) $^g$ | 0.485*** | 0.072* | 0.064 | 0.239** | 0.095* | 0.051 |
| Cycle paths (few) $^g$ | 0.500*** | 0.022 | 0.066** | 0.297*** | 0.054 | 0.028 |

***: p-value < 0.001, **: p-value < 0.05, *: p-value < 0.1; $^g$ refers to geographical data

### 3.4.5. Multigroup analysis

### 3.4.6. Behavioural intention to use a Pedelec and Speed-Pedelec

Psychological constructs, socio-demographic characteristics, geographical and safety-related effects on behavioural intention are presented in Table 3.10. All the UTAUT2 constructs positively affect behavioural intention to use a Smart Pedelec except the social status. Performance expectancy, hedonic motivation and perceived safety have the most substantial impacts, followed by social influence and effort expectancy. The impact of the socio-demographic characteristics varies on behavioural intention. Behavioural intention increases with the increase of age. Also, on the one hand, people older than 60 and people with high digital skills are willing to use a Smart Pedelec. On the other hand, people with high education levels are less willing to use a Smart Pedelec. Gender has no impact on behavioural intention.

Regarding safety-related factors, lack of infrastructure negatively influences people's intention to use a Smart Pedelec, while crashes positively impact behavioural intention. There is neither a positive nor negative impact considering the geographical dimensions of behavioural intention on Smart Pedelec.

All the UTAUT2 constructs on behavioural intention for the Smart Speed-Pedelec have a positive sign; however, only performance expectancy and hedonic motivation significantly impact behavioural intention, and there is no significant impact regarding the other variables.

### Table 3.10 Behavioural intention of Smart Pedelec and Smart Speed-Pedelec

| Variables | Smart Pedelec | Smart Speed-Pedelec |
|---|---|---|
| **Dependent variable: behavioural intention** | | |
| Performance expectancy | 0.382*** | 0.448*** |
| Effort expectancy | 0.033** | 0.059 |
| Social influence | 0.075*** | 0.053 |
| Hedonic motivation | 0.368*** | 0.330*** |
| Social status | 0.022 | 0.053 |
| Perceived safety | 0.121*** | 0.058 |
| Gender (male) | - 0.003 | - 0.032 |
| Age | 0.028** | - 0.004 |
| Age (> 60) | 0.018* | 0.024 |
| Education (high) | - 0.019* | - 0.015 |
| Income (high) | 0.000 | - 0.055 |
| Technology (high) | 0.018* | - 0.010 |
| ADAS (yes) | - 0.004 | 0.017 |
| Lack of infrastructure (high) | - 0.025** | - 0.023 |
| Perceived safety of infrastructure (high) | 0.001 | 0.015 |
| Traffic density (high) | 0.007 | 0.007 |
| Crash (yes) | 0.025** | 0.022 |
| Population density (high) $^{g}$ | 0.002 | 0.011 |
| City size (< 50k) $^{g}$ | - 0.002 | 0.009 |
| City size (> 500k) $^{g}$ | 0.000 | - 0.016 |
| Cycle paths (few) $^{g}$ | 0.006 | - 0.007 |

***: p-value < 0.001, **: p-value < 0.05, *: p-value < 0.1, $^{g}$ refers to geographical data

### 3.4.7. Cross-country analysis

Table 3.11 presents the investigation of cross-country differences and shows that performance expectancy has the highest impact and is significant across all countries. It has the highest impact in Germany and the lowest in the Netherlands. Hedonic motivation shows no impact in Austria, while for the remaining countries, it strongly impacts behavioural intention. Perceived safety has a strong and positive impact on Germany, Belgium, and the Netherlands, while there is no significance in Austria and Greece. Social influence remains a strong and positive construct in behavioural intention in Austria, Greece and the Netherlands, while there is no significance in Belgium, and it is negative in Germany. Effort expectancy has a positive relationship in Austria and the Netherlands. Social status has a positive but weak influence on behavioural intention in all countries except the Netherlands.

Socio-demographic characteristics indicate that high income has a negative impact on German respondents, while the increase in age has a positive and significant impact. High digital skills positively impact the behavioural intention of the Greek sample.

For the safety-related effects, people involved in crashes have a positive intention about the Smart e-bike in Greece, and there is no effect on the other countries. For the rest of the countries, there are various positive impacts in Austria and the Netherlands and negative ones in Germany and Belgium; however, these effects are not significant. To conclude, there is no significance for the geographical factors, such as city size, low availability of cycle paths and population density.

## 3.5. Discussion

In the previous sections, the results revealed several insights regarding factors that affect the behavioural intention to use a Smart e-bike. This section discusses the results, their implications, and the contribution of this study to the literature. Table 3.12 summarises the hypotheses and sub-hypotheses that were tested.

### 3.5.1. Smart e-bike implications and contribution of this study

With the increased living cost and the trend of electrification and more environmentally friendly transport modes, the number of people who switch from cars to e-bikes is increasing (de Haas & Huang, 2022; Shimano, 2022). While this is desirable since it reduces travel costs, emissions and congestion in cities, the number of crashes is increasing (Haustein & Møller, 2016; Kapousizis et al., 2022). Therefore, it was essential to investigate the user acceptance of the emerging Smart Pedelec and Speed-Pedelec, which can influence cycling safety and comfort.

The scope of this paper was to understand the extent to which e-bike users may consider using smart bicycle technologies. Note that we are not making an argument that cyclists should use these technologies. By presenting these findings, we aim to provide empirical insights to stakeholders and policymakers. While important, the assessment of our study countries' driving/cycling culture was not within the scope of our analysis. Also, while not all countries worldwide allow speed Pedelecs, interested stakeholders might focus only on the Pedelecs' results of this study. From the six hypotheses tested, five were supported (Performance expectancy, Effort expectancy, Social influence, Hedonic motivation, and Perceived safety), with performance expectancy, hedonic motivation and perceived safety having a strong and positive relationship with users' intention to use a Smart e-bike in the aggregated data sample.

A comparison of the findings with those of other studies confirms that these constructs play a significant role in behavioural intention of new technologies (Kapser et al., 2021; Venkatesh et al., 2012). This is also congruent with previous studies on the acceptance of shared bicycle systems and e-bikes (Jahanshahi et al., 2020; Simsekoglu & Klöckner, 2019a; Wolf & Seebauer, 2014). Specifically, performance expectancy has a higher impact on behavioural intention to buy and use a Smart e-bike, indicating that the usefulness of the Smart e-bike is the key element.

Hedonic motivation also has a strong and positive impact on behavioural intention, which indicates that the Smart e-bike offers fun and enjoyment to potential users, affecting their intention to use it. In addition, perceived safety is the third highest construct that affects behavioural intention, which means that behavioural intention to use and buy a Smart e-bike increases with the safety improvement offered by the Smart e-bike.

**Table 3.11 Multi-countries analysis of behavioural intention**

| Variables | AT | BE | DE | GR | NL | ALL |
|---|---|---|---|---|---|---|
| **Dependent variable: behavioural intention** | | | | | | |
| Performance expectancy | 0.433*** | 0.420*** | 0.451*** | 0.442*** | 0.378*** | 0.394*** |
| Effort expectancy | 0.127* | 0.056 | 0.015 | 0.056 | 0.033* | 0.037** |
| Social influence | 0.156** | 0.027 | -0.054 | 0.100** | 0.111*** | 0.080*** |
| Hedonic motivation | 0.127 | 0.228** | 0.332*** | 0.311*** | 0.396*** | 0.356*** |
| Social status | 0.071 | 0.076* | 0.076 | 0.046 | -0.001 | 0.027 |
| Perceived safety | 0.071 | 0.188*** | 0.196** | 0.028 | 0.111*** | 0.112*** |
| Gender (male) | 0.048 | 0.034 | 0.034 | - 0.003 | - 0.011 | - 0.003 |
| Age | 0.049 | 0.006 | 0.045* | 0.042 | 0.008 | 0.022 |
| Age > 60 | 0.051 | - 0.007 | 0.022 | 0.045 | 0.006 | 0.016* |
| Education (high) | 0.036 | - 0.027 | 0.025 | - 0.030 | - 0.004 | - 0.017* |
| Income (high) | 0.023 | -0.014 | - 0.028 | 0.001 | - 0.006 | - 0.005 |
| Digital skills (high) | 0.101 | - 0.002 | 0.003 | 0.053* | 0.015 | 0.015 |
| ADAS (yes) | - 0.021 | - 0.006 | - 0.036 | - 0.032 | 0.003 | - 0.002 |
| Lack of infrastructure (high) | 0.008 | 0.003 | - 0.017 | - 0.023 | 0.010 | - 0.013 |
| Perceived safety infrastructure (high) | - 0.033 | - 0.020 | - 0.39 | 0.043 | - 0.019 | 0.002 |
| Traffic density (high) | - 0.031 | 0.024 | 0.004 | - 0.047 | 0.005 | 0.007 |
| Crash (yes) | 0.026 | - 0.007 | - 0.001 | 0.067** | 0.008 | 0.024** |
| Population density (high) $^g$ | - 0.043 | 0.022 | - 0.011 | - 0.026 | 0.005 | 0.002 |
| City size (< 50 k) $^g$ | 0.013 | 0.004 | - 0.030 | 0.005 | 0.016 | 0.001 |
| City size (> 500 k) $^g$ | - 0.043 | - 0.008 | 0.034 | 0.003 | 0.004 | 0.003 |
| Cycle paths (few) $^g$ | 0.042 | 0.021 | - 0.029 | 0.001 | 0.004 | - 0.004 |

***: p-value < 0.001, **: p-value < 0.05, *:p-value < 0.1, $^g$ refers to geographical data

Social influence also positively impacts behavioural intention, which indicates that the pressure of relatives and family members influences potential users' intention towards Smart e-bikes. Effort expectancy has a moderate positive impact on behavioural intention, in agreement with other studies about AVs (Curtale et al., 2021; Nordhoff et al., 2020a), hence the Smart e-bike needs to be simple in use to be acceptable to people. Finally, social status has a positive impact, although it is not significant. In other words, some people think that with the Smart e-bike, they could be part of a group or prove their social status.

We also controlled the model with numerous sub-hypotheses considering socio-demographic, infrastructural, geographical, and safety-related variables. We found that behavioural intention to use Smart e-bikes increases, especially among people involved in crashes and people older than 60 years. A possible explanation might be that most older people own e-bikes and are prone to crashes (de Haas & Huang, 2022; Fishman & Cherry, 2016; Statistics Netherlands (CBS), 2021). Furthermore, the lack of cycling infrastructure negatively influences behavioural intention to use Smart e-bikes which supports the requirement for cycling infrastructure to attract more people to cycling (Buehler & Pucher, 2021; Nikitas et al., 2021). Lastly, we controlled for differences in behavioural intention among e-bike users and participants willing to buy one; however, we did not capture any significant difference among these groups.

**Table 3.12 Hypotheses and sub-hypotheses tested**

| Hypothesis | Path and proposed effect | AT | BE | DE | GR | NL | ALL |
|---|---|---|---|---|---|---|---|
| H1 | PE → BI (+) | S | S | S | S | S | S |
| H2 | EE → BI (+) | S | - | - | - | S | S |
| H3 | SI → BI (+) | - | S | - | S | S | S |
| H4 | HM → BI (+) | - | S | S | S | S | S |
| H5 | ST → BI (+) | - | S | - | - | - | S |
| H6 | PS → BI (+) | - | S | S | - | S | S |
| H7a | Gender (male) → BI (+) | - | - | - | - | - | - |
| H7b | Age → BI (+) | - | - | S | - | - | - |
| H7c | Age (older than 60) → BI (+) | - | - | - | - | - | S |
| H7d | Education (high)→ BI (+) | - | - | - | - | - | - |
| H7e | Income (high)→ BI (+) | - | - | - | - | - | - |
| H8a | Digital skills (high) → BI (+) | - | - | - | S | - | - |
| H8b | ADAS (yes)→ BI (+) | - | - | - | - | - | - |
| H9a | Lack of infrastructure → BI (+) | - | - | - | - | - | - |
| H9b | Perceived safety infrastructure (high)→ BI (+) | - | - | - | - | - | - |
| H9c | Traffic density (high)→ BI (+) | - | - | - | - | - | - |
| H9d | Crash (yes)→ BI (+) | - | - | - | S | - | S |
| H10a | Population density (high)→ BI (-) | - | - | - | - | S | - |
| H10b | City size (> 50 k)→ BI (+) | - | - | - | - | - | - |
| H10c | City size (> 500 k)→ BI (+) | - | - | - | - | - | - |
| H10d | Few cycle paths → BI (-) | - | - | - | - | - | - |
| H11 | Countries are heterogenous → BI (≠) | S | S | S | S | S | S |

S: Supported

Regarding the Smart Pedelec, all constructs except for social status are positive and significantly influence behavioural intention, with the strongest being performance expectancy, hedonic motivation and perceived safety. In addition, older age, involvement in a crash and familiarity with technology are the variables with the strongest positive influence on behavioural intention to use Smart Pedelec. On the contrary, the perceived lack of cycling infrastructure and high education have the strongest negative influence. In relation to the Smart Speed-Pedelec, only performance expectancy and hedonic motivation positively and significantly influence behavioural intention. The rest of the UTAUT constructs have a positive impact, even though they are not significant. No additional variables significantly influence behavioural intention to use Smart Speed-Pedelec either positively or negatively. Several factors could explain this difference between Smart Pedelec and Smart Speed-Pedelec: first, the small sample size for Smart Speed-Pedelec; second, Speed-Pedelecs are a special category of transport mode and are mainly used by middle age commuters who might tend to feel safe and capable (Vlakveld et al., 2021). Due to these factors, Speed-Pedelec users might find the variables which comprise the constructs of performance expectancy and hedonic motivation more important than the rest; third, that generally people keep a relatively neutral attitude toward emerging transport modes (Van den Steen et al., 2019). However, since no clear reason exists, further investigation is needed to draw conclusions.

The cross-country comparison allowed us to understand better the differences between countries that vary in cycling rates and cycling infrastructure towards the Smart e-bike. More specifically, the results of the cross-country analysis highlight some key elements. Performance expectancy is a strong and positive predictor for Austria, Belgium, Germany and Greece, while hedonic motivation is higher and stronger in the Netherlands, followed by performance expectancy and social influence. This is expected due to the presence of a higher cycling rate in the Netherlands than the other countries (Goel et al., 2021). The impact of effort expectancy in Austria is stronger than in the other countries but is still lower than the other constructs. The reason for this is not clear, but it may have something to do with the distribution of the respondents in Austria since 50% of them live in Vienna and might be familiar with new mobility technologies. Perceived safety positively and significantly impacts behavioural intention toward the Smart e-bike in Belgium and the Netherlands; this could probably be due to the dense cycling infrastructure and the high penetration of e-bikes in these countries. In contrast, perceived safety has no significant impact in Austria and Greece. A possible explanation is that Austria and Greece have fewer cycle paths than the other countries. Social status is slightly negative in the Netherlands, probably due to the high penetration rate of e-bikes and cycling (de Haas & Huang, 2022; Goel et al., 2021). High income has mainly negative and no significant impact across the countries. This relationship may partly be explained by the fact that high income people are described with high car ownership (Buehler et al., 2016). High digital skills and experience of crashes positively impact behavioural intention in the Greek sample.

### 3.5.2. Theoretical implications

From a theoretical point of view, this study is the first and contributes to existing knowledge investigating user acceptance of the Smart e-bike by utilising an extension of the UTAUT2. Thus, while UTAUT2 is one of the most comprehensive psychological frameworks so far, adjustments are needed to capture the different objectives of new, state-of-the-art technologies better (Kapser et al., 2021; Nordhoff et al., 2020a). The present study shows that the UTAUT2 model can be applied to new smart cycling technologies and explain users' behavioural intentions by integrating new constructs, such as perceived safety. Moreover, this study confirms that perceived safety and experiences with crashes are essential factors which explain behavioural intention to use Smart e-bikes.

An important takeaway of this study is that while the UTAUT2 and SEM are widely used in the transportation domain, making comparisons among groups is not well-established in the literature. The analysis of the measurement invariance undertaken in this paper contributes to the literature by extending our knowledge of multigroup comparisons in the transportation domain. Studies in transportation typically do not examine measurement equivalence among cross-country or multigroup analyses, creating uncertainty about whether comparing the latent variables across groups/countries measures the same objects. This study shows that MI is essential in multigroup analysis to ensure meaningful group comparisons. We obtained scalar invariance for the smart Pedelec and smart Speed-Pedelec comparison and metric invariance for the country's comparison, which are satisfactory levels to allow comparisons among groups. This allowed us to proceed properly with the multigroup analysis and draw firm conclusions among countries. Finally, the model used in this study indicates that different psychological factors better fit and explain behavioural intention due to the cultural differences among the selected countries. Thus, the cross-cultural comparison allowed us to examine the differences between countries and better understand the factors influencing users' acceptance of the Smart e-bike.

### 3.5.3. Practical implications

From the practical point of view, this study shows that performance expectancy was the most important construct of behavioural intention across most countries, followed by hedonic motivation and perceived safety. Thus, improving the characteristics of the Smart e-bike related to these constructs will be beneficial in promoting it. However, our analysis found variability among the constructs that impact users' intentions between countries, hence, it is important to interpret the results carefully since different factors affect the behavioural intention to use and buy a Smart e-bike. For instance, performance expectancy was a significant construct in all countries, meaning that participants in this study expect that the Smart e-bike will enhance their lives. This implies that, bicycle manufacturers and designers should pay more attention to users' needs in designing and promoting Smart e-bikes compared to users' regular e-bikes. Hedonic motivation strongly influences the behavioural intention to use and buy the Smart e-bike in all countries but not in Austria. Hence, improving the Smart e-bike's characteristics, which make it more enjoyable and pleasurable, would be an advantage in all countries except Austria. Social influence was found positive in Austria, Greece, and the Netherlands; therefore, promoting the Smart e-bike using social pressure regarding its positive features would positively influence its promotion in these countries. Perceived safety influences Belgium and Dutch respondents, indicating that the Smart e-bike has a higher acceptance as it is perceived as safer. Given the significant strength of the perceived safety construct in these countries, it may be beneficial for policymakers to foster the Smart e-bike as a comfortable and safe mode of travel. Some countries had particularly low levels of perceived safety, e.g., Greece. Smart e-bikes alone cannot meet the fundamental safety needs of cyclists. The provision of safe infrastructure and other steps to ensure the safety of vulnerable road users is needed as a prerequisite. However, providing safer infrastructure may encourage cycling uptake, and for some, smart e-bikes may still be attractive. Policymakers may want to promote smart e-bikes. Furthermore, effort expectancy has a lower impact on behavioural intention; hence, the ease of use of the Smart e-bike is a principal factor for its promotion. Policymakers should consider the context of areas in defining where and for whom it may be appropriate to promote the smart e-bike. For instance, in the Netherlands, a high proportion of crash fatalities lay to cyclists older than 75 (Statistics Netherlands (CBS), 2023). Thus, promotion in this group might be beneficial since people will continue to use active travel modes with extra safety features.

Potential Smart e-bike users need to be convinced about the performance of a bike before they consider buying one. This can be done by developing and testing prototypes, allowing potential users to test the Smart e-bike's features and realise its usefulness. For this, a collaboration between governments and bicycle manufacturers could benefit society, first by providing help for field trials and later by subsidising such safety functionalities. Furthermore, the results of this study suggest that policymakers should consider the national context to better decide which features of Smart e-bikes meet local needs and based on these, decide which functionalities might be appropriate to be promoted.

To conclude, encouraging the acceptance of the Smart e-bike and other smart technologies on bicycles can benefit society and improve sustainability in cities since such systems can support users and reduce crash risk (Kapousizis et al., 2022; Oliveira et al., 2021). This requires governments and municipalities' support to prioritise the development of digital infrastructure, an underlining factor of performance expectancy related to the Smart e-bike's functionalities, such as B2I communication. Also, we recommend that countries lacking cycling infrastructure prioritise improvements in physical infrastructure since the lack of infrastructure is a negative factor in users' intention to use the Smart e-bike. Thus, the introduction of Smart e-bikes should go hand in hand with the development of dedicated cycling infrastructure.

### 3.5.4. Limitations and future work

This study investigated users' acceptance of the Smart e-bike in a hypothetical setting, hence users' hands-on experience with these bicycles is not yet captured. This is a common limitation with studies exploring the user acceptance of emerging technologies. In addition, the sample of this study comes mainly from e-bike users and people willing to buy one. While we chose to get more reliable results at this time, we recommend further research to survey the entire population and investigate whether such technologies can influence people who do not cycle to switch to e-bikes. Also, the sample size differs among the countries, which might impact the results for the cross-country comparison. Furthermore, this study investigates the behavioural intention to use a Smart e-bike, hence, the willingness to pay for such technologies is still unknown. This is an important factor for investigation since it can determine the penetration rate of such bicycle features and help designers build more suitable ones. In future work, we will examine if stated choice experiments will help to better understand people's preferences regarding different smart e-bike functionalities. In addition, since the Smart e-bike examined here is not on the market yet, it is relevant to examine the differences between ex-ante preferences and user acceptance after riding smart e-bikes in future field trials and/or simulation environments. Human-machine interaction is another point for further research to prevent users from getting distracted by such systems, potentially increasing crash risks. Hence, designing the Smart e-bike while considering the communication of the systems with the users and under different traffic situations is a key element in the introduction of Smart e-bikes. While this study focused on users' acceptance of bicycle technologies, the automotive industry also examines Bicycle-to-vehicle communication. This is one of the many scenarios for improving the future of urban transport, however, the arguments for the digital conspicuity of other road users through devices such as smart e-bikes should be stronger. Many studies have investigated this, which could further improve cycling safety, and there is room for further research on user acceptance and willingness to pay on this topic. Lastly, another potential avenue for future research is to investigate to what extent factors such as the topographical and climate characteristics of these countries influence users' acceptance of Smart e-bike.

## 3.6. Conclusion

This study provides the first extensive assessment of behavioural intention to use the Smart e-bike as a potential solution to reduce e-bike crashes and improve comfort. We employed a comprehensive tailor-made framework based on the UTAUT2 to analyse the survey data collected from five European countries. Our key findings are summarised below:

- Six psychological constructs were tested; however, the results prove that only three of them (performance expectancy, hedonic motivation, and perceived safety) significantly influence behavioural intention to use Smart e-bikes in the aggregate sample. Among other variables, age and people who had experienced crashes have a positive and significant effect on behavioural intention.
- The cross-country analysis clearly indicates that the constructs influencing behavioural intention on Smart e-bikes are heterogeneous across the five countries. This supports the idea that different psychological constructs play a key role among countries.
- Due to inconsistencies in behavioural intention across countries, customised actions per country must be taken to promote Smart e-bikes.

In addition, we further examined the behavioural intention to use Smart e-bikes in the subdivision of Smart Pedelec and Smart Speed-Pedelec in the aggregated sample:

- The multigroup analysis revealed that behavioural intention for Smart Pedelec is stronger compared to Smart Speed-Pedelec, with five constructs supporting this.
- It is evident that both performance expectancy and hedonic motivation are dominant positive constructs. However, even though more constructs influence behavioural intention for the Smart Pedelec, these are the only constructs affecting the intention to use the Smart Speed-Pedelec.

The findings offer new insights into the deployment of new technologies on e-bikes and will be of interest to different stakeholders, such as policymakers and industry. Industry can integrate these insights to develop and design such innovative systems, and policymakers can modernise traffic lights and implement digital infrastructure to achieve B2I communication to foster Smart e-bikes penetration rate (Kapousizis et al., 2022).

# Chapter 4

# Willingness to Pay for Smart Technologies Enhancing Cycling Safety on e-bikes: A European-Based Latent Class Choice Analysis

This chapter is based on: Georgios Kapousizis, Mehmet Baran Ulak, Karst Geurs & Paul J. M. Havinga: Willingness to Pay for Smart Technologies Enhancing Cycling Safety on e-bikes: A European-Based Latent Class Choice Analysis. Submitted for publication in Transportation Research Part A: Policy and Practice. *(2nd review round)*.

## 4.1. Introduction

The number of Europeans who use bicycles has risen and will continue in the coming years due to the increasing living costs and the climate change-oriented tendency towards more sustainable mobility solutions (Buehler & Pucher, 2021; Schleinitz & Petzoldt, 2023; Shimano, 2022). The shift of car owners to alternative mobility modes, especially bicycles, is even evident in countries with heavy automobile industries, such as Germany (PWC, 2017). Many countries with low as well as with high cycling rates (e.g., the Netherlands) are building new cycling infrastructure or improving the existing one to promote cycling with a common target to reduce CO2 emissions and enhance city sustainability (Buehler & Pucher, 2023). New types of bicycles, such as the electric bicycles (e-bikes) already overrun the bicycle market, stimulating people to ride more and further thanks to motor assistance (Fishman & Cherry, 2016).

In Europe, more than 5 billion e-bikes were sold in 2023, five times more than in 2016, and the market share has increased up to 55% in the Netherlands, 49% in Austria, 48% in Germany, and 47% in Belgium since 2015 (Bike Europe, 2023; Statista, 2023). In addition, some recent studies found that in the Netherlands, the share of e-bikes increased from 5% to 37% of the total cycling kilometres ridden in the past ten years (2012-2022). However, in parallel to the increase in cycling, the number of bicycle crashes has also increased, especially those involving e-bikes, although there is an ongoing reducing trend in the number of motor-vehicle crashes (European Transport Safety Council, 2020; Schepers et al., 2020; SWOV, 2022b). Many studies have been conducted on the safety-related aspects due to the growing number of e-bike crashes (Haustein & Møller, 2016; Schepers et al., 2020; Vlakveld et al., 2021). It has been found that e-bike users are more likely to be involved in crashes than conventional bicycle users. A naturalistic study conducted by Huertas-Leyva et al. (2018) found that e-bikes move up to 5 km/h faster than conventional bicycles, which influences their riding behaviour as well as their ability to predict potential hazards. However, the evidence of e-bike crash risk is mixed; on the one hand, Schepers et al. (2020) found that e-bike crash risk is almost equal to that of conventional bicycles, at least in the Netherlands. On the other hand, Gadsby and Watkins (2020); Petzoldt et al. (2017) found that the unfamiliarity of e-bike users and the underestimation of e-bike speeds by vehicle drivers could lead to a higher number of collisions. Nevertheless, the recent annual report published by the ITF (2023) shows that while the cyclists' fatalities decreased by almost 3% in 2022 compared to 2017-2019, the number of e-bike user fatalities increased for the same year. In detail, 55% of cyclist fatalities in Switzerland were e-bike users, around 40% in Belgium and Germany, and 34% in the Netherlands, raising concerns regarding e-bike users' safety (ITF, 2023). Additionally, the number of single-e-bike crashes has increased as well (Panwinkler & Holz-Rau, 2021). Note that we use the term "crash" rather than "accident" for any road collision.

### 4.1.1. Emerging technologies

In an attempt to increase cycling safety, comfort and reliability, a growing stream of research focuses on emerging technologies consisting of sensors, radars and advanced information and communication technologies (ICT) embedded in bicycles, mainly on e-bikes (Kapousizis et al., 2022; Oliveira et al., 2021). These technologies vary in functionalities (i.e., anti-theft and safety assistance systems) and technology readiness levels. For instance, anti-theft systems are already commercially available and gaining ground in the market (Nikolaeva et al., 2019; Sparta, 2016). However, systems that influence cyclists' safety are still under development, with only a small portion of those, with restricted functionalities, on the market. For example, a rear-side radar with a light that warns cyclists of vehicles approaching from behind already exists (Garmin, 2023). Safety experts see the potential influence of such technologies on cycling safety, and bicycle manufacturers are interested in filling the potential market gap. These systems can warn cyclists in dangerous situations and/or assist them in avoiding crashes (Boronat et al., 2021; Kapousizis et al., 2022).

Even though there is rapid deployment of safety-enhancing bicycle technologies in research environments, such technologies are not widely commercially available yet. Various reasons affect their penetration rate and their establishment in the market. The users' acceptance and willingness to pay for such technologies are key elements in market penetration. In the transportation domain many studies have investigated technological adoption and user preferences and willingness to pay for electric vehicles, alternative fuel vehicles, autonomous vehicles, and safety improvements in air travel (Ferguson et al., 2018; Hackbarth & Madlener, 2016; Molin et al., 2017; Wang et al., 2021). However, few studies have examined emerging bicycle technologies. Only recently Kapousizis et al. (2024) investigated the user acceptance of a smart e-bike and found that different sociodemographic characteristics explain people's acceptance. Furthermore, emerging bicycle technologies might be adopted differently by people who favour new technologies and people who live in areas with low/high cycling rates and available infrastructure. Therefore, it is essential to understand people's preferences and willingness to pay before the market introduction of such technologies for bicycles.

### 4.1.2. Research objective

To address the aforementioned knowledge gaps, the objectives of this paper are three-fold: 1) investigating the willingness of e-bike users to pay towards smart bicycle technologies enhancing cycling safety, 2) examining the role of respondents from different countries, which vary in cycling infrastructure, on preferences regarding the smart bicycle technologies, and 3) identifying the sociodemographic variables that explain the differences among these preferences. For this purpose, a survey was conducted in five European countries (Austria, Belgium, Germany, Greece, and the Netherlands), and user preferences were collected through a stated choice experiment. To the authors' knowledge, this paper is the first study in the literature to investigate the willingness to pay for smart bike technologies with a large-scale European survey.

The rest of this paper is organised into five sections. Section 4.2 describes the methodology, data collection, and survey design. Section 4.3 presents the collected data, model results, and the willingness to pay for smart bicycle technologies, followed by the discussion and policy implications in Section 4.4. Section 4.5 concludes the paper.

## 4.2. Methodology

### 4.2.1. Survey and data collection

A web-based survey was conducted in five European countries: Austria, Belgium, Germany, Greece and the Netherlands. The questionnaire can be found in Appendix E. The survey was designed and distributed using the Lighthouse Studio platform (Sawtooth Software, 2022) and hosted locally at the University of Twente. The survey was administered in full compliance with the General Data Protection Regulation (GDPR). Lastly, the Natural Sciences and Engineering Sciences (NES) of the University of Twente gave ethical approval for this survey.

The survey was distributed between November 2022 and January 2023 in the official language of each country to avoid bias and increase national representation. Hence, the survey was translated into five languages (Dutch, English, German, Greek, and French). Native speakers checked the accuracy of the translation in each language. The survey was distributed via the official local European Cyclists' Federation (ECF) members and their social media to recruit people who own or are willing to buy an e-bike. In addition, we used a mixed-method approach in the Netherlands by distributing the survey online and on-site. The on-site distribution occurred in the bicycle experience centre of a major Dutch bicycle manufacturer, which welcomes visitors from all over the country to test different types of bicycles. The reason behind the choice of the mixed-method distribution was to recruit people who are in the process of buying an e-bike. In addition, a second group of respondents was recruited through panel market research (Panelclix) to ensure representative samples. In total, we recruited 83% of the respondents via the online distribution in all countries, 3% from our on-site visits and 14% via the Panelclix for the Netherlands.

The five countries were chosen based on the variety of cycling infrastructure quality and cycling rates among them. On the one hand, the Netherlands is known for its high-quality cycling infrastructure, extended network, bicycle culture and high bicycle rate. Also, in the Netherlands, most citizens use a bicycle as a common mode of everyday transportation. On the other hand, Austria, Belgium, and Germany have medium cycling infrastructure and bicycle rates, and they cycle mostly for recreational purposes. Lastly, Greece has a scarce, low-quality infrastructure network and a low cycling rate (European Commission, 2020). Thus, this allows us to investigate the role of these differences on preferences and WTP.

The main part of the survey was the Stated Choice (SC) experiment; hence, it was structured accordingly. Respondents first received a short introductory text explaining the aim of the survey. The rest was split into three parts: 1) screening questions and travel behaviour, 2) a short explanation and illustration of what an e-bike with smart technologies looks like and the six SC tasks, and 3) sociodemographic questions. The survey was designed to explore individuals' preferences for smart features, which increase safety and to capture other characteristics that might influence their choices (e.g., perceived safety, traffic density).

### 4.2.2. Stated choice design

A complete enumeration experimental design, which produces a most nearly orthogonal design, for the SC scenarios, was developed using the Lighthouse studio (Sawtooth Software, 2022).

The choice for the specific design was made since, in the test of the ratio of strengths of the designs, complete enumeration had a better fit and lower standard errors. The attributes and attribute levels used in this choice experiment are mainly derived from Kapousizis et al. (2022). In particular, the attributes in this SC included smart technologies/functionalities for e-bikes that could assist users in increasing their safety while cycling. These attributes are listed below:

- *Assistance systems* that detect incidents and send emergency alerts to hospitals or to saved contacts and/or navigation systems offering routes with low crash risk.
- *Automatic speed adjustment systems* that automatically adjust the e-bike speed to comply with the speed limits, reduce speed in critical locations, and maintain a safe distance from the preceding vehicles.
- *Collision avoidance systems* that can detect obstacles and warn cyclists to avoid a collision.
- *Cost* is the price that needs to be paid to purchase these systems.

Each attribute was divided into three levels, while "Cost" was divided into four levels. Table 4.1 presents the attributes and their levels for the choice tasks.

We opted for a realistic SC setup by setting prices that could represent the potential future market estimation. Thus, the sale price used in this design ranged from €400 to €1000. The price estimation for each functionality/system was decided with the support of bicycle industry experts, representing an increase of 16% to 40% compared to the average price of an e-bike sold in the Netherlands in 2022 (de Haas & Kolkowski, 2023). In addition, we imposed some constraints so that attribute levels with high-end functionalities were presented to respondents with higher prices. This choice was because we aimed to test a hypothetical scenario that could reflect the future market and estimate robust WTP values. Finally, 50 distinct SC scenarios were developed and implemented as 25 blocks of two scenarios. Each respondent received six "unlabelled" SC tasks and had to choose among two alternatives and the opt-out choice (no choice). Thus, we analysed 7410 observations (i.e., 1235 respondents * 6 SC tasks). Also, we did not pivot the SC; hence, participants received the same values.

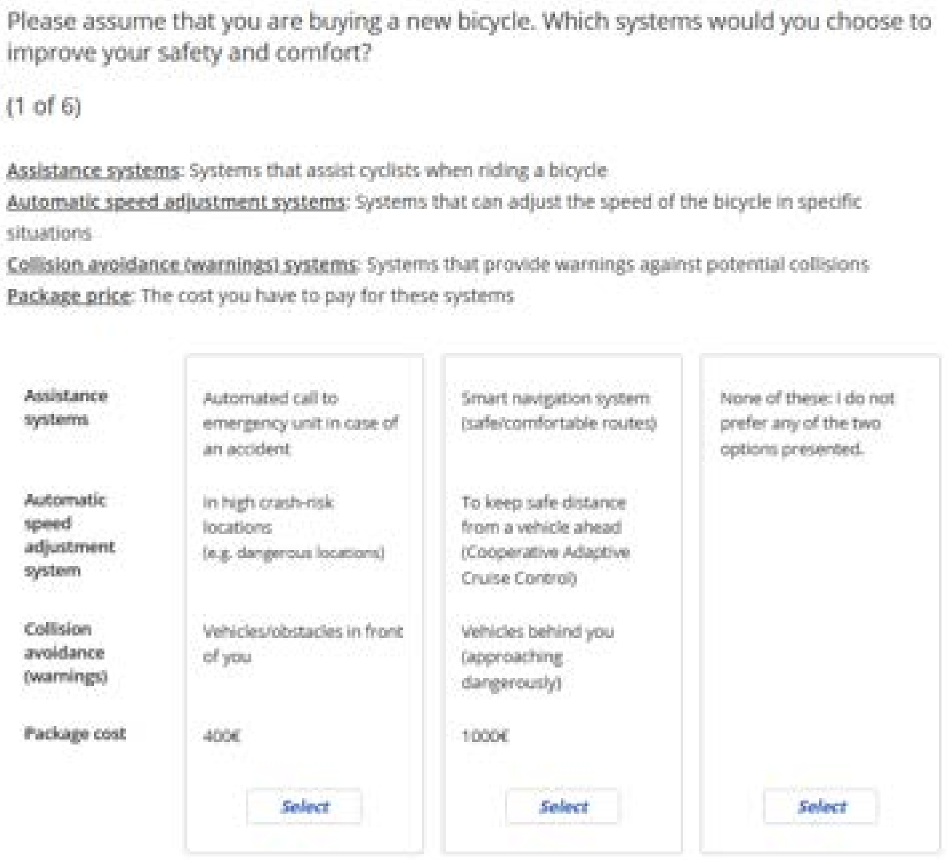
Since respondents might be unfamiliar with new technologies on e-bikes, we presented a short text description of an e-bike with new technologies and an illustration of what an e-bike with such features would look like. In addition, respondents received an explanation of the choice experiment as follows:

*"In this part of the survey, you have to imagine that you are about to buy a new e-bike which costs around €2000. We will present six different scenarios of bicycles to you, which vary in the safety level, functionalities and price. Please mark the bicycle that best fulfils your expectations by ticking the "select" button below."*

Figure 4.1 presents a SC scenario. The order of the attributes was the same for all tasks to avoid any burden to the respondents. The price for the e-bike stated in the SC was based on the average cost that consumers pay in Europe, which is €2000, (Bike Europe, 2023).

**Table 4.1 Attributes and levels for the choice tasks**

| Attributes | Attribute levels |
|---|---|
| Assistance systems | Automated call to the emergency unit in case of an accident. |
| | Automated call to your emergency contacts in case of an accident |
| | Smart navigation system (safe/comfortable routes) |
| Automatic speed adjustment systems | In busy streets, cycle paths, near schools, etc |
| | In high crash-risk locations (e.g., dangerous locations) |
| | To keep a safe distance from a vehicle ahead |
| Collision avoidance systems | Vehicles/obstacles in front side |
| | Vehicles behind you (approaching dangerously) |
| | Blind Spot detector (left and right assist) |
| Cost | €400 |
| | €600 |
| | €800 |
| | €1000 |



Please assume that you are buying a new bicycle. Which systems would you choose to improve your safety and comfort?

(1 of 6)

Assistance systems: Systems that assist cyclists when riding a bicycle

Automatic speed adjustment systems: Systems that can adjust the speed of the bicycle in specific situations

Collision avoidance (warnings) systems: Systems that provide warnings against potential collisions

Package price: The cost you have to pay for these systems

| | | | |
|---|---|---|---|
| Assistance systems | Automated call to emergency unit in case of an accident | Smart navigation system (safe/comfortable routes) | None of these: I do not prefer any of the two options presented. |
| Automatic speed adjustment system | In high crash-risk locations (e.g. dangerous locations) | To keep safe distance from a vehicle ahead (Cooperative Adaptive Cruise Control) | |
| Collision avoidance (warnings) | Vehicles/obstacles in front of you | Vehicles behind you (approaching dangerously) | |
| Package cost | 400€ | 1000€ | |

**Figure 4.1: A choice task scenario**

### 4.2.3. Modelling approach-Latent class choice model

The main aim of this study is to capture people's preferences and investigate willingness to pay (WTP) for smart technologies to increase safety on e-bikes. For this purpose, a Stated Choice (SC) method was used to ask people to make choices and trade-offs, among hypothetical alternatives to examine their preferences (Train et al., 2019). Discrete choice models (DCM) have been used for many years to predict people's choices based on SC experiment data. In transportation, we see studies focus on the trade-off between travel time and cost, in order for researchers to estimate the value of time (Ben-Akiva & Lerman, 1985). Various applications of DCM range from route choice preferences to willingness to pay for electric vehicles, alternative fuel vehicle, autonomous vehicles, and safety improvements in air travel (Ferguson et al., 2018; Hackbarth & Madlener, 2016; Molin et al., 2017; Wang et al., 2021).

DCMs are also powerful tools for demand forecasting and predicting users' adoption of specific travel modes and technologies. Thus, a survey was designed with its main core being the SC experiment, first to collect peoples' preferences for smart bicycle technologies and second to extract sociodemographic characteristics, attitudinal questions, and geographical variables. Then, we estimated respondents' preferences, derived the WTP for different attributes, and captured random heterogeneity among people by linking the choices of respondents with the abovementioned variables.

Choice analysts seek to assess random heterogeneity across the analysed sample (Hess, 2014). Due to the nature of the study and the collected data across five countries, which vary in cycling behaviour as mentioned above, we presume that there is heterogeneity in our sample. Thus, a Latent Class Choice Model (LCCM) was deemed to be the most appropriate method to capture the heterogeneity among individuals (Ferguson et al., 2018; Hess, 2014; Molin et al., 2016; Zito & Salvo, 2012). The LCCM captures discrete random heterogeneity and incorporates the panel effects since it is a mixed model (Greene & Hensher, 2003; Hess, 2014). LCCMs have been used in choice modelling for many years to analyse individual heterogeneity (Hess, 2014; Kamakura & Russell, 1989), and recent studies see advantages over mixed logit models (Greene & Hensher, 2003; Keane & Wasi, 2012; Potoglou & Kanaroglou, 2007). Araghi et al. (2016); Molin and Maat (2015) examined the price of walking trade-offs for bicycle parking and the air travellers' preferences; Zito and Salvo (2012) investigated the WTP for transit user information in Palermo, Italy; Hackbarth and Madlener (2016) estimated a LCCM to calculate the WTP for alternative fuel vehicle characteristics; Ferguson et al. (2018) analysed the WTP for electric vehicles at a national level in Canada, while Rossetti and Daziano (2022) examined the relation between user's health status and preferences for cycling infrastructure in New York City, USA.

The LCCM uses a probabilistic model to allocate respondents into different classes, where a respondent (n) belongs to a class (k) with a probability $\pi_{n,s}$ where $0 \leq \pi_{n,s} \leq 1 \; \forall n, s$ and $\sum_{s=1}^{S} \pi_{n,s} = 1$ . The estimation of the LCCM is based on the multinomial logit (MNL) model (McFadden, 1972), however, other structures can be adopted (Hess, 2014). Specifically, we observe $(T_n)$ choices for a respondent $(n)$, with alternatives $(j_n)$, where an alternative $(j_{n,t})$ is chosen in a choice task $(t)$. Then the model is given by:

$$P_{nit}(\beta, \chi_{nt}) = \frac{e^{V_{int}}}{\sum_{j=1}^{J} e^{V_{jnt}}}, \tag{1}$$

where $(i)$ is the probability of a respondent choosing an alternative, conditional on $(\beta)$ and $(x_{nt})$ is a vector of all attributes.

Following the notation of Hess (2014) eq.2 represents the probability of a respondent $(n)$ choosing alternative $(i)$ in a choice task $(t)$, which is conditional to $(n)$ falling in class $(s)$.

$$L_n(\beta,\pi) = \sum_{s=1}^{S} \pi_{ns}\left(\prod_{t=1}^{T_n} P_{nit}(\beta_s)\right), \tag{2}$$

The main advantage of a LCCM is that it incorporates random heterogeneity in respondents' choices by linking them to different classes; thus, the analyst needs to specify the number of appropriate classes (s). In choice modelling, sociodemographic characteristics can explain part of the heterogeneity, but a significant proportion of components remain unobserved. With $(z_s)$ denotes a vector of characteristics for a respondent $(n)$, the probability of respondent n falling into class k is given by:

$$\pi_{ns} = \frac{e^{\delta_{s+g(\gamma_{s,}z_n)}}}{\sum_{l=1'}^{S} e^{\delta l + g(\gamma_l, z_n)}}, \tag{3}$$

where $(\delta_s)$ is a class-specific constant, $(\gamma_s)$ is a vector of parameters to be estimated, and $(g)$ corresponds to the functional form of the utility function in the class allocation model

## 4.3. Results

### 4.3.1. Data and descriptive statistics

In total, 2475 individuals completed the survey. However, since this study aims to investigate the WTP, only people who own and/or are interested in buying an e-bike within the next five years participated in the SC. Thus, since 1103 respondents stated they did not own or want to buy an e-bike, they were excluded from the analysis. Finally, a total sample of 1372 respondents remained. This target group was considered to reflect the perspective of collecting responses from people interested in cycling, especially on e-bikes, rather than collecting data from people who are not interested and/or unfamiliar with e-bikes.

Lighthouse Studio tracks the total time spent on the survey and the time spent on the SC tasks. This information was used to assess respondents' attentiveness. A threshold of at least one minute was chosen for the SC experiment part, since this timing was deemed necessary to complete the survey properly after piloting. Respondents who spent less than one minute, a total of 137, were excluded from the analysis. Therefore, 1235 responses remained, however, the sample is still sufficiently representative. Table 4.2 shows the sample characteristics. In our sample, 54% (670) of all the respondents were male, 59% (726) were highly educated, and 43% (533) earned monthly salaries above the average. Almost 59% (725) of the respondents came from the Netherlands, 15% (188) from Belgium, 11% (139) from Greece, 9% (112) from Germany and 6% (71) from Austria. In detail, the population distribution differs in our sample. Males are overrepresented in Austrian, German and Greek samples as well as respondents who earned a university degree, including Belgians. In contrast, the Dutch sample is equally distributed. In addition, the average age of the respondents from Austria, Germany and Greece are 52, 51, and 45 years old, respectively, while for the Belgian and Dutch samples, the average age is 56 and 58 years old, respectively. The Greek sample is the youngest among the five countries. Furthermore, the Dutch sample has a higher concentration (65%) of respondents who earn less than the average income in the Netherlands. In comparison, there is a slight concentration of respondents who earn more than the average for Austria (54%), Belgium (58%)

and Germany 54%. The Greek sample is equally distributed. Regarding the geographical distribution of the respondents, there is a greater concentration of respondents living in highly populated areas, especially in Germany (78%) and Belgium (69%). In contrast, the respondents from Austria, Greece and the Netherlands are almost equally distributed geographically.

Lastly, as was expected, 97 % of Dutch respondents live in areas with a high level of available cycling infrastructure, following respondents from Belgium with 85%. Of the respondents from Austria and Germany, 79% live in areas with a high level of available cycling infrastructure, and none of the Greek respondents live in areas with high cycling infrastructure. The Dutch sample is comparable to an earlier study investigating the purchase and use of e-bikes in the Netherlands conducted by de Haas and Huang (2022) (Kennisinstituut voor Mobiliteitsbeleid, 2021). There is no available database for cyclists to compare our samples for the rest of the countries.

During the survey, respondents were asked to answer sociodemographic questions, questions related to their familiarity with new technologies and their cycling experience, and to give their living area's postcode (4 digits). In total, we obtained 1184 correct postcodes out of 1235 respondents. In detail, we were able to identify 70 postcodes from Austria, 187 from Belgium, 82 from Germany, 125 from Greece and 720 from the Netherlands. Hence, we linked the postcodes with the Nomenclature of Territorial Units for Statistics 3 (NUTS3) dataset (Eurostat, 2023). Similarly, we matched the available cycling infrastructure of each postcode using the Open Street Map data (OSM) (OpenStreetMap, 2023). We associated the postcodes we received from each respondent and conducted a spatial analysis by linking each postcode to the geographical area of the NUTS3. We used a buffer analysis based on each postcode's point for the available cycling infrastructure. Firstly, we used a buffer zone analysis of 10 km for each postcode. Then, we estimated the length of all available cycling infrastructure within each buffer zone. Thus, we extracted information about the population density (NUTS3) and available cycling infrastructure (OSM) in each respondent's local area. In detail, 44% (509) of the respondents lived in low population density areas (less than 462 people per km2) and 17% (406) in areas with low cycling infrastructure density (less than 100km length of available cycling infrastructure within the buffer zone 10km). Figure 4.2 shows the population and cycling infrastructure density for our final sample; each dot represents a respondent. It becomes apparent that most of the Greek respondents live in areas with low or no cycling infrastructure, while a portion of them live in areas with a high population density. In contrast, most of the Dutch respondents live in areas with around 800 people/km2 and high cycling infrastructure. A high number of Austrian respondents live in high density population areas and with a relatively high number of available cycling infrastructure (more than 100km per 10km buffer zone). Respondents from Belgium and Germany live mainly in areas with a high number of available cycling infrastructure and population density of around 900 and 1500 people/km$^2$, respectively.

### 4.3.2. Model

We used the Apollo package (Hess & Palma, 2019) in R (R Core Team, 2023) to estimate the LCCM and the WTP. Initially, we estimated a MNL model and then a series of LCCMs to determine the optimal number of classes in our model. Models with three or more classes returned high standard errors, and thus, a model with two classes was chosen due to better model fit. In general, a large number of classes in a model can be problematic and return insignificant coefficient values (Hess, 2014).

**Table 4.2 Sample composition and socioeconomic characteristics**

| Variable | Austria | Belgium | Germany | Greece | Netherlands | Total |
|---|---|---|---|---|---|---|
| Number of respondents | 71 (6) | 188 (15) | 112 (9) | 139 (11) | 725 (59) | 1235 (100) |
| **Gender** | | | | | | |
| Male | 51 (72) | 99 (53) | 78 (70) | 100 (72) | 342 (47) | 670 (54) |
| Female | 17 (24) | 87 (46) | 33 (29) | 38 (27) | 371 (51) | 546 (44) |
| Non-binary | 2 (3) | 0 (0) | 0 (0) | 0 (0) | 4 (1) | 6 (0) |
| Other/prefer not to answer | 1 (1) | 2 (1) | 1 (1) | 1 (1) | 8 (1) | 13 (1) |
| **Age** | | | | | | |
| 18-29 | 2 (3) | 10 (5) | 10 (9) | 16 (12) | 32(4) | 70 (6) |
| 30-39 | 13 (18) | 24 (13) | 14 (13) | 29 (21) | 80 (11) | 160 (13) |
| 40-49 | 10 (14) | 26 (14) | 16 (14) | 44 (32) | 72 (10) | 168 (14) |
| 50-59 | 23 (32) | 35 (19) | 36 (32) | 34 (24) | 153 (21) | 281 (23) |
| 60-69 | 18 (25) | 60 (32) | 29 (26) | 16 (12) | 201 (28) | 324 (26) |
| >70 | 5 (7) | 33 (18) | 7 (6) | 0 (0) | 187 (26) | 232 (19) |
| **Education** | | | | | | |
| Low (high school or lower) | 25 (35) | 49 (26) | 35 (31) | 37 (27) | 363 (50) | 509 (41) |
| High (univ. degree or higher) | 46 (65) | 139 (74) | 77 (59) | 102 (73) | 362 (50) | 726 (59) |
| **Net monthly income (€/month)** | | | | | | |
| Less than 1000 | 5 (7) | 4 (2) | 8 (7) | 61 (44) | 44 (6) | 122 (10) |
| 1001-1500 | 6 (8) | 9 (5) | 13 (12) | 36 (26) | 77 (11) | 141 (11) |
| 1501-2000 | 7 (10) | 39 (21) | 12 (11) | 15 (11) | 117 (16) | 190 (15) |
| 2001-2500 | 15 (21) | 50 (27) | 17 (15) | 8 (6) | 129 (18) | 219 (18) |
| 2501-3000 | 10 (14) | 29 (15) | 8 (7) | 4 (3) | 103 (14) | 154 (12) |
| 3001-3500 | 7 (10) | 13 (7) | 10 (9) | 3 (2) | 73 (10) | 106 (9) |
| 3501-4000 | 3 (4) | 8 (4) | 7 (6) | 2 (1) | 35 (5) | 55 (4) |
| 4001-4500 | 1 (1) | 5 (3) | 6 (5) | 0 (0) | 17 (2) | 29 (2) |
| 4501-5000 | 1 (1) | 3 (2) | 5 (4) | 1 (1) | 11 (2) | 21 (2) |
| 5000 and more | 1 (1) | 1 (1) | 7 (6) | 1 (1) | 18 (2) | 28 (2) |
| Prefer not to answer | 15 (21) | 27 (14) | 19 (17) | 8 (6) | 101 (14) | 170 (14) |
| **Average country income** | | | | | | |
| Below average | 33 (46) | 79 (42) | 52 (46) | 70 (50) | 468 (65) | 702 (57) |
| Above average | 38 (54) | 109 (58) | 60 (54) | 69 (50) | 257 (35) | 533 (43) |
| **Population density*** | | | | | | |
| Low (0-462) | 36 (51) | 50 (31) | 18 (22) | 72 (58) | 333 (46) | 509 (44) |
| High (463-20.965) | 34 (49) | 113 (69) | 64 (78) | 53 (42) | 387 (54) | 651 (56) |
| **Cycling infrastructure, OSM#** | | | | | | |
| Low (0-100 km) | 15 (21) | 28 (15) | 17 (21) | 125 (100) | 18 (3) | 406 (17) |
| High (>100 km) | 55 (79) | 159 (85) | 65 (79) | 0 (0) | 702 (97) | 1962 (83) |

* Population density refers to people per km$^2$ by NUTS3; # Cycling infrastructure, OSM: available cycling infrastructure based on the Open Street Map dataset; * # the values differ due to the missing postcodes and missing data from the related databases; number in parentheses indicate the percentage (%)

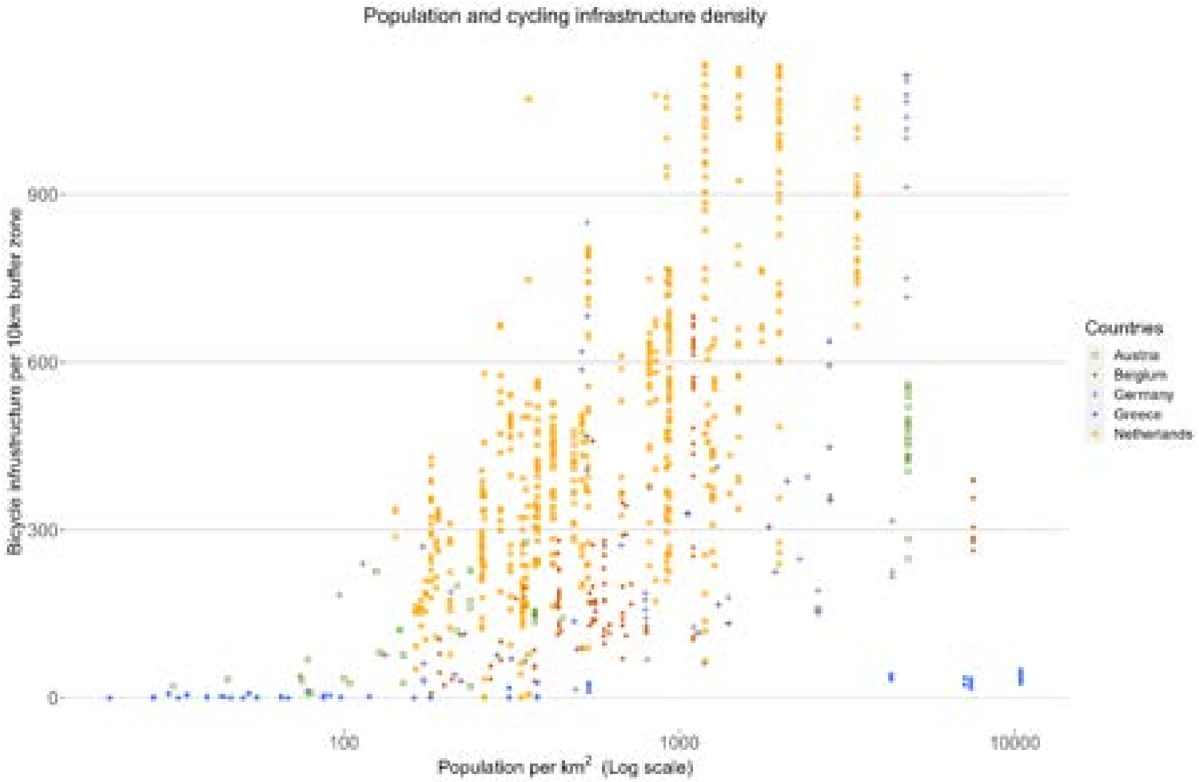


Figure 4.2: Population and cycling infrastructure density per respondent

Note that all the model components were estimated simultaneously and are based on the reference values. In addition, no interactions between attribute levels were made. We used the no-choice option alternative as the base and set it to zero. Table 4.3 shows the choices respondents made per alternative during the SC experiment. The proportion of the respondents' choices for the opt-out alternative is higher for all countries except Greece, where we can see a higher concentration of choices for the opt-out alternatives, namely alternative A or B. This means that respondents from Austria, Belgium, Germany and the Netherlands tend to select the opt-out option; on the contrary, Greek respondents tend to to select a technology. In addition, even though the Dutch sample is overrepresented by 59%, as was mentioned in Section 4.3.1, it does not influence the results of this study significantly due to the lack of significant differences from the other countries.

### 4.3.3. Explanators of class allocation

We used sociodemographic variables, geographical information, and other questions, such as digital skills and whether respondents have been involved in a crash during model estimation, to link individual characteristics with the class allocation model. We made many attempts to include different variables such as gender, safety-related factors (presence of cycling infrastructure, perceived safety), and age during model estimation; however, only four variables were significant and remained in the final model. Table 4.4 presents these variables. All the variables were obtained from the survey. Based on this, we can explain who is more likely to fall into a specific class, Class 1 or Class 2. During the model estimation of the class allocation, we kept Class 1 as a reference and compared it against Class 2.

**Table 4.3 Proportion of respondents' choices across countries**

| Country | Alternative A or B | Opt-out |
|---|---|---|
| Austria | 45.3% | 54.7% |
| Belgium | 46.9% | 53.1% |
| Germany | 44.9% | 55.1% |
| Greece | 68.8% | 31.2% |
| Netherlands | 47.1% | 52.9% |

Sociodemographic characteristics include education level and income, which were extracted from the survey. The variable "Education level (high)" contains only respondents with a university degree and higher. However, for the income, due to the significant differences in wages among the five countries, Greece has the lowest monthly income and the Netherlands the highest, we first obtained the average net income per country (Eurostat, 2022a). We found that the average net monthly income at the time the survey was distributed was €1100 in Greece, €2400 in Austria, €2425 in Belgium, €2830 in Germany, and €2840 in the Netherlands (DSTATIS, 2023; Hellenic Statistical Authority, 2023; StatBEL, 2022; Statistics Netherlands, 2023; Statistik Austria, 2022). Then, we linked the average income with these respondents stated on the survey and created a dummy variable, 1 for those who earn more than the average and zero for those who fall below the average. Regarding the geographical variable, "Country", we asked respondents to indicate their residency. Lastly, for the variable "Other" we asked respondents during their participation in the survey whether they had been involved in a crash in the last three years while cycling, and their digital skills based on smartphone use (Horjus et al., 2022). Note that countries were estimated as categorical variables while all the rest of the variables were transformed into dummy-coded variables due to the nature of the questions. The comparisons were made to the levels displayed in the parenthesis in Table 4.4.

**Table 4.4 List of variables which were considered in the class allocation**

| Variables | Explanation |
|---|---|
| Sociodemographic | |
| Education level (high) | Respondents with at least a university degree |
| Income (high) | Respondents with above-average income in their countries |
| Geographical | |
| Country (AT, BE, GE, GR, NL) | Respondents from different countries |
| Other | |
| Digital skills (high) | People who are using smartphones to pay in a shop or to plan a trip |
| Crash (yes) | People who have been involved in a crash within the past 3 years while riding a bicycle |

Highly educated respondents are more likely to fall in Class 1 – Technology cautious. However, respondents who are characterised as highly digitally skilled tend to fall in Class 2 – Technology prone. It becomes apparent, there is a higher likelihood of respondents from Austria, Belgium, and Germany being assigned to Class 1. Respondents from Greece have an increased likelihood of belonging to Class 2. The Dutch sample, used as a reference, is more likely to fall into Class 1. In addition, having been involved in bicycle crashes increases the likelihood of being assigned to Class 1. Lastly, respondents with high digital skills are more likely to fall into Class 2 – Technology prone. The results from the class allocation model can be found in Table 4.5.

### 4.3.4. Model results

Table 4.5 presents the results of the MNL and the LCCM for the sake of comparison. It becomes apparent that the LCCM has a better fit compared to the MNL model. The adjusted rho squared is 0.2825 for the LCCM model and 0.0835 for the MNL, meaning that the former can better fit the data and explain the variance. Similarly, the loglikelihood for the LCCM has increased by more than 1600 units compared to the MNL model, showing better goodness of fit for the former. We also estimated alternative specific constants (ASC) parameters in both models to account for left-right bias. The LCCM estimated two distinct classes and has superior specifications to the MNL model, including 25 parameters. The Bayesian Information Criterion (BIC) and Akaike Information Criterion (AIC) also show a better fit in the LCCM. In addition, Table 4.5 contains all the parameters tested, with their estimations, standard errors and robust t-ratios, with a significant level of 95%, equal to 1.96. The two classes are: Class 1 - Technology cautious, respondents who do not show a higher preference for advanced technologies, and Class 2 - Technology prone, respondents who have a higher preference for advanced technologies. We discuss the classes below:

**Class 1: Technology cautious.** This class includes more cost-sensitive respondents since it has a negative cost utility (-0.0072) and a low preference for the technologies. We see only two positive coefficients, smart routes, and collision avoidance blind spot, with the smart routes attribute level having a higher coefficient (0.7450) and a significant t-ratio (4.5496) compared to collision avoidance blind-spot with a coefficient of 0.0093. The rest of the attribute levels have negative coefficients, with the automatic speed limit system being negative and significant at a high confidence interval level. This means the latter is the least preferred option among the other attribute levels. In addition, we see that respondents falling in this class have a higher preference for the reference categories for some attributes. Namely, the attribute levels in the automatic speed adjustment systems, automatic speed limit, and automatic speed risky areas have negative values, meaning that the reference category, automatic speed safe distance, is the preferred option. Assistance emergency call is the least preferred option for the attribute assistance systems. Similarly, the attribute level Collision rear side is the least preferred option for the collision avoidance systems.

**Class 2: Technology prone.** This class includes less cost sensitive respondents (-0.0013) and shows that all attributes have positive utilities, meaning there is a higher preference for the technologies than Class 1. Specifically, we see that smart routes, collision avoidance rear-side, and blind spots have positive and significant t-ratios. Both collision avoidance systems have the highest utility in this class (0.2626 and 0.2627), while the assistance smart routes have a utility of (0.2446). Emergency call system, automatic speed limit and automatic speed risky areas systems are still positive but with insignificant t-ratio (below 1.96). Moreover, the cost is the only negative coefficient in this class with a high and significant t-ratio (-7.8445).

## Table 4.5 Model results

| | **MNL (baseline)** | | | **LCCM Class 1** | | | **LCCM Class 2** | | |
|---|---|---|---|---|---|---|---|---|---|
| | Coeff. | Rob. Std.err. | Rob. t-ratio | Coeff. | Rob. Std.err. | Rob. t-ratio | Coeff. | Rob. Std.err. | Rob. t-ratio |
| ASC a | 0.2394 | 0.0941 | 2.5430 | 1.8320 | 0.1245 | 14.7076 | | | |
| ASC b | 0.2083 | 0.1041 | 2.0012 | 1.8418 | 0.12852 | 14.3311 | | | |
| ASC c | 0 (fixed) | NA | NA | 0 (fixed) | NA | NA | | | |
| Choice component | | | | | | | | | |
| **Assistance systems** | | | | | | | | | |
| Assistance emergency unit | 0 (fixed) | | | 0 (fixed) | | NA | 0 (fixed) | | NA |
| Assistance emergency call | -0.0073 | 0.0388 | -0.1896 | -0.1329 | 0.0993 | -1.3382 | 0.0328 | 0.0489 | 0.6716 |
| Assistance smart routes | 0.2313 | 0.0501 | 4.6126 | 0.7454 | 0.1657 | 4.5496 | 0.2446 | 0.0629 | 3.8951 |
| **Automatic speed adjustment systems** | | | | | | | | | |
| Automatic speed safe distance | 0 (fixed) | | | 0 (fixed) | NA | NA | 0 (fixed) | NA | NA |
| Automatic speed limit | 0.1096 | 0.0601 | 1.8241 | -0.3187 | 0.1386 | -2.2990 | 0.0296 | 0.0553 | 0.5352 |
| Automatic speed risky areas | 0.1023 | 0.0426 | 2.4030 | -0.2391 | 0.1399 | -1.7085 | 0.0805 | 0.0577 | 1.4450 |
| **Collision avoidance systems** | | | | | | | | | |
| Collision front side | 0 (fixed) | | | 0 (fixed) | NA | NA | 0 (fixed) | NA | NA |
| Collision rear side | 0.1952 | 0.0416 | 4.6922 | -0.0148 | 0.1055 | -0.1408 | 0.0519 | 0.0511 | 5.1549 |
| Collision blind spot | 0.1997 | 0.0455 | 4.3887 | 0.0093 | 0.1156 | 0.0808 | 0.2627 | 0.0565 | 4.6450 |
| **Cost** | | | | | | | | | |
| Cost | -0.0017 | 0.0001 | -15.0058 | -0.0072 | 0.0004 | -20.1834 | -0.0013 | 0.0002 | -7.7380 |
| Choice component*Variables | | | | | | | | | |
| Constant | | | | Reference Class 1 | | | 0.8857 | 0.4813 | 1.8403 |
| Country level | | | | | | | | | |
| Austria | | | | | | | -0.2143 | 0.2717 | -0.7889 |
| Belgium | | | | | | | -0.0598 | 0.1781 | -0.3357 |
| Germany | | | | | | | -0.1390 | 0.2237 | -0.6215 |
| Greece | | | | | | | 0.9906 | 0.2416 | 4.0994 |
| Netherlands (ref.) | | | | | | | 0 (fixed) | NA | NA |
| Sociodemographic | | | | | | | | | |
| Education (high) | | | | | | | -0.4863 | 0.1347 | -3.6099 |
| Income (high) | | | | | | | 0.5472 | 0.1343 | 4.0739 |
| Other variables | | | | | | | | | |
| Technology friendly | | | | | | | 0.3224 | 0.1370 | 2.3528 |
| Crash | | | | | | | -1.1207 | 0.4731 | -2.3690 |
| Class weight | | | | 52% | | | 48% | | |
| Parameters | | | 9 | | | | | | 25 |
| Final Loglikelihood | | | -7452.04 | | | | | | -5815.76 |
| Adjusted Rho-squared | | | 0.0835 | | | | | | 0.2825 |

(Table 4.5 continued on the next page)

| | | |
|---|---|---|
| AIC | 14922.07 | 11681.52 |
| BIC | 14984.27 | 11854.29 |
| Individuals | 1235 | 1235 |
| Observations | 7410 | 7410 |

ASC refers left-right bias.

### 4.3.5. Posterior class analysis

Posterior class analysis is derived from the choices respondents have made and the sample-level results (Amaris et al., 2021; Greene & Hensher, 2003; Hess, 2014) and reveals further insights into the probability that a person belongs to a specific class. Figure 4.3 presents the posterior analysis and illustrates variations in class allocation considering different variables, mainly derived from questions through the survey. In addition, we used variables related to the population density and the availability of cycling infrastructure, as we mentioned earlier in sub-section 4.2.1

The posterior class allocation shows that 56% of the respondents who belong to the age group between 18-39 fall in Class 2 – Technology prone, while the age group “older than 60” falls by 57% in Class 1 – Technology cautious. Middle aged respondents, between 40 and 60 years old, are more likely to fall in Class 1 (52%). This shows that the elderly hold a more neutral attitude towards new technologies. Regarding the gender effect on the posterior class analysis, we analysed only males and females due to the low number of the other genders; we found that males and females have a higher concentration of Class 1 (51% and 53%, respectively).

Respondents living in high-population-density areas are more likely to fall in Class 1 by 53%. We also compared the posterior share of respondents living in areas with different levels of cycling infrastructure. Based on the OSM data, we found that respondents living in areas with low cycling infrastructure are more likely to fall into Class 2 (63%), while those living in areas with dense cycling infrastructure are more likely to fall into Class 1 (54%).

In addition, we estimated the posterior probability for other variables we obtained from the survey. In detail, in the questionnaire, we asked respondents additional questions about whether they live in areas lacking cycling infrastructure, “Lack infra (survey)”, and whether they had driven a car with Advanced Driving Assistance Systems. Also, we asked respondents with young children whether they carry them on their bicycles. We incorporated these answers into the variables mentioned above and estimated the posterior probabilities for these variables. We found that respondents’ responses to this variable were almost equally distributed among classes, with a favour over Class 1 (51%). Respondents who have used Advanced Driving Assistance Systems (ADAS) are more likely to fall into Class 2 (53%); respondents who carry their children on a bicycle (kid on bike) are more likely to fall into Class 1 (57%). Class 1 is considered cost-sensitive and less likely to favour advanced technologies since only smart routes show a high utility.

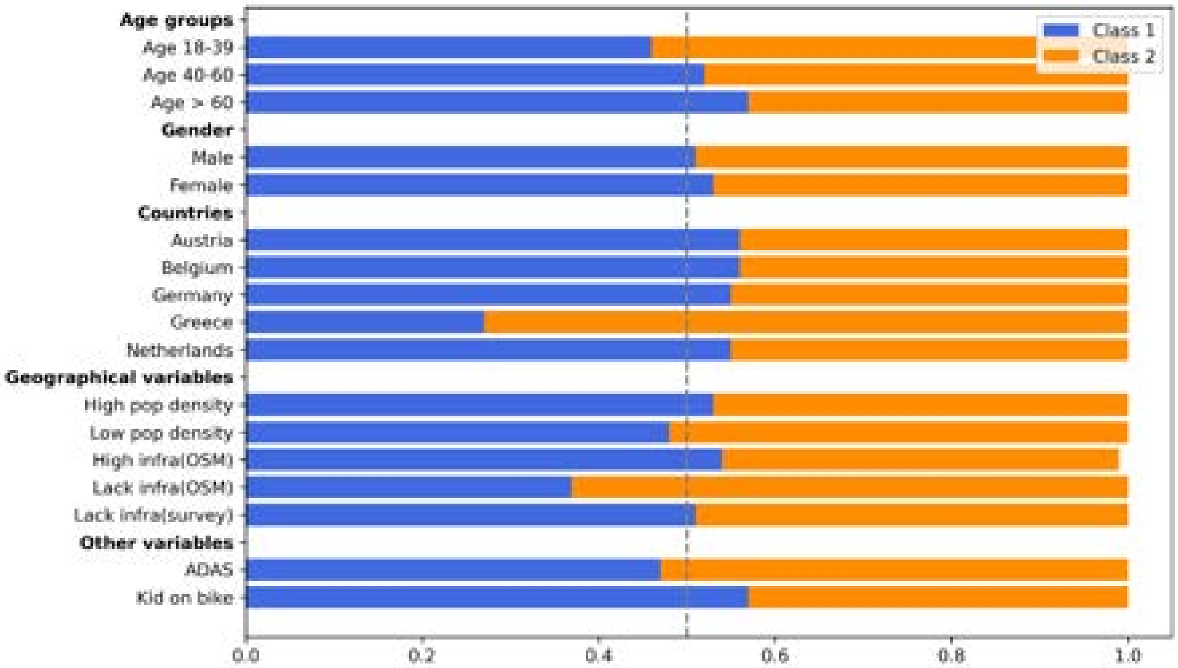


**Figure 4.3: Posterior class analysis**

### 4.3.6. Posterior analysis per country

It is evident that while respondents living in Austria, Belgium, Germany, and the Netherlands are more likely to fall into Class 1 (56%), Greek respondents are more likely to fall into Class 2 rather than Class 1 with more than 73% (Figure 4.3). This is because Greece has very limited cycling infrastructure or cycling culture, so people might seek advanced systems to increase their cycling safety. For the rest of the countries, cycling infrastructure exists and is particularly developed in the Netherlands; hence, people might opt to increase their safety with a smart route system.

We further analysed the distribution of different countries across classes and found that there is a different composition (Table 4.6). Around 58% of our sample is respondents from the Netherlands, followed by respondents from Belgium 15.22%, respondents from Greece 11.26%, respondents from Germany 9% and lastly are respondents from Austria 5.75% of the total sample. We see a higher concentration of Greeks in Class 2, while for the other countries, we found a slightly higher concentration in Class 1.

### 4.3.7. Willingness to Pay

Willingness to pay is described in terms of the ratio of the marginal utility of an attribute (j) and the cost attribute (c). The WTP values are relative to the reference levels (reference), as mentioned in Table 4.5.

It is apparent that Class 2 – Technology prone has mainly higher utilities, which is reflected in higher WTP for all functionalities compared to Class 1 – Technology cautious; thus, Class 2 has a higher expected WTP. Respondents with high income (above the average per country), who have high digital skills, and who are from Greece are more likely to be assigned to this class,

Class 2. However, respondents with high education levels and who have been involved in cycling crashes are more likely to fall in Class 1. Figure 4.4 presents the WTP for each class. More specifically, people who fall in Class 2 are willing to pay around €187 for the assistance smart routes compared to only €25 for the assistance emergency call. People in Class 1 are willing to pay around €104 for a smart route system, they have a negative WTP of €-18 for an emergency call system, meaning they have a higher preference for the reference level, emergency unit system.

**Table 4.6 Country-based posterior analysis**

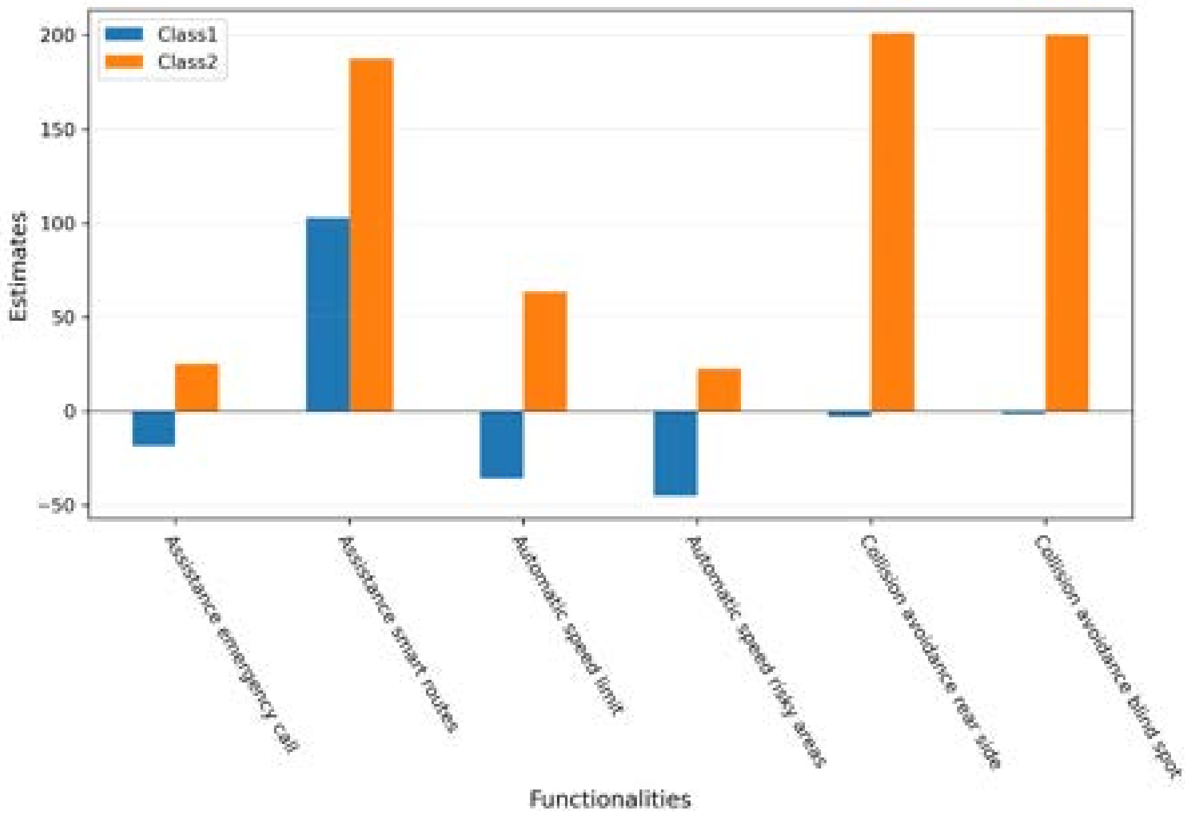
| Country | Class 1 | Class 2 | Sample average |
|---|---|---|---|
| Austria | 6.24% | 5.22% | 5.75% |
| Belgium | 16.38% | 13.97% | 15.22% |
| Germany | 9.67% | 8.42% | 9.07% |
| Greece | 5.93% | 17.00% | 11.26% |
| Netherlands | 61.78% | 55.39% | 58.70% |

Regarding the second set of attributes, automatic speed adjustment systems, people in Class 2 are willing to pay around €62 for a system which adjusts the e-bike speed to the speed limits, namely an automatic speed limit system and around €23 for an automatic speed risky areas system, which intervenes in the e-bike's speed at risky locations. On the contrary, respondents who fall in Class 1 have a higher preference for the reference category, automatic speed safe distance, which turns a negative willingness of around €44 for an automatic speed risk areas system and around €33 for an automatic speed limit system.

Regarding the last set of attributes, the collision avoidance system, again, Class 2 has a higher WTP for the collision avoidance rear side and collision avoidance blind-spot. People who fall in this class are willing to pay around €201 for each of those systems. However, people in Class 1 have almost zero WTP for the same systems, with around €1 for a collision avoidance blind-spot system and €-2 for a collision avoidance rear side system. Again, here, respondents falling in Class 1 have a higher preference for the reference category, collision avoidance front side, compared to the latter, collision avoidance rear side system.

The people who fall in Class 1 are more cost-sensitive (-0.0072), while those in Class 2 are less sensitive (-0.0013). This difference in cost-utility influences the WTP; thus, people in Class 2 have a higher expected WTP for smart functionalities.

To sum up, from these two classes, we see that people in Class 1 favour smart routes, which means they prefer simpler technologies rather than active assistance systems and are willing to pay less overall. Considering that people who have high digital skills are more likely to fall into Class 2, they are more open to using more advanced bicycle technologies. In addition, people from Greece are more likely to fall into Class 2; they seem willing to pay more for active systems such as collision avoidance systems, probably due to the low cycling infrastructure, as it results in more risky roads for cyclists.



Note that the WTP values are relative to the reference levels.

**Figure 4.4: Willingness to pay per functionality in Euros**

In addition, we calculated the conditional probability for the functionalities and Table 4.7 shows the descriptive statistics of the WTP (Hensher et al., 2005). The mean value of assistance smart routes has the highest WTP (€144.44) among the rest of the attributes. Collision avoidance systems, rear side and blind spot have a mean value of €97.48 and €95.69, respectively, while the automatic speed adjustment systems come next with a mean WTP of €12.15 for the automatic speed limit and €12.46 for the automatic speed risk areas. The “Min value” and “Max value” represent the WTP values each functionality can take irrespective of the class allocation.

## 4.4. Discussion

In the following part, we focus on the implications of the findings of this study. This study investigated users’ preferences and WTP for various types of smart bicycle technologies with different support levels (from advanced to less advanced), as proposed in the literature by Kapousizis et al. (2022). We used a combination of these technologies in three main attributes: assistance systems, collision avoidance systems, and automatic speed adjustment systems, and we estimated a LCCM. We accounted for left-right bias in our model, and there was no difference in respondents’ choices for the two alternatives. However, 49% of all choices made were for the opt-out option. While this percentage seems high, we would like to mention that people usually tend to keep a neutral attitude toward emerging technologies and need some time before adopting them, which is also reflected in our study (Rogers, 1995). In relation to this, it is worth mentioning that Greek respondents had a higher percentage; almost 70% of the choices made were for a smart bicycle technology, namely options A and B, rather than the opt-out one. Conversely, for the rest of the countries, the opt-out option was selected by almost 53%. This shows that Greek participants are more likely to choose a bicycle technology compared to the rest.

**Table 4.7 Descriptive statistics of the WTP**

| Functionalities | Mean value | Min value | Max value | SD value |
|---|---|---|---|---|
| *Assistance emergency unit* | - | - | - | - |
| Assistance emergency call | €2.52 | €-18.42 | €25.19 | €20.92 |
| Assistance smart routes | €144.44 | €104.44 | €187.75 | €39.95 |
| *Automatic speed safe distance* | - | - | - | - |
| Automatic speed limit | €12.15 | €-44.15 | €22.53 | €31.98 |
| Automatic speed risk areas | €12.46 | €-33.12 | €61.80 | €45.53 |
| *Collision avoidance front side* | - | - | - | - |
| Collision avoidance rear side | €95.69 | €-2.06 | €201.56 | €97.65 |
| Collision avoidance blind spot | €97.48 | €1.30 | €201.64 | €96.08 |

Note: Functionalities in italics are the reference levels compared to which the WTP was estimated; this is the reason for the negative values.

The LCCM defined two classes, showing that respondents' choices were diverse. In detail, almost half (48%) of the respondents are more likely to use advanced smart bicycle technologies (Class 2). At the same time, 52% of the respondents are more sceptical towards advanced technologies and are more cost-sensitive (Class 1). We included different sociodemographic characteristics, mobility patterns, familiarity with new technologies, and country-related variables in the model estimation to explain heterogeneity among individuals' preferences. However, only a few of these variables were significant and included in the model. Sociodemographic characteristics, higher education, and high income (above-average per country) were significant variables explaining respondents' choices in this analysis. Respondents who are highly educated are more likely to fall into Class 1, which might have to do with the use of bicycles by the different groups and/or their opinions about the usefulness of advanced bicycle technologies. However, this result aligns with a recent study investigating user acceptance of smart e-bikes by Kapousizis et al. (2024), which found that high education does not influence behavioural intention to use and accept smart bicycle technologies. Also, as mentioned above, respondents in our sample are reluctant about smart bicycle technologies. In addition, respondents earning more than their countries' average income are more likely to fall into Class 2. This was expected since high-income people are less sensitive to cost and have a higher WTP (Haddak et al., 2016; Wang et al., 2021). A striking result is that considering the countries as variables, respondents from Greece have a higher probability of falling into Class 2 – Technology prone. Class 2 has lower sensitivity to cost, and all the utilities are positive. Two reasons could explain this; first, the absence of cycling infrastructure in Greece (as shown in Figure 4.2), can result in higher preferences for smart bicycle technologies to increase cyclist safety. The utility of smart bicycle technologies for Greeks is higher, per euro spent, compared to other countries with cycling infrastructure since these technologies can play a crucial role in decreasing cycling crash risk (Kapousizis et al., 2022). Second, a purchase scheme for electric bicycles runs in Greece, which subsidises up to 40% or €800 per bicycle (ECF, 2023); however, we cannot be sure if respondents were aware of this and they have taken this into account. Lastly, respondents who have high digital skills are more likely to be assigned to Class 2. With regards to the respondents who have been involved in a bicycle crash, they are more likely to fall into Class 1. This probably has to do with the types of crashes respondents have been involved in, such as collisions with other modes or single-bicycle crashes. For the latter, respondents might not see an immediate benefit of using advanced technologies.

Regarding the WTP results, it becomes apparent that respondents who are enthusiastic about technology (Class 2) have higher WTP for almost all the functionalities. They are willing to pay up to €200, except for the automatic speed risky areas in which respondents in Class 1 – technology cautious have a higher WTP, and they are willing to pay up to almost €45. If we go back, respondents from countries with high cycling rates and infrastructure comprise the technology cautious class and might prefer this functionality. While there are no other studies available to compare the results of this work, we searched on the web for the Garmin Varia (Garmin, 2023), which cost the time we are writing this paper around €200, which falls to the expected WTP we found for the Class 2 – Technology prone (€201.56).

Lastly, we observed that the WTP for smart bicycle technologies, as derived from our model, is lower than the initial price range we set on the design for the package cost (€400 to €1000). This is due to the choices respondents made in the SC experiment and the fact that we investigated respondents' preferences for functionalities rather than packages. Thus, bicycle manufacturers can consider promoting individual functionalities since our results show that the respondents have different preferences among functionalities, making them less willing to pay for them.

## 4.5. Practical Implications

In the following part, we focus on the implications of the findings of this study. Our analysis suggests that a significant proportion of the respondents is open to new smart bicycle technologies, and as was presented earlier in Section 4.3, there is room for smart bicycle technologies in the market.

The findings of this study might help policymakers at high levels, such as the European Union and/or governments, to implement new plans, regulations, and directions for deploying smart bicycle technologies. Smart bicycle technologies, together with safe infrastructure and education programs, could be one of the measures to improve cyclist safety. Also, policymakers can investigate geographical areas that may need specific types of smart bicycle technologies and promote these ones. A closer collaboration with the municipalities and local traffic authorities would be needed for the latter since different areas have different needs. In addition, policymakers may consider making some smart bicycle technologies mandatory for the new e-bikes being sold to enforce speed limitations in specific areas. Those areas could be places with high traffic and crash risk, city centres, nearby schools, as well as along bicycle lanes. Enforcing speed limitations for the latter will help reduce crash risk and severity, not only for e-bike users but also for other vulnerable road users, such as conventional bicycle users and pedestrians who interact and use the same infrastructure. Lastly, policymakers may also consider promoting smart bicycle technologies to specific groups of people, such as people older than 65 and males, since they have the highest fatality rate among cyclists, almost 47% and 82% in 2020, respectively (European Commission, 2023a).

Bicycle manufacturers and the industry can also benefit from the results of this study and develop bicycle technologies aligning with cyclist preferences and willingness to pay. However, they may consider first prioritising and testing the efficiency of such technologies, especially those that were found to have high preference in our study. Additionally, bicycle manufacturers may consider deploying different smart bicycle technologies among different countries and sociodemographic groups.

## 4.6. Limitation

The sample used in this study consists of e-bike users and people willing to buy an e-bike. This was a deliberate choice as the research focuses on capturing opinions from people interested in cycling; however, the sample does not represent the entire population of the countries included. A source of attention is the inconsistent sample size among countries, with around 59% of the respondents being from the Netherlands, while the sample size for the other countries was around 10% per country. We estimated different models without the Dutch sample. We found only non-significant statistical differences in the weight composition for the two classes and in the estimations of the model. Otherwise, the class memberships remained the same. An additional uncontrolled factor is that while the Dutch sample was nationally comparable to e-bike users in the Netherlands, this was proportionally greater than the rest of the countries.

In this paper, we explored hypothetical scenarios, since the smart bicycle technologies examined are not yet available on the market. Thus, the utilities and WTP were estimated as expected utilities and might differ when such technologies come out on the market, and users can have a hands-on experience. In addition, the model in this study shows the preference of respondents concerning the reference category. Thus, the estimated results and the WTP values are relative to the reference levels described above.

Lastly, the difference in the weight of the two classes is relatively small (Class 1: 52% and Class 2: 48%), indicating that the analysed sample is almost equally distributed between them. Also, the significant levels in some attribute levels are small. However, the classes show significant differences in WTP for cycling technologies. Given the scope of the survey and differences in recruitment of respondents between countries, results should be treated with some caution.

## 4.7. Future work

Future research may include a slightly different approach to the choice task by first asking respondents' preferences towards smart technologies and then the WTP. In this way, the collected data may explain respondents' choices better. Furthermore, this study only recruited people who own and/or are willing to buy an e-bike, gaining more realistic estimates of willingness to pay. However, future studies can aim to collect data from the general population to investigate to what extent people who are not considering using an e-bike now, might do so if e-bikes become safer or achieve higher subjective safety using such technologies.

Another potential avenue for future research is to investigate to what extent people from the same country might have different preferences and sensitivities towards smart bicycle technologies using a mixed logit model or a hybrid choice model since regions/municipalities within the countries may also vary in cycling infrastructure, traffic density and population density. Also, the latter model may better incorporate questions into latent variables and elucidate additional dimensions during the analysis. Lastly, it is worth investigating the preferences and attitudes toward smart technologies on e-bikes when such technologies start being available on the market or through field trials.

## 4.8. Conclusion

With the current focus on sustainable mobility, more and more people are expected to ride e-bikes. This will increase the number of kilometres ridden per person and probably lead to more crashes since people are unfamiliar with, for instance, the high speed of e-bikes. This paper aimed to investigate the potential use of cycling technologies to enhance cycling safety and examine e-bike users' preferences and willingness to pay. In addition, it provides novel results about user preferences for smart bicycle technologies enhancing cyclist safety for e-bike users.

We estimated a latent-class model using survey data collected via a stated choice experiment from five European countries with varying cycling rates, travel behaviour, and infrastructure to examine users' preferences and WTP for smart bicycle technologies. Results contribute to the literature regarding bicycle technologies that have the potential to reduce crash risk. In addition, results show that people have diverse preferences. The main findings of this paper are summarised as follows:

- Even though this is the first study investigating survey data for smart bicycle technologies, there are indicators that such technologies are perceived positively by an important portion of respondents.
- The Latent Class Choice Model indicates two classes: Class 1 - Technology cautious, respondents who do not show a higher preference for advanced technologies, and Class 2 - Technology prone, respondents who have a higher preference for advanced technologies.
- WTP for smart bicycle technologies showed significant differences between the two classes, with respondents falling whitin Class 1 willing to pay up to €100 and respondents falling within Class 2 up to €200.
- Heterogeneity exists even among people with the same sociodemographic characteristics towards smart bicycle technologies enhancing cycling safety.
- Heterogeneity can partially be explained by linking sociodemographic, geographical, and other variables, such as the respondents' technology friendliness and safety-related questions, to the class allocation.
- Respondents from the five countries show differences in their preferences; thus, policymakers and bicycle manufacturers should consider the results of this study when formulating policies and promoting such technologies.

Considering the future deployment of smart bicycle technologies, it is worth noting that respondents with high income (above average), technologically savvy, and those living in areas with low cycling infrastructure have a higher probability of opting for more advanced "collision avoidance systems" that can provide warnings against potential collisions.

# Chapter 5

# Assessing Potential Uptake and Willingness to Pay for Smart Bicycle Technologies Affecting Cycling Safety. A Stated Preference Survey Among e-bike Users in The Netherlands

This chapter is based on: Georgios Kapousizis, Mehmet Baran Ulak, Karst Geurs & Paul J. M. Havinga: Assessing Potential Uptake and Willingness to Pay for Smart Bicycle Technologies Affecting Cycling Safety. A Stated Preference Survey Among e-bike Users in The Netherlands. Submitted for publication.

## 5.1. Introduction

Electric cycling is the new trend in mobility, and the market share of electric bikes (e-bikes) is growing fast in Europe (Bike Europe, 2023). It is estimated that e-bike sales in Europe increased by around 10% between 2015-2022 (Bike Europe, 2023). The Netherlands is the country with the highest penetration rate of e-bikes per person in Europe. The e-bike sales accounted for 80% of the total bicycle sales in 2022, with the market share of e-bikes valued at around 1.2 billion euros in 2022 (Bike Europe, 2023; BOVAG en Vereniging, 2023; Deloitte, 2021). E-bike usage increased from 5% to 37% of the total cycling kilometres in the past ten years (2012-2022).

Increasing e-bike usage also has road safety implications. In the Netherlands, bicycle crashes have increased by 43% from 2019 to 2022, and almost 30% of all cyclist fatalities are e-bike users (Statistics Netherlands (CBS), 2021, 2023). Currently, over one-third of serious bicycle crashes involve e-bikes (VeiligheidNL, 2023). These percentages will continue to increase due to the high adoption of e-bikes in the country. Moreover, the distribution of travelled distance on e-bikes is higher in vulnerable groups (Westerhuis et al., 2024), and hence, crashes with e-bikes tend to be more severe than those with conventional bikes. Also, taking into account the cycling fatalities per kilometre cycled, there is a higher risk of a fatal crash for e-bikes (Westerhuis et al., 2024). Furthermore, new types of e-bikes have emerged, the so-called "Speed-Pedelec" and "Fat e-bikes", reaching up to 50km/h (ECF, 2017). Younger people favour the latter after the Dutch government made helmets mandatory for scooters (Ministry of Infrastructure and water management, 2022a). In addition, in large Dutch cities such as Amsterdam, the streets have become busy with cyclists and other soft modes, and the different speeds among cyclists on bicycle paths between e-bikes, fast e-bikes and conventional bicycles increase the risk of bicycle crashes (Amsterdam, 2022).

Many Dutch municipalities are trying to improve cyclists' safety by improving the current cycling network and by developing new ones, for instance, cycling highways, so that cyclists can use them for long-distance trips without intersections and interactions with motor vehicles. At the same time, national and local governments are introducing or discussing regulations to increase cyclist safety. The Dutch government banned the Speed-Pedelec from bicycle paths in urban areas in 2017, which made them less appealing to users (Stelling et al., 2021). The municipality of Amsterdam has expressed concerns about the different speeds between cyclists and has organised public discussions to solve this issue (Amsterdam, 2022). Recently, it has focused on smart bicycle technologies such as Intelligent Speed Adaptation (ISA) system for e-bikes to decrease the speed in specific areas or zones (Tollenaar & Plazier, 2023), which may decrease bicycle crash risk. Imposing restrictions on e-bikes to avoid crashes can however make them less attractive as an alternative for the car, reducing potential societal benefits. That is, e-bikes have found to increase physical activity of the users and reduce emissions when people replace motor vehicles with e-bikes (Rérat et al., 2024).

Recent years have witnessed a growing academic interest in addressing cycling safety issues by adopting new technologies, such as bicycle sensors, the Internet of Things (IoT), user interfaces and possible interventions to prevent and reduce e-bike crashes and increase comfort (Kapousizis et al., 2022). These technologies can be embedded in the e-bike frame and operate using the battery's power, aiming to forestall an imminent collision and, consequently, decrease the risk of a crash. In addition, the relative value of these new technologies to the value of the e-bikes is lower; thus, focusing on e-bikes, there is a higher potential market. A recent literature review conducted by Kapousizis et al. (2022) examined state-of-the-art bicycle technologies that can influence cycling safety and proposed a classification for bicycle smartness level based on the technology readiness level of these technologies. While the potential benefits of such technologies to increase safety and comfort are high, and the literature on smart bicycle technologies is growing, consumer preferences and willingness to pay (WTP) for these technologies are yet to be examined.

This research aims to investigate 1) willingness to pay for smart bicycle technologies to enhance cycling safety among e-bike users in the Netherlands, and 2) variables which explain individuals' choices of smart bicycle technologies. We used discrete choice analysis (DC) and employed a mixed logit model with random parameters capturing the expected utility of 725 respondents from the Netherlands towards different bicycle technologies. E-bike users' preferences and willingness to pay for technologies to improve cycling safety have rarely been examined in the literature. To our knowledge, only a recent study by Kapousizis et al. (under review-b) examined cyclists' willingness to pay for smart technologies, focusing on a European-based analysis using a latent class choice model. However, the current study adds to the literature since it focuses on identifying deterministic and random heterogeneity and gives in depth details on differences among respondents from the same country. Also, it examines differences between population segments and gives fresh insight from the Netherlands. Analysis of the preferences of Dutch cyclists also contributes to the literature, as the Netherlands is the European Union's leading e-bike market, and globally is second only to China as the world's leading e-bike market. In the Netherlands, e-bikes are a common mode of transport with a large variety of users, including commuters, young and old people, allowing an analysis of preference heterogeneity (de Haas et al., 2021b; Sun et al., 2023).

The remainder of this paper is structured as follows. Section 5.2 discusses the available literature; Section 5.3 describes the research methodology and data collection. Sections 5.4 and 5.5 present the model results, followed by a detailed application of the willingness to pay. Section 5.6 discusses the results, implications, limitations and future work, and Section 5.7 concludes this study.

## 5.2. Literature

While there is increased research on users' preferences and WTP for new technologies for motor vehicles to increase safety, this is not the case for bicycles. Only recently, during the last decade, some new studies have focused on new bicycle technologies (Kapousizis et al., 2022; Oliveira et al., 2021). These studies investigated the technologies that can be used on bicycles and the digitalisation of smart infrastructures, digital and physical, rather than user acceptance and preferences towards these technologies. Only a few studies examined users' preferences and acceptance of smart bicycle technologies. User acceptance and the influential factors for a smart e-bike were studied by Kapousizis et al. (2024). They found that performance expectancy, hedonic motivation and perceived safety are the leading factors for user acceptance. De Angelis et al. (2019) studied bicycle users' preferences and WTP for different warning channels, such as audio-visual and handlebar vibration warnings, among European countries. Kapousizis et al. (under review-b) recently examined users' preferences for smart bicycle technologies in five

European countries with a stated choice (SC) experiment and applied a latent class model. They defined two classes of potential users: individuals prone to advanced smart bicycle technologies and those who are cautious and prefer less advanced systems. In addition, they found that individuals living in areas with low cycling infrastructure are more likely to fall into the class prone to smart bicycle technologies (Kapousizis et al., under review-b).

As discussed above, a few studies on bicycle technologies have also examined them using preferences and WTP, and only Kapousizis et al. (under review-b). Investigating user preferences and WTP using DC models is a common technique in the transportation domain. In general, researchers focus on the trade-off between alternatives, such as travel time and cost, to estimate the time value (Ben-Akiva & Lerman, 1985). There is extensive literature on studies that used DC models to examine Advance Driving Assistance Systems (ADAS), automated vehicles and different engine consumptions (e.g., petrol, electric, hybrid) (Daziano et al., 2017; Ferguson et al., 2018; Ghasri et al., 2021; Haddak et al., 2016; Solvi Hoen et al., 2023; Wang et al., 2021). These studies used DC models to examine people's preferences based on the number of choices they made using SC surveys. SC surveys allow people to make trade-offs among hypothetical scenarios presented to them with different attributes (K. Train et al., 2019).

Furthermore, studies have already examined user preferences and WTP for new technologies influencing safety and comfort for motor vehicles. Shin et al. (2015) studied potential consumer WTP for advanced vehicle technologies, aiming to shed light on the potential deployment of smart vehicle technologies. Similarly, Nickkar and Lee (2022) investigated WTP for advanced vehicle safety technologies. They found that respondents in their survey were willing to pay around €1600 on top of the vehicle price to add safety features to their new vehicles, representing around 8%. These studies focused on understanding user preferences by conducting DC models.

Overall, the studies above used different approaches to examine user preferences, such as behavioural and DC models. Regarding the studies examining bicycle technologies, we can see that they all focused on multiple countries at the European level rather than focusing on a specific country and drawing results. Thus, there is a need to explore WTP of safety enhancing technologies for different population segments and countries with developed cycling cultures and high usage of e-bikes, such as the Netherlands, to help bicycle manufacturers and policymakers prioritise developing specific systems at a cost individuals are willing to pay and governments to examine potential substitutions for smart bicycle technologies for people prone to bicycle crashes.

## 5.3. Methodology

### 5.3.1. Sample recruitment

A web-based survey was designed and distributed using the Lighthouse Studio platform (Sawtooth Software, 2022) and can be found in Appendix E. The survey was conducted in the Netherlands between November 2022 and January 2023. The target population was individuals who own and/or are interested in buying an e-bike in the next five years. This choice was made since we wanted to examine WTP of cycling enhancing technologies by individuals experienced or interested in using e-bikes.

The survey was translated into Dutch and English to capture the opinions of people who live in the Netherlands but do not speak Dutch. We used a mixed-method approach, online and on-site, to distribute the survey. The survey was distributed online via the official Dutch cycling union (Fietsersbond) and other relevant cycling networks (Fietsberaad) on their social media (LinkedIn, Facebook and mailing list). Respondents were also recruited from a bicycle experience centre in the middle of the Netherlands, which welcomes visitors from all over the country interested in trying out different types of bicycles. In addition, to ensure a representative sample, a group of respondents was recruited through a market research panel, panelclix (Panelclix, 2023). The reason for choosing this mixed method was twofold: 1) to recruit participants whom we could not reach via an online survey, meaning people unfamiliar with the technologies (e.g. do not use smartphones or computers) and elderly, and 2) to recruit people who are in the process of buying an e-bike. Ultimately, 69% of our sample came from the online distribution, 6% from the on-site distribution and 25% from the Panelclix. Respondents distribution across the country can be found in Appendix D.

### 5.3.2. Survey design and the stated choice experiment

The survey was structured around the SC experiment. Participants first received a short introductory text for outlining the aims of the survey. The survey comprised three parts: 1) screening questions and travel habits, 2) a short explanation and illustration of what an e-bike with smart technologies looks like with explanatory questions and the six SC choice tasks, and 3) sociodemographic questions.

An unlabelled experimental design for the SC scenarios was developed using the Lighthouse studio (Sawtooth Software, 2022). To ensure as realistic scenario as possible, we consulted bicycle experts to set a representative price range for these systems to better correspond to the potential market prices. Hence, we posed constraints to the design concerning prices, so high-end functionalities were associated with higher prices. Thus, even though we designed an orthogonal experiment after the constraints were placed, this was adjusted. The price scale used in this design ranged from €400 to €1000. Overall, 50 distinct scenarios were developed and implemented as 25 blocks of two scenarios.

This SC experiment aimed to examine the trade-off and WTP for smart bicycle technologies affecting cycling safety as investigated by Kapousizis et al. (2022), and all the attributes are based on this study. Table 5.1 presents the SC attributes and levels. Attributes for this SC experiment included the following:

- **Assistance systems** that detect incidents and send emergency alerts to hospitals or to saved contacts and/or navigation systems offering low-rash risk routes.
- **Automatic speed adjustment systems** automatically adjust the e-bike’s speed in busy streets and school zones, in high crash-risk locations, and keep a safe distance from the preceding vehicles.
- **Collision avoidance systems** that can track vehicles and obstacles around the bicycle and give warnings to the cyclists to avoid a collision.

- **Cost** refers to the additional price to purchase the systems.

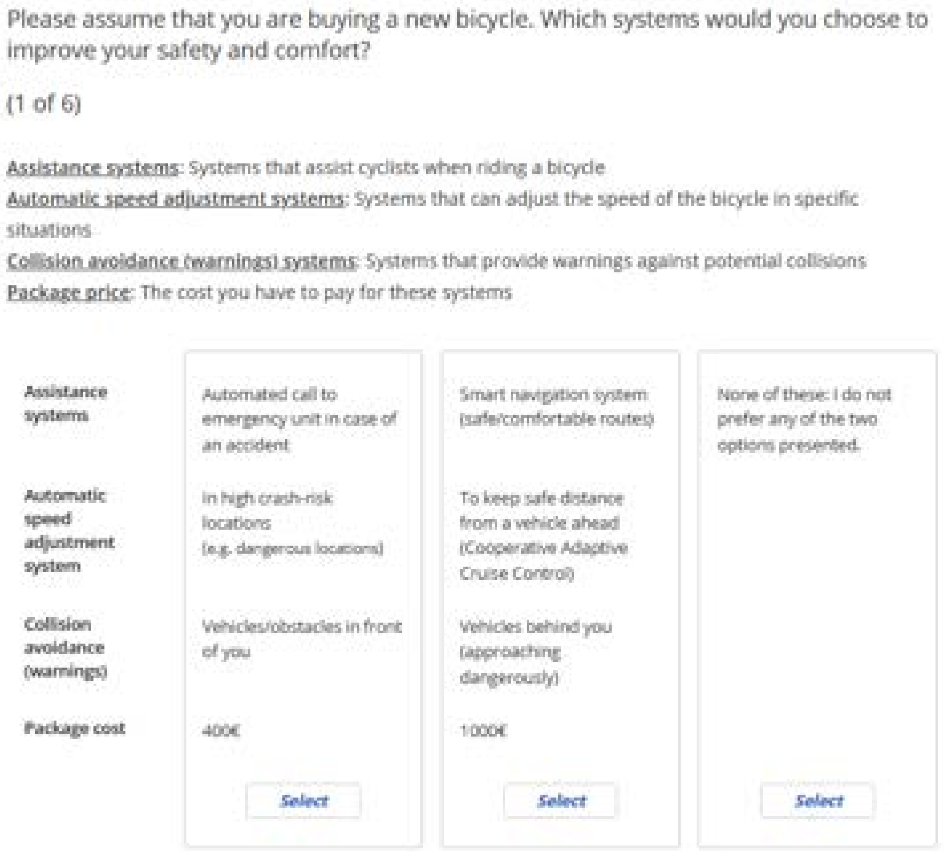
**Table 5.1 Attribute levels for the choice experiment.**

| Attributes | Levels | Attribute levels |
|---|---|---|
| Assistance systems | 3 | 1. Emergency unit: Automated call to the emergency unit in case of an accident.<br>2. Emergency call: Automated call to your emergency contacts in case of an accident<br>3. Smart routes: Smart navigation system (safe/comfortable routes) |
| Automatic speed adjustment systems | 3 | 1. Speed limit: In busy streets, cycle paths, near schools<br>2. Speed risk areas: In high crash risk locations (e.g. dangerous locations)<br>3. Speed safe distance: To keep a safe distance from a vehicle ahead |
| Collision avoidance (warnings) | 3 | 1. Front side: Vehicles/obstacles in front side<br>2. Rear side: Vehicles behind you (approaching dangerously)<br>3. Blind spot: Blind Spot detector (left and right assist) |
| Cost | 4 | 1. €400<br>2. €600<br>3. €800<br>4. €1000 |

Each respondent received six choice tasks, consisting of two alternatives each and the opt-out choice (no choice). All participants received the same values in the SC experiment. In detail, participants first received an explanation, followed by the six hypothetical SC scenarios:

*"In this part of the survey, you have to imagine that you are about to buy a new e-bike which costs around €2000. We will present six different scenarios of bicycles to you, which vary in the safety level, functionalities and price. Please mark the bicycle that best fulfils your expectations by ticking the "select" bottom below."*

The price of the e-bike in the hypothetical scenario was selected based on the average cost Dutch consumers paid to buy an e-bike in 2022 (BOVAG en Vereniging, 2023). Figure 5.1 shows a hypothetical SC scenario describing a smart e-bike. On top of each choice task, a brief explanation of the choices appeared to the participants each time. The order of the attributes was the same for all tasks; thus, it offered less burden to the respondents.



Please assume that you are buying a new bicycle. Which systems would you choose to improve your safety and comfort?

(1 of 6)

Assistance systems: Systems that assist cyclists when riding a bicycle
Automatic speed adjustment systems: Systems that can adjust the speed of the bicycle in specific situations
Collision avoidance (warnings) systems: Systems that provide warnings against potential collisions
Package price: The cost you have to pay for these systems

| | | | |
|---|---|---|---|
| **Assistance systems** | Automated call to emergency unit in case of an accident | Smart navigation system (safe/comfortable routes) | None of these: I do not prefer any of the two options presented. |
| **Automatic speed adjustment system** | In high crash-risk locations (e.g. dangerous locations) | To keep safe distance from a vehicle ahead (Cooperative Adaptive Cruise Control) | |
| **Collision avoidance (warnings)** | Vehicles/obstacles in front of you | Vehicles behind you (approaching dangerously) | |
| **Package cost** | 400€ | 1000€ | |

Figure 5.1: Stated choice task

### 5.3.3. Model specifications

A mixed logit model was estimated to account for the panel effect since each respondents answered six choice tasks and to account for random heterogeneity (Train, 2009). In addition, to account for left-to-right bias, we estimated individuals' preferences for each attribute level of the SC experiment and three alternative specific constants, even though we tested an unlabelled SC experiment. Also, we search for deterministic heterogeneity with the interaction between attribute levels and sociodemographic and other characteristics. We used the following variables for the interactions: sociodemographic variables (age, gender, education, income), geographical differences (city size, population density), and safety-related factors (perceived safety, traffic level) in the living area of each participant to capture deterministic heterogeneity in the observed choices. However, only participants between 25-44 years old, older than 60 years, and gender (male) were found to have significant differences in high confidence levels (95%) and only these variables were included in the model.

We calculated nine random coefficients for the main attribute levels for the mixed logit model and estimated the fixed coefficients for the interaction variables. We assume participants are cost-sensitive, meaning they have negative utility for the cost attribute; thus, a lognormal distribution for the cost parameter was used. The rest of the attributes were found to have positive utilities in the model estimated earlier, and we tested different specifications, such as lognormal and normal distributions; however, the latter was found to have better performance and was used. In addition, we estimated seven non-random parameters, three alternative-specific constants, and four fixed terms (as explained above). We used the Apollo package (Hess & Palma, 2019) in R (R Core Team, 2023) to estimate the model and the willingness to pay. A series of models were developed to determine the most suitable for this study. Note that all the components of the model were estimated simultaneously. We used the assumption of Random Utility Theory (McFadden & Train, 2000) to estimate our model. The probabilities in the mixed logit model are defined as an integral of a distribution of the unobserved taste parameters (β). Thus, the probability for a participant (n) to choose an alternative (i) in a choice task (t) is given by:

$$P_n = \int_\beta \prod_{t=1}^{T} \left[ \frac{e^{V(\beta,\ X_{ni*t})}}{\sum_{j=1}^{J(n)} e^{V(\beta,\ X_{njt})}} \right] f(\beta) d\beta \tag{1}$$

## 5.4. Results

### 5.4.1. Sample and descriptive statistics

A total of 1345 people were recruited, of which 48 used the English version of the survey. Of these 835 (62.1%) owned or were planning to buy an e-bike within the next five years. The remaining 510 participants who did not own an e-bike and were not interested in buying an e-bike were excluded from the analysis. In addition, responders (in total 110) who spent less than one minute on the SC section were omitted since, based on previous trials, we know that it was not feasible to properly fill in this part of the survey within that time. A final sample of 725 valid responders was included in the analysis. Table 5.2 presents the sample characteristics. In detail, 47% (342) of the total sample were male, 50% (362) earned a university degree or higher, 35% (257) earned more than €2500/month net personal income and 55% (397) owned an e-bike. Our sample was not random; rather, we focused on people who own and/or are willing to buy an e-bike, as mentioned in Section 2.1. We compared our sample with the Netherlands Mobility Panel (Hoogendoorn-Lanser et al., 2015; Ministry of Infrastructure and Water Management, 2022b) for the e-bike users and people willing to buy one. Our sample is representative of gender, and balanced in terms of age compared to the MPN 2021 data. It is overrepresented by individuals older than 65 and highly educated and is underrepresented by individuals with income below €1500 and e-bike owners. Table 5.2 summarises the respondents' distribution.

### 5.4.2. Model results

The mixed logit model results can be found in Table 5.3. All the main attributes have a positive sign (except the automatic speed risk areas), meaning that participants have a higher utility on those than the reference ones. The attribute level Automatic speed risk areas have a negative sign but no significance, meaning that participants have a higher utility relative to the reference level. However, the interaction with participants younger than 45 years old showed positive and significant value. In addition, as was expected, the attribute cost has a negative and significant value. In detail, we see that the two alternative specific constants are positive, meaning that participants have a positive opinion of smart technologies.

**Table 5.2 Sample composition**

| Variable | Sample | | MPN 2021 |
|---|---|---|---|
| | **Count** | **Percentage** | **Percentage** |
| Number of respondents | 725 | 100% | 100% |
| **Gender** | | | |
| Male | 342 | 47% | 46% |
| Female | 371 | 51% | 53% |
| Non-binary | 4 | 4% | - |
| Other/prefer not to answer | 8 | 2% | - |
| **Age** | | | |
| <25 | 7 | 1% | 6% |
| 25-44 | 138 | 19% | 25% |
| 45-65 | 279 | 38% | 38% |
| >65 | 301 | 42% | 31% |
| **Education** | | | |
| Low (high school or lower) | 363 | 50% | 70% |
| High (university degree or higher) | 362 | 50% | 30% |
| **Net monthly individual income (€/month)** | | | |
| Less than 1000 | 44 | 6% | 9% |
| 1001-1500 | 77 | 11% | 14% |
| 1501-2000 | 117 | 16% | 16% |
| 2001-2500 | 129 | 18% | 16% |
| 2501-3000 | 103 | 14% | 17% |
| 3001-3500 | 73 | 10% | 12% |
| 3501-4000 | 35 | 5% | 5% |
| 4001-4500 | 17 | 2% | 2% |
| 4501-5000 | 11 | 2% | 1% |
| 5000 and more | 18 | 2% | 1% |
| Prefer not to answer | 101 | 14% | 0% |
| No income | 0 | 0% | 8% |
| **Net average monthly individual income (€/month)** | | | |
| Low-medium (below 2500) | 367 | 51% | 68% |
| High (above 2501) | 257 | 35% | 32% |
| Prefer not to answer | 101 | 14% | - |
| **E-bike** | | | |
| Owners | 397 | 55% | 82% |
| Willing to buy | 328 | 45% | 18% |

Additionally, the means of the alternative specific constants are equal; hence, the SC experiment has no order effects. Note that the negative values of the standard deviation are due to how a random coefficient is coded and should be ignored (Hess & Palma, 2019).

**Table 5.3 Estimates of the mixed logit models**

| **Attributes** | **Mixed Logit model** | | |
|---|---|---|---|
| | **Coefficient** | **Rob S.E.** | **Rob t-value** |
| ASC_A | 2.7275 | 0.2452 | 11.1257 |
| ASC_B | 2.7893 | 0.2540 | 10.9802 |
| ASC_C | (ref.) | - | - |
| Assistance emergency unit - $\mu$ | (ref.) | - | - |
| Assistance emergency unit - $\sigma$ | (ref.) | | |
| Assistance emergency call - $\mu$ | 0.4190 | 0.1113 | 3.7661 |
| Assistance emergency call - $\sigma$ | *-0.3518* | *0.2689* | *-1.3082* |
| Assistance smart routes - $\mu$ | 0.5478 | 0.1206 | 4.5429 |
| Assistance smart routes - $\sigma$ | -1.3530 | 0.1963 | -6.8932 |
| Automatic safe distance - $\mu$ | (ref.) | - | - |
| Automatic safe distance - $\sigma$ | (ref.) | | |
| Automatic speed limit - $\mu$ | 0.2622 | 0.1307 | 2.0059 |
| Automatic speed limit- $\sigma$ | -0.4584 | 0.2194 | -2.0899 |
| Automatic risk areas - $\mu$ | -0.0559 | 0.1160 | -0.4817 |
| Automatic risk areas - $\sigma$ | 0.6824 | 0.1656 | 4.1197 |
| Collision front side - $\mu$ | (ref.) | - | - |
| Collision front side - $\sigma$ | (ref.) | | |
| Collision rear side - $\mu$ | 0.4070 | 0.1184 | 3.4362 |
| Collision rear side - $\sigma$ | 0.4606 | 0.2317 | 1.9874 |
| Collision blind spot - $\mu$ | 0.2561 | 0.1032 | 2.4803 |
| Collision blind spot - $\sigma$ | 0.9240 | 0.1632 | 5.6614 |
| Cost - $\mu^{\#}$ | -5.0605 | 0.0970 | -59.8973 |
| Cost - $\sigma^{\#}$ | -1.3612 | 0.1053 | -14.7366 |
| **Sociodemographic variables (fixed)** | | | |
| Assistance emergency call shift >60 | -0.5650 | 0.1500 | -3.7660 |
| Collision rear side shift >60 | -0.3419 | 0.1548 | -2.2084 |
| Automatic risk areas shift age 25-44 | 0.4104 | 0.1966 | 2.0878 |
| Automatic speed limit shift males | -0.4765 | 0.1510 | -3.1554 |
| **Model summary** | | | |
| Number of individuals | 725 | | |
| Number of observations | 4350 | | |
| Number of parameters | 23 | | |
| Final log-likelihood | -3155.06 | | |
| AIC | 6356.12 | | |
| BIC | 6502.82 | | |
| Adjusted Rho-squared | 0.335 | | |
| Number of draws for random parameters* | 5000 | | |

*MLHS draws, $\mu$: mean, $\sigma$.: standard deviation, $^{\#}$ The coefficient for the cost followed a negative lognormal distribution, while all the rest of the coefficients followed the normal distribution.

#### 5.4.2.1. Assistance systems

Both attribute levels, assistance emergency calls and smart routes, have positive means. However, smart routes functionality is the preferred option and is significant at a high confidence level ($p \leq 0.001$), meaning participants prefer this attribute level more. For the smart routes we found heterogeneity (standard deviation: -1.353 at high confidence levels $p \leq 0.001$; note that the minus sign should be ignored), however the standard deviation for the emergency unit is not significant, while for the assistance emergency call, the standard deviation is weak ($p=0.190$).

#### 5.4.2.2. Automatic speed adjustment systems

The attribute level automatic speed limit has a positive coefficient at a high confidence level ($p=0.04$), while the automatic speed risk areas have a negative sign; however, it is not significant, meaning participants do not differentiate from the other attributes level. Furthermore, all attribute levels show high heterogeneity among the participants, with the automatic speed safe distance having the highest standard deviation.

#### 5.4.2.3. Collision avoidance systems

Both attribute levels, collision avoidance rear side and collision avoidance blind spot, have positive coefficients, with the former higher at 0.407 compared to 0.256 for the latter. This means that participants have a higher preference for collision avoidance on the rear side. Investigating the heterogeneity of these functionalities, we discovered a high level of heterogeneity for all functionalities.

#### 5.4.2.4. Cost

We found that the cost has the highest coefficient mean value of -5.060 of all the other coefficients, and it is significant at a very high confidence level ($p \leq 0.001$), meaning that the probability of people buying such systems decreases with the increased cost.

### 5.4.3. Interactions attribute levels with sociodemographic variables

As discussed in Section 2.3, we encountered heterogeneity between the functionalities of assistance emergency call, collision avoidance rear side with participants older than 60, automatic speed risky areas with participants between 25-44 years old, and automatic speed limit with males.

In detail, we found that participants between 24 and 44 have a higher preference for the automatic speed risky areas at a high confidence interval (p-value two-sided test): $p = 0.003$. Also, we found that participants older than 60 have a lower preference for the assistance emergency call and collision avoidance rear side at a high confidence level of $p \leq 0.001$ and 0.02, respectively. Lastly, males have a lower preference and significance $p \leq 0.001$ for the automatic speed limit. Thus, we prove that heterogeneity exists among different age groups and genders with different functionalities.

## 5.5. Willingness to Pay

This section describes the willingness to pay (WTP) values estimated for the main attributes of this paper. Many researchers commonly use a fixed coefficient or a normal distribution (which is assumed positive utilities for cost) for the random coefficient for the cost, which results in misleading WTP values (Daly et al., 2011). However, as was mentioned in Section 3, all the random coefficients in our model followed the normal distribution, while the cost coefficient followed a negative lognormal distribution. Usually, to estimate the WTP, we can calculate the ratio of an attribute (j) to the cost attribute (c). However, in order to estimate the WTP for the random coefficients, it is common first to simulate the full distribution of each random coefficient and then calculate the ratio (Greene et al., 2015). Hence, we simulated the distribution for each smart bicycle functionality and then calculated the ratio to the cost coefficient. The mean values of the WTP of each attribute is presented in Table 5.4.

Our model indicated that participants showed a high preference for smart routes, with a mean value of the WTP of €216.40, and the lowest for the automatic speed risk areas, €-22.40. The WTP for the assistance emergency call was found €166.90, while the WTP for the assistance emergency unit was not estimated since it was the reference level. We found that on the set of automatic speed adjustment systems, the WTP is €104.30 for the automatic speed safe distance, and €-22.40 for the automatic speed risky areas, meaning that participants have a higher WTP for the automatic speed limit. The last set of systems, "collision avoidance", was found to have a WTP of €161.50 for the collision avoidance read side and €103.30 for the collision avoidance blind spot, relatively to the reference category.

**Table 5.4 Willingness to pay in euros for smart bicycle technologies**

| **Attributes** | **Mean values** |
|---|---|
| *Assistance emergency unit* | - |
| Assistance emergency call | €166.91 |
| Assistance smart routes | €216.42 |
| *Automatic speed adjustment safe distance* | - |
| Automatic speed adjustment speed limit | €104.37 |
| Automatic speed adjustment in risk areas | €-22.42 |
| *Collision avoidance front side* | - |
| Collision avoidance rear side | €161.51 |
| Collision avoidance blind spot | €103.37 |

In addition, we calculated the confidence intervals for each attribute to understand the WTP variation of our sample. Note that the negative values for the WTP among different attributes arise since the reference attribute level for each attribute set is compared. This means that some participants prefer the reference level, which turns out to have a higher WTP.

Figure 5.2 shows the confidence interval (CI) distribution and the mean values of the WTP (markers) for the assistance systems. For the assistance emergency unit, the mean value of the WTP was not estimated since this attribute level was the reference category in this set of attributes. The second level, assistance emergency call, has €166.91 mean value of the WTP and CI(95%) [-24.56,702.64]. More than 90% of the participants have a positive WTP for this functionality, and 40% are willing to pay more than €100 to have such a system in their e-bikes. For the last level in this first set of attributes, assistance smart routes, 80% of the participants have a positive WTP, and 40% are willing to pay more than €100. This functionality has the higher mean value, among the rest of the assistance systems, of the WTP with €216.42 and CI(95%) [-568.95,1476.229]. The negative values of the WTP for these two functionalities mean that some participants have a higher preference for the reference level, assistance emergency unit.

Regarding the second group of attributes, "Automatic speed adjustment systems", the reference level was the automatic speed safe distance functionality, and therefore, the WTP could not be estimated. Around 80% of the participants have a positive WTP for the automatic speed limit, and 30% are willing to pay more than €100. In addition, the mean value of the WTP was found to be at €104.30 and the CI(95%)[-145.49,584.75]. We found that around 60% of the participants have a positive WTP for the automatic speed risk areas, and 20% are willing to pay more than €100 for this functionality, while the mean value of the WTP was estimated at €22.40 and the CI(95%)[-445.39,537.19]. Figure 5.3 shows that the automatic speed limit has a smaller variation for the WTP, and only 20% has a negative WTP compared to the other level. In addition, the automatic speed risk areas have the highest variation among the other functionalities in this set.

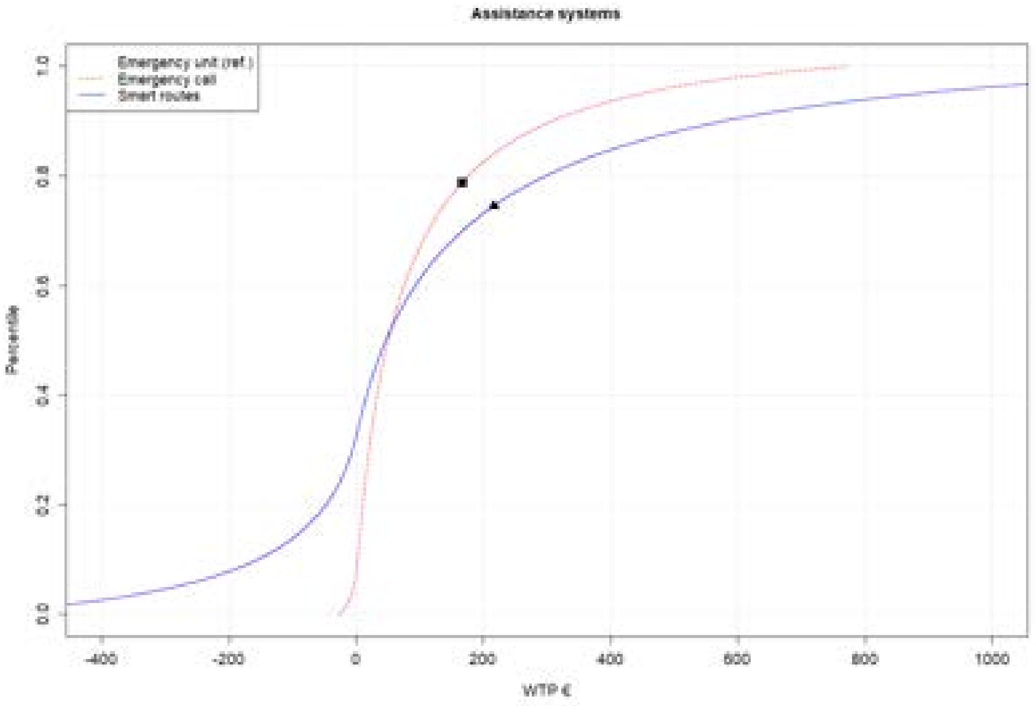


**Figure5.2: CI of WTP distribution for assistance systems (markers indicate the mean values)**

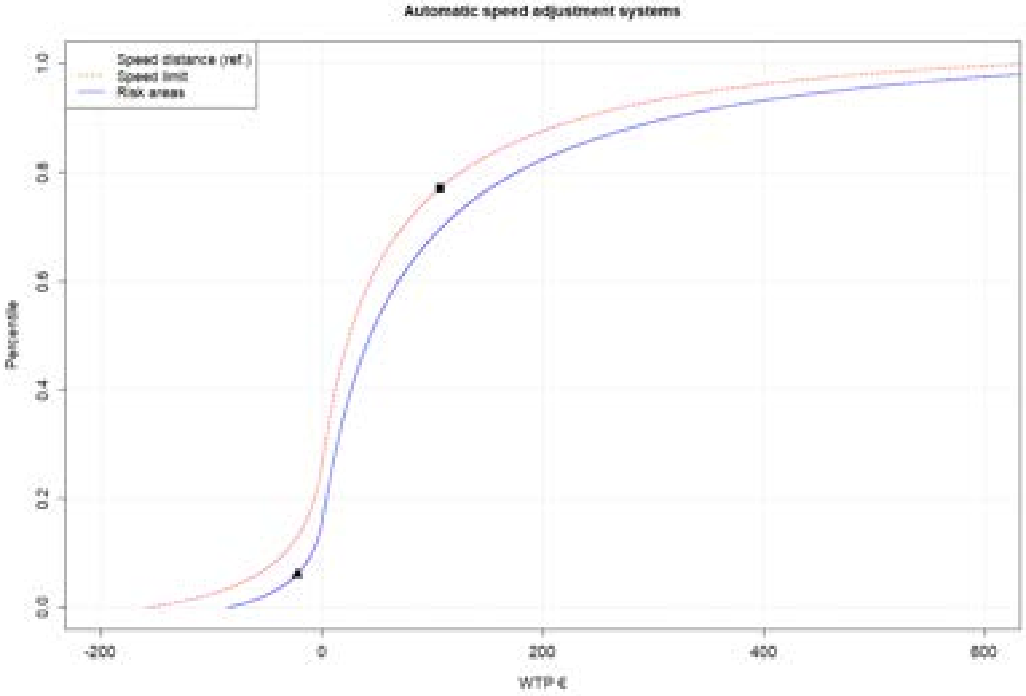


**Figure 5.3: CI of WTP distribution for automatic speed adjustment systems (markers indicate the mean values**

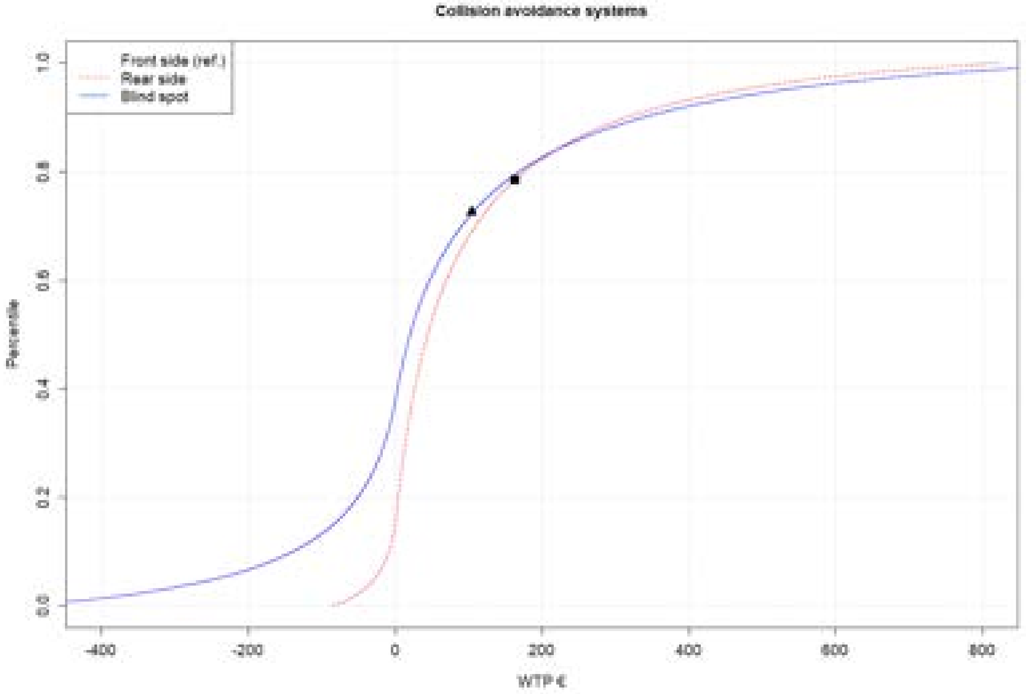


**Figure 5.4: CI of WTP distribution for collision avoidance systems (markers indicate the mean values)**

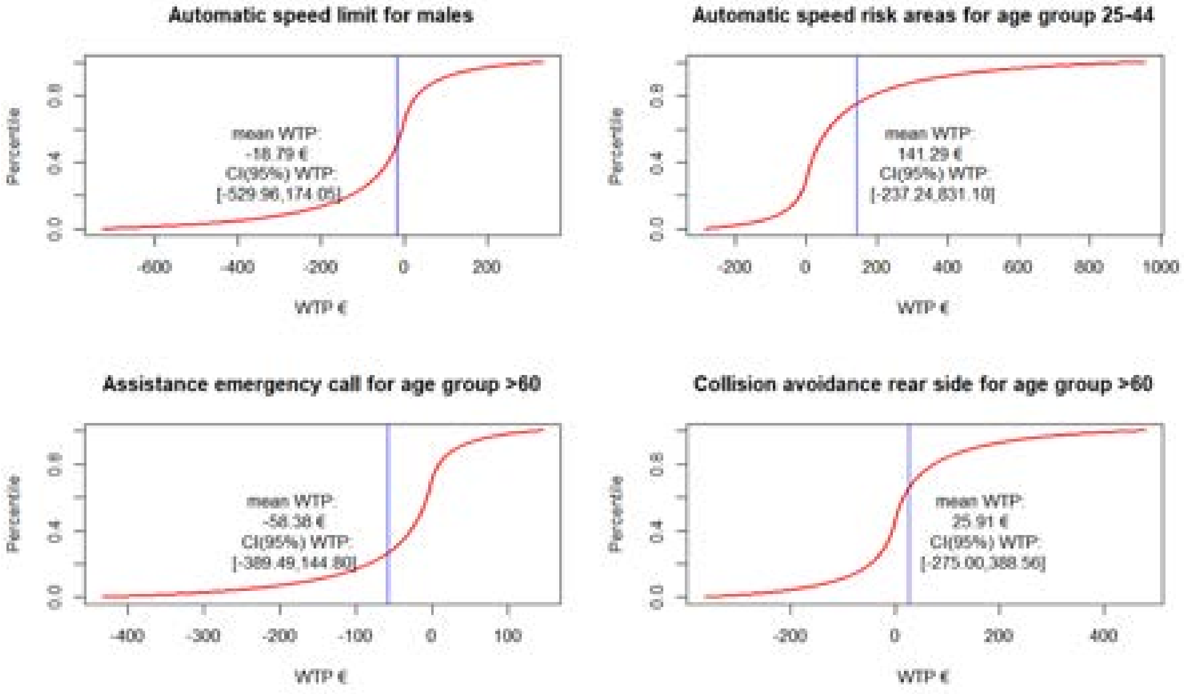


**Figure 5.5: CI and WTP for interaction variables (blue vertical lines indicate the mean values)**

Lastly, Figure 5.4 shows the CI distribution and the mean values for the WTP for the "Collision avoidance systems". The functionality collision avoidance front side was used as the reference level during the model estimation; hence, we did not estimate the WTP for this level. For the collision avoidance rear side, 90% of participants have a positive WTP, and around 35% are willing to pay more than €100 to have this functionality on their e-bikes. The mean value of the WTP for this functionality was estimated at €161.5 and the CI(95%)[-78.40,745.82]. Regarding the last functionality, collision avoidance blind spot, 30% of the participants have a positive WTP, and around 75% are willing to pay more than €100 for this functionality. The mean value of the WTP was found to be €103.30 with a CI(95%)[-465.81,896.67]. Collision avoidance front side and collision avoidance blind spot have high variation among participants' WTP, with the former having the highest among the other functionalities in this set.

### 5.5.1. Willingness to pay for interaction variables

In Section 4, we presented the estimated WTP for the main attribute levels of the model. In this section, we estimated the WTP for the interaction variables, which were found statistically significant at the conventional 95 % reliability level. These are the interactions of different sociodemographic variables with different functionalities, as discussed in Section 5.3. Figure 5.5 shows the WTP for these categories.

In detail, participants older than 60 have a negative WTP of €58 for the assistance emergency call, which means that they have a higher WTP for the reference level of this set of attributes, namely assistance emergency unit. However, 40% of the participants have a positive WTP for the assistance emergency call, and almost 5% were willing to pay more than €10. The same age group, older than 60, was found to have a negative utility for Collision avoidance rear side (-

0.342) compared to the reference category. The final utility is still positive; thus, the mean WTP for this group is €25.40, which was substantially lower for the reference mean of the WTP, at €161.50. We also found a significant difference between the age groups 25 and 44 with the interaction of the automatic risk areas. Participants in this group are willing to pay €141.20 to have this functionality in place, with 10% willing to pay more than €400. Lastly, we found that males have a negative WTP of €-18.70 for the automatic speed limit, meaning they prefer the reference level and automatic speed safe distance; however, 30% have a positive WTP.

### 5.5.2. Market segmentation and willingness to pay

Overall, we partially explained heterogeneity in our model using interaction variables since we found some deterministic heterogeneity, as explained in Section 5.3.3. However, the mixed logit model results, Table 5.3, indicated still significant variation in participants' choices, which is reflected by the random taste heterogeneity, which we were not able to capture deterministically. Thus, in this section, we estimated the WTP for different population segments across our sample in order to get better insights into participants' WTP for different functionalities.

Multiple studies related to autonomous and electric vehicles (Lim et al., 2015; Potoglou et al., 2020) have estimated the WTP for different market segmentation to investigate and examine marketing strategies. Thus, the aim is to identify different groups of potential buyers for different smart bicycle technologies. We divided our sample into different sociodemographic groups, such as gender (male and female), income level (high and low-medium income), education level (high and low) and participants who own or are willing to buy an e-bike. Note that while we included gender-neutral or non-binary due to the low number of participants, we excluded them from this analysis.

The average WTP values for all smart functionalities for males and females can be found in Figure 5.6.a, gender groups. It becomes apparent that females have a positive preference for all functionalities, and this turns into a positive WTP for all functionalities. However, males have a negative WTP for the automatic speed limit and risk areas, which means they have a higher preference for the reference level and automatic speed safe distance. Males are estimated to have a mean value of €400 for the assistance smart route, while the WTP for females is €140. In addition, both genders have similar WTP for collision avoidance systems, with males willing to pay €30 more than females.

Regarding the income groups, we used two groups described in Table 5.2; however, we excluded participants who did not state their income. Figure 5.6.b, income groups shows that participants who earn above the average are willing to pay up to €500 for smart routes and have negative WTP for the automatic speed limit and risk areas since they prefer the reference level, automatic speed safe distance. Also, they are willing to pay up to €100 for assistance emergency call, up to €162 for collision avoidance blind spot and €54 for collision avoidance rear side. Participants who earn below the average income are willing to pay around €100 for smart routes and €40 for assistance emergency call. In addition, they are willing to pay around €30 for automatic adjustment systems, up to €90 for collision avoidance rear side and €60 for blind spot, compared to the reference categories.

Participants with high education are willing to pay more than those with low education levels to buy smart bicycle technologies. Figure 5.6.c, education groups, shows that highly educated participants are willing to pay up to €290 for smart routes while low-educated participants pay up to €180. Both groups have almost zero WTP for automatic adjustment speed systems. However, high-education participants have high WTP values for collision avoidance rear side (€140) and blind spot (€200), while low-education participants were found to have a WTP of €17 and €70, correspondingly.

Lastly, regarding participants who own an e-bike, Figure 5.6.d, e-bike user groups shows that e-bike users have higher WTP to all functionalities than participants who plan to buy an e-bike. In detail, we found that e-bike user participants are willing to pay up to €300 for smart routes, while participants who are willing to buy an e-bike are willing to pay up to €200. An important takeaway from this segmentation is that e-bike users have a higher preference for automatic speed adjustment systems compared to the rest, and especially for automatic speed risk areas with a WTP value of €170. Also, e-bike users have almost double WTP for collision avoidance systems with a WTP value of more than €200.

## 5.6. Discussion

This study used a mixed logit model to the survey data from a SC experiment. We also searched for interaction effects in sensitivities using sociodemographic variables, and we partially explained heterogeneity in our model deterministically. Then, we estimated a mixed logit model to allow for the panel effect of the respondents with ten random coefficients and simulated with 5,000 draws to investigate the expected utility towards smart bicycle technologies. In addition, we estimated sub-models and examined the WTP for different population segments.

### 5.6.1. Preferences toward smart bicycle technologies

Model results indicated that most of the random coefficients were positive and significant. This means that participants have a positive preference towards smart bicycle technologies.

- The assistance smart routes functionality is the one with the highest preference, with a mean of 0.547, followed by the assistance emergency call, with a mean of 0.419. In addition, the collision avoidance rear side functionality was found to be significant (0.407) and at a high confidence level (p = 0.000).
- The only coefficient that was negative and strong at the high confidence interval was cost (-5.065, p = 0.000).

In detail, we found that, regarding the assistance systems, participants have a higher preference for the attribute smart navigation providing safe routes. This system can provide them with a smart navigation system which provides safe routes. Furthermore, participants showed a higher preference for assistance emergency calls, meaning that they have a preference for a system to call a contact person rather than an emergency unit in case of a collision or fall.

Figure 5.6.a)

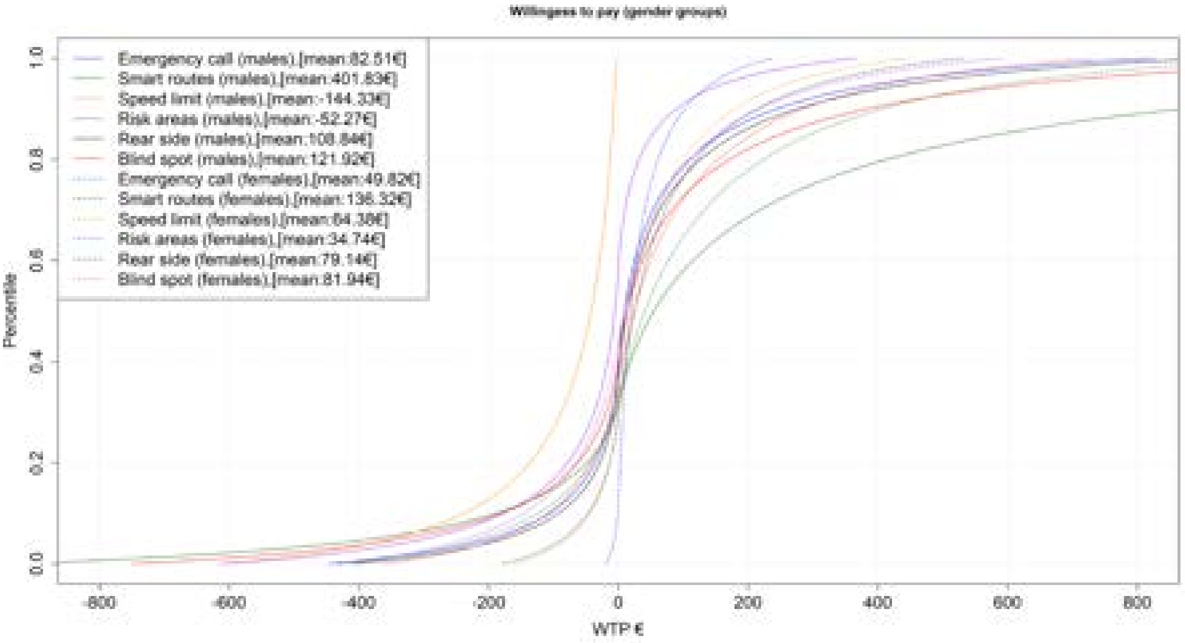
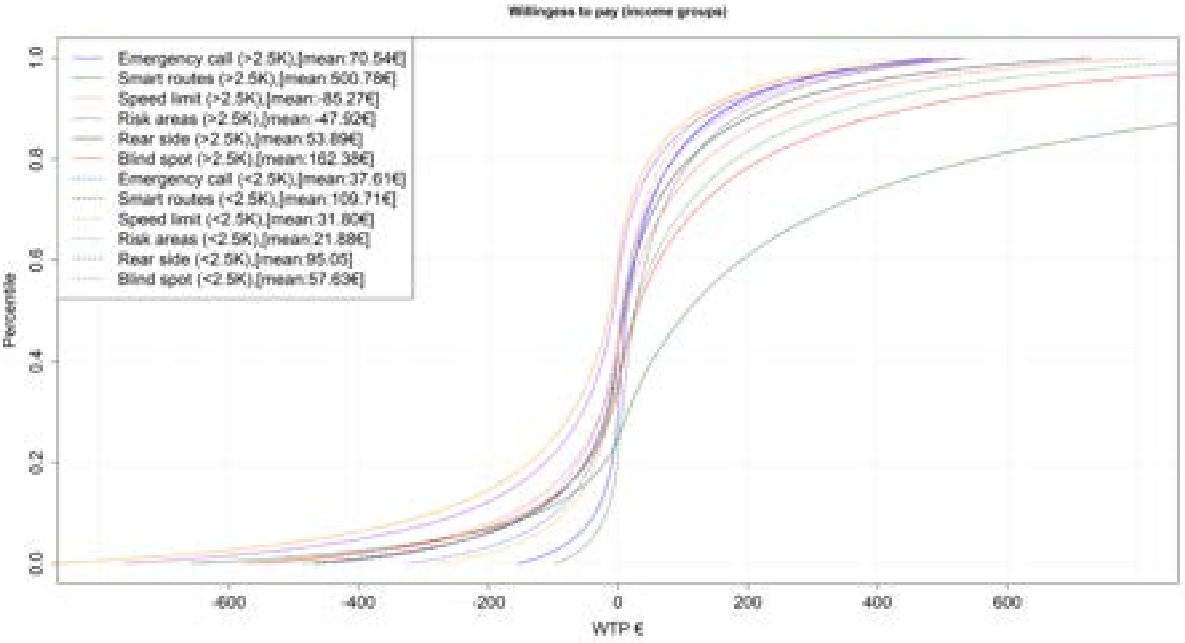


Figure 5.6.b)



Generally, people hold a relatively neutral or negative attitude toward systems that intervene in their speed, at least this was found in studies related to automated vehicles. However, this study shows that participants have positive preferences towards automatic adjustment systems. In detail, we found that participants are more likely to choose the automatic speed limit, a system that can intervene in their speed when users approach schools or cycle on the cycle paths. We want to remind the readers that the Dutch government has banned the Speed-Pedelecs from the cycle paths since 2017 (Stelling et al., 2021). This might influence users' opinions towards this functionality as well as the fact that many e-bike crashes happen due to high speed. Furthermore, participants showed a higher preference for automatic speed in risky areas, which is the system that can warn and/or reduce e-bike speeds when users approach a critical location. The above indicates that participants are open to a system to intervene at their speed in order to reduce the risk of a collision.

Figure 5.6.c)

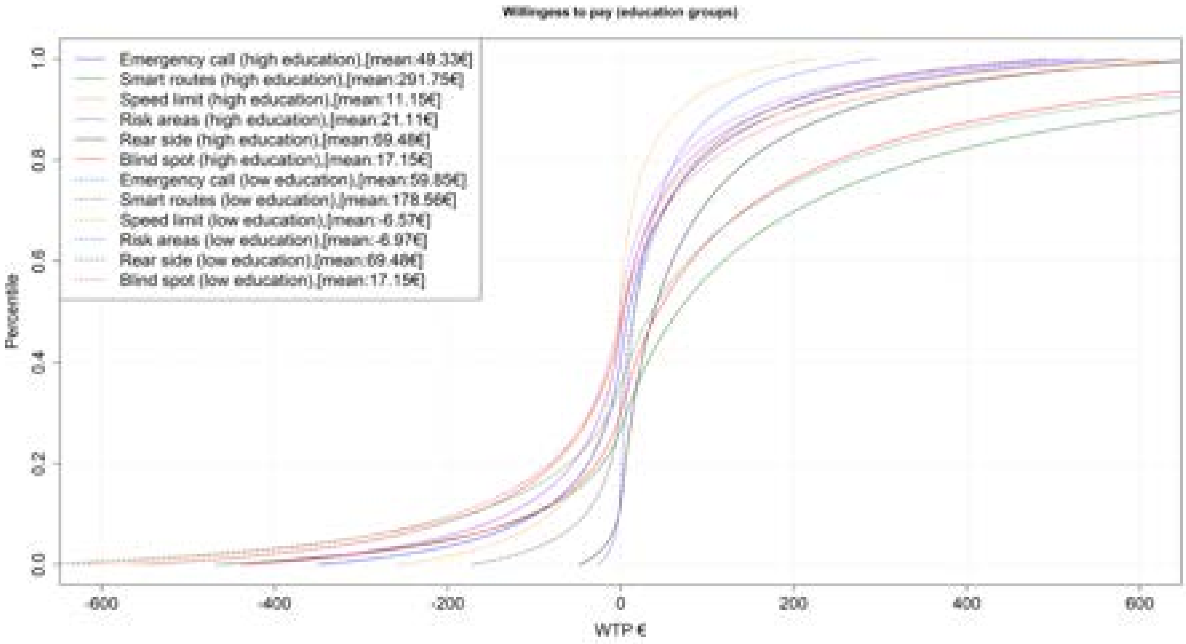


Figure 5.6.d)

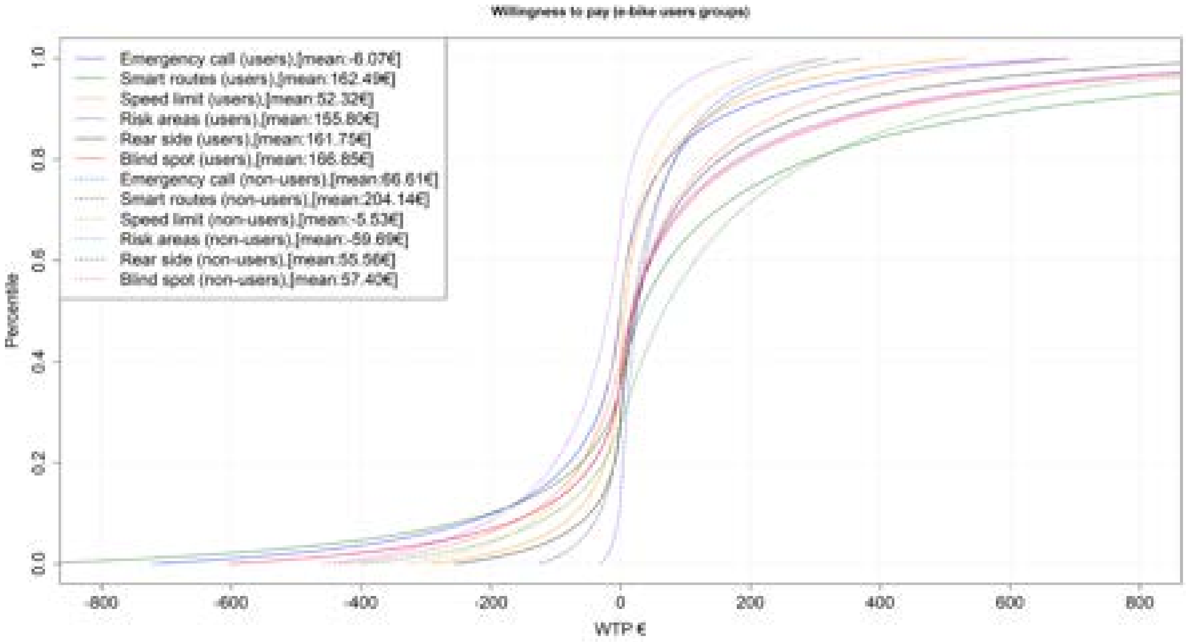


**Figure 5.6: WTP for different sociodemographic groups, (a) gender, (b) income level, (c) education level, (d) e-bike users**

- Considering the last set of functionalities, "Collision avoidance systems", we found that participants prefer the collision avoidance blind spot and second comes the collision avoidance rear side. However, the former has almost double utility (0.4070) compared to the latter (0.2561). Participants justifiably preferred these systems since many crashes happened from the blind spot or rear side of the bicycle. Also, some bicycle manufacturers include such a system on their high-end racing bicycles, which can warn cyclists in case a vehicle approaches from behind at high speed (Cannondale, 2023).

- We found that participants have a negative utility towards cost, meaning that they are sensitive to cost, which is in line with other studies investigating people's preferences and WTP for automated vehicles and alternative fuel (Ghasri et al., 2021; Potoglou & Kanaroglou, 2007; Solvi Hoen et al., 2023).
- Deterministic heterogeneity shows that participants aged 25-44 have a higher preference towards automatic speed adjustment systems, namely, automatic risky areas, than the participants in the rest ages. It proves that young people are more open to advanced bicycle technologies. In addition, males have lower preferences for automatic speed limit -0.4765 compared to females. Lastly, participants older than 60 were found to have a negative utility for the assistance emergency call and collision avoidance rear side. This shows that this age range holds a more neutral and even negative attitude towards those technologies.

### 5.6.2. Implications

Several implications can be derived from this study. First, our study covered research and market gaps on bicycle technologies enhancing cycling safety. To the best of our knowledge, it is the first study to investigate user preferences and WTP towards emerging smart bicycle technologies enhancing cycling safety. The main model showed heterogeneity in participants' choices; thus, we estimated different sub-models using different segments of the sample. The segmentations allow us to better understand participants' choices and WTP for bicycle technologies.

Second, the finding can shed light on the future deployment of bicycle technologies based users' preferences and WTP. Thus, bicycle manufacturers and system designers can consider this study to understand cyclists' needs better and target specific functionalities' development. Also, bicycle manufacturers can consider promoting specific systems/functionalities rather than creating packages from different ones. This will help deploy such technologies in the market since our findings confirm that participants have different preferences towards smart bicycle technologies.

Third, we showed that e-bike and potentially e-bike users are willing to accept and pay for smart bicycle technologies. Participants are generally open to smart bicycle technologies affecting cycling safety and willing to pay sufficient money to use such systems. This paper offers new insights regarding the future of cycling in the Internet of Things era, and policymakers, governments and businesses (e.g., bicycle manufacturers) can benefit from this work and further develop their policy packages and business strategies. For instance, an additional option is that the Speed-Pedelec, available on the market, can be allowed within the city centres and use bicycle paths only if they have specific safety characteristics such as speed limitation.

Lastly, validation of the WTP values was not possible for all other functionalities examined in this study, since we found no other published studies to compare our results, and this was beyond the scope of this paper. However, we were able to find some of these technologies available on the market. When comparing the prices in the market to our WTP estimation, the values for the collision avoidance rear side are quite close to the collision avoidance systems available in the market, which can, at the time we are writing this paper, range between around €109–200 (Garmin, 2023; Magene, 2024) our WTP estimation €160.

### 5.6.3. Limitations and future work

While the investigated topic is gaining popularity, many people may not be familiar with it; hence, the expected utilities we calculated may vary when such technologies are out on the market. Also, this study analysed data targeting e-bike users and people willing to buy an e-bike, and is comparable to the Mobility panel data in the Netherlands (Kennisinstituut voor Mobiliteitsbeleid, 2021). Hence, the collected sample of this study may not represent the census population of the Netherlands since this was not the aim of our study.

Future studies could include a broader audience and collect data for the general population to examine whether non-e-bike users or people who do not use bicycles would be willing to switch to e-bikes due to the use of smart bicycle technologies to increase cycling safety. In addition, future research might focus on estimating more advanced choice models, such as hybrid models, to incorporate latent variables, which may better explain the random heterogeneity (Hess & Daly, 2014). Another topic for consideration could be conducting field trials with smart bicycle technologies, where people can try out such systems before participating in a survey. This approach will give multiple insights since people can have a real experience with an e-bike embedded with smart technologies, which may affect their preferences, since the expected utility will most likely be different from the experienced utility. Thus, when these systems reach a high technology readiness level and are almost ready to go out on the market, we would like to highlight the importance of implementing these systems in field trials.

Further research can also determine the potential use of smart bicycle technologies on fast-delivery bicycles, and policymakers can force delivery companies to use such systems to reduce the crash risk. Furthermore, considering that the number of shared e-bikes and other micromobility modes is increasing within the Netherlands and worldwide, it would be interesting to investigate their users' needs and WTP of such smart bicycle technologies. Mainly, the users of these shared e-bikes are tourists and people unfamiliar with cycling, especially e-bikes; hence, investigating the possibility of such systems being mandatory for shared e-bikes and specific scenarios of speed enforcement would also be a great point of interest to municipalities and policymakers. Lastly, while this study focused on smart technologies enhancing cycling safety, other technologies focusing on increasing cycling comfort are around the imminent, which seek investigation and research. Such technologies include bike-to-infrastructure communication, pedalling support systems, and technologies related to improving the health condition of the users. While in this study, we focused on only examining users' preferences and WTP for individual functionalities, a potential avenue for further research could be the investigation of a combination of functionalities during the CE since functionalities might have a synergistic relationship. Thus, some expected results could show if the combination of different functionalities turns to higher or lower utility than the derived one from a single functionalityValidation of the WTP values was not possible, no other studies have been published to compare our results, and it was beyond the scope of this paper to compare WTP with technology/market costs of the smart bicycle technologies.

Lastly, we used a realistic price range (€400–€1000) for the choice experiment, we found that respondents in this study were willing to pay €200 more compared to the base category. Thus, further research with lower price ranges is to be advised to understand users' WTP better. Furthermore, the set-up of this study allows us only to examine user preferences among different smart bicycle technologies rather than a specific technology versus no technology at all. Hence, we suggest that further research includes no technology option as an attribute level of the SC experiment; hence, the real WTP will be estimated.

## 5.7. Conclusion

The present research aimed to examine Dutch e-bike users’ and people willing to buy an e-bike in the next five years, preferences, and willingness to pay for the state-of-the-art smart bicycle technologies increasing cycling safety. The study included 725 respondents across the Netherlands, and the sample is comparable to the Mobility panel data in the Netherlands (Kennisinstituut voor Mobiliteitsbeleid, 2021). We estimated a mixed logit model with random coefficients, including interactions with sociodemographic, to allow for sensitivities and heterogeneity. This approach allowed us to estimate a superior model and revealed ample results.

We proved that e-bike and potentially e-bike users are willing to accept and pay for smart bicycle technologies. Participants are generally open to smart bicycle technologies affecting cycling safety and willing to pay sufficient money to use such systems. This paper offers new insights regarding the future of cycling in the Internet of Things era, and policymakers, governments and businesses (e.g., bicycle manufacturers) can benefit from this work and further develop their policy packages and business strategies. For instance, an additional option is that the Speed-Pedelec, available on the market, can be allowed within the city centres and use bicycle paths only if they have specific safety characteristics such as speed limitation.

The results of this study show that Dutch participants have a positive attitude towards smart bicycle technologies; all nine functionalities tested were found to be significant. Dutch participants are willing to pay a significant amount of money on top of the price of an e-bike in order to increase their safety using smart bicycle technologies. The key findings are summarised below as follow:

- Smart routes functionality is the more significant attribute level, followed by the automatic speed limit. Collision avoidance rear side and blind spot are the rest. Cost, as was expected, is negative and significant.
- Certain sociodemographic groups can explain heterogeneity and differentiate in sensitives towards technologies on bicycles.

To conclude, this study offers an in-depth analysis of users’ preferences and willingness to pay for smart bicycle technologies. Results suggest that Dutch e-bike users can adopt such technologies, and we see a potential room in the market for smart bicycle technologies in the Netherlands.

# Chapter 6

# How do cyclists experience a context-aware prototype warning system? Assessing perceived safety, trust, perception and riding behaviour changes through a field study

This chapter is based on: Georgios Kapousizis, Annemarie Jutte, Mehmet Baran Ulak, & Karst Geurs: How do cyclists evaluate a context-aware prototype warning system? A safety assessment through a field study. Submitted for publication in *Journal of Cycling and Micromobility Research (2<sup>nd</sup> review round).*

## 6.1. Introduction

The number of bicycle crashes and fatalities increases yearly worldwide (European Commission, 2023a; ITF, 2023). Europe counts every year around 2000 cycling fatalities happen, which represents around 10% of all road fatalities, and there has been no decrease in cycling fatalities since 2011 (European Commission, 2023a, 2023b). This is probably due to the increased number of people cycling in the last few years and exposure to motor vehicles in many countries with and without cycling culture (European Commission, 2023b; Uijtdewilligen et al., 2022). Moreover, when we account for road fatalities in urban areas, cyclists and other vulnerable road users, such as pedestrians, represent almost 70% of the total fatalities (European Commission, 2023b). The majority of road fatalities within urban areas involve motor vehicles with cyclists and pedestrians.

The recent report from the International Traffic Safety Data and Analysis Group (IRTAD) shows a discouraging trend in cycling fatalities, especially for e-bike users. The share of e-bike users in cyclist fatalities has been increasing in many countries, such as Switzerland (55%), Germany (44%), Belgium (38%), and the Netherlands (34%) (ITF, 2023). In the Netherlands, well known for its cycling policies, culture, and infrastructure, bicycle fatalities represented 40% of all road fatalities in 2022, and the e-bike rate of all cycling fatalities increased by 9% in 2022 since 2018. This is mainly due to the e-bike users' exposure, age and health factors (Westerhuis et al., 2024). In addition, since 2020, the number of cycling fatalities in the Netherlands has been higher than that of passenger cars (Statistics Netherlands (CBS), 2023). Therefore, additional actions should be taken to decrease cycling crash risk and bring these numbers down.

### 6.1.1. Background

Smart bicycle technologies have rapidly developed over the last decades, aiming to influence cyclists' safety and the general view of bicycles, e-bikes and the future of soft transport modes, especially in the era of Internet of Things (IoT) and smart cities (Behrendt, 2016; Kapousizis et al., 2022; Oliveira et al., 2021). These technologies and systems have various functionalities with potentially different impacts on road safety (Engbers, 2019; Westerhuis et al., 2021). Smart bicycle technologies may attract more people to cycling since they could offer a sense of increased perceived safety, and as well as an actual increase in cyclists' safety. Smart bicycle technologies can assist cyclists in reducing the risk of crashes, collisions with other vehicles, and single-bicycle crashes due to the wide range of applications. However, users' perception of smart bicycle technologies and trust will influence their deployment and penetration rate into the market.

Recently, considerable literature has grown on warning systems aiming to prevent collisions (Kapousizis et al., 2022). Linder et al. (2024) examined users' perceived safety and the effectiveness of a bicycle warning system in reducing crashes and human interaction with autonomous vehicles in different scenarios and intersections using a bicycle simulator. Other studies investigated an intersection safety application alert system in field trials using an on-site camera capturing traffic and identifying conflicts based on time to collision (TTC) and post encroachment time (PET) measurements (Soro et al., 2024). When both TTC and PET values were less than 3 seconds, a warning was sent out to the cyclist approaching the intersection. The results of this study showed that participants were willing to use the safety application and preferred to receive simple and clear warnings (Soro et al., 2024). Similarly, Schories et al. (2024) examined the performance of a warning triggers system for cyclists based on a TTC warning with 4 seconds. They applied this method in a virtual simulation, and the results showed positive safety benefits of avoiding a collision with a vehicle. Lastly, Hagelen et al. (2019); Husges and Degen (2021) used radar and lidar sensors on the bicycles to scan the surroundings and estimate TTC and, in case of an imminent collision, send warnings to the cyclists. The findings of these studies indicate the potential benefits of such systems and sensors on cyclists' safety.

To increase cycling safety, researchers also designed and investigated the effectiveness of external nudging approaches aiming to adjust cyclists’ behaviour (Fyhri et al., 2021; He et al., 2019; Kovaceva et al., 2022; Wallgren et al., 2020). While a viable option, this type of feedback is more rigid than having an easily adjustable on-bicycle system. However, previous research on on-vehicle safety communication has mostly focused on drivers (Biondi et al., 2017; Grushko et al., 2021; Spence & Ho, 2008). Drawing from the literature on drivers, Biondi et al. (2017) found that multimodal audio-tactile warnings decreased the braking reaction time more than single modal warnings in the simulation environment. However, Geitner et al. (2019) found that audio-tactile multimodal warnings were perceived as being more startling.

Erdei et al. (2020) found that cyclists most consistently responded to acoustic signals across different real-world environments compared to visual and tactile signals. Tactile signals performed significantly worse on rough roads. However, Erdei et al. (2020) did not consider how users perceived the different signals, which will be explored in this research. Recently, the municipality of Amsterdam conducted a field experiment in order to test users’ reactions when they received warnings (Tollenaar & Plazier, 2023). They used multimodal audio-visual communication, with the visuals serving to inform the cyclist of speed warnings, and the audio serving to make participants aware of the system. However, participants mentioned low satisfaction with the manner of communication (Tollenaar & Plazier, 2023).

For the effectiveness of any warning system, perceived safety and trust are major factors (Jahanshahi et al., 2020; Nordhoff et al., 2020a; Simsekoglu & Klöckner, 2019a); therefore, it is important to test users’ perceptions and preferences towards new technology (Jahanshahi et al., 2020; Nordhoff et al., 2020a; Simsekoglu & Klöckner, 2019a). Moreover, Kapousizis et al. (2024) found that perceived safety has a major role in user behavioural intention to adopt a technology, especially in the Netherlands. Kapousizis et al. (2024) also indicated that testing a smart e-bike in a real environment would capture users’ preferences better, although several studies used online surveys to investigate user’s preferences for an on-bicycle warning system. For instance, using an online survey, De Angelis et al. (2019) examined user preferences for warning systems with audio-visual or haptic modes; however, they did not find a significant difference between them. Nonetheless, Kapousizis et al. (under review-a, under review-b) found that such warning systems have potential and users are willing to pay for them. This means that bicyclists are open to use warning systems to improve their safety. Although there is evidence in the literature for the perceived safety and preferences of cyclists towards warning systems, the majority of existing studies used hypothetical scenarios and surveys. Soro et al. (2024) recently utilized field trials to examine perceived safety in intersections and imminent collision scenarios.

### 6.1.2. Research objective

The studies above provide valuable insights into different types of warning systems and the importance of user acceptance. While different studies examine users' perceptions of some systems and reaction time (Erdei et al., 2020; Strohaeker et al., 2022; Westerhuis et al., 2021), little is known about users' opinions and acceptance of a warning system.

studies above provide valuable insights into different types of warning systems and the importance of user acceptance. However, little is known about users' opinions and interactions with warning systems. This is the first study to conduct field trials to examine users' perceived safety and preferences towards a context-aware warning system based on high crash risk locations, and to evaluate the effectiveness of these systems in improving the safety of cyclists.

This study aims to develop and test a context-aware prototype warning system to support e-bike users in high crash risk locations. For this purpose, we designed an experiment, developed a warning system, identified high crash risk locations, designed a survey, and devised a data collection plan. The objectives of this study are as follows:

1) To investigate cyclists' perceived safety, trust and overall perception of the context-aware cyclist warning system.
2) To investigate the effect of users' riding behaviour receiving warnings from the warning system.
3) To evaluate cyclists' preferences for different communication methods and test whether the audio or haptic may offer a more intuitive interaction with the users.

The developed warning system falls to the bicycle smartness level 2, "warning assistance", based on the classification proposed by Kapousizis et al. (2024), which also has the highest technology readiness level. In addition, Kapousizis et al. (2024) mentioned the importance of users trying out different systems since it might influence their opinions and attitudes. Therefore, alternative communication methods were tried to identify the approaches which cyclists find valuable and motivating while not being too distracting or startling.

The rest of the paper is organised as follows: Section 6.2 describes the methodology, field trials, system development, and data collection approach; Section 6.3 presents the collected data and analyses of the results; Section 6.4 discusses the results, and Section 6.5 presents the conclusion of this paper.

## 6.2. Methodology

### 6.2.1. Field trial setup

The methodology followed in this paper is divided into six parts: 1) the experiment design of the field trials, 2) the safety system design, 3) the cycling crash density model, 4) the apparatus, 5) participants recruitment, and 6) questionnaire and collected data. Figure 6.1 illustrates these parts and serves the conceptual model of this study. In detail, we designed a field experiment and used bicycle crash data to develop a safety model. To develop the safety model we used bicycle crash data and the road network to identify high crash risk locations using the Kernel

Density Estimation (KDE) (we discuss this in Section 6.2.2). Then we used the results of the safety model to feed into a smartphone application to design a system to warn users via visual, oral, and tactile (vibration) notifications, which consists the context-aware warning system. In addition, we developed a survey distributed throughout the field trials to evaluate the context-aware safety support system and users' perceived safety, trust, perception, and riding behaviour changes. The results from this study could be used to further improve the system, as indicated in Figure 6.1. Overall, we organised field trials in Enschede, the Netherlands, including various types of infrastructure (mixed traffic, dedicated bicycle paths/lanes) to investigate how users react to receiving notifications and examine their perceived safety.

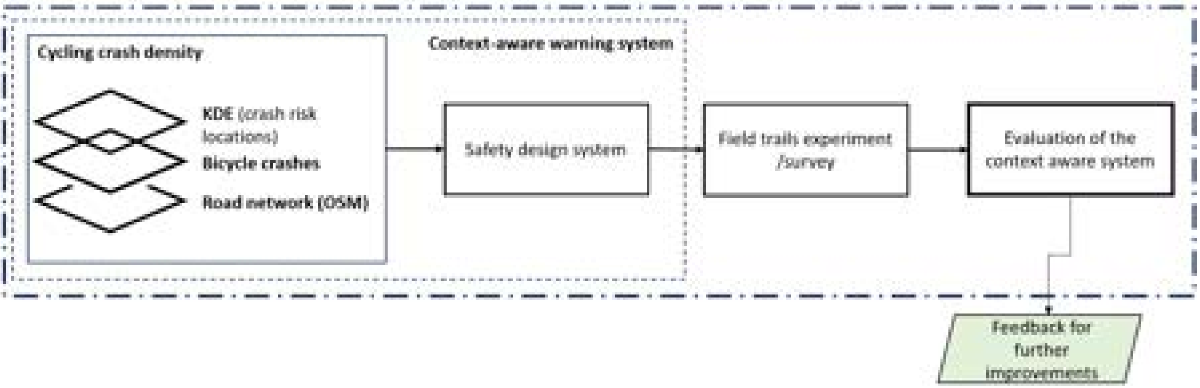


**Figure 6.1: Conceptual model of the study's approach**

### 6.2.1.1. Field trial experiment design

A smartphone-based application was developed and was fed with high crash risk locations as identified based on the crash density model described in the following section. The aim was for participants to ride an instrumented e-bike on a predefined route and receive warnings when they approached a high-risk location to pay more attention and reduce their speed. We selected a route around the University of Twente for the field trial. The reason for this was twofold: 1) practical, we were able to host participants in the university's room, and also the bicycles were there, and 2) we were able to identify a route which was 3.4 km long with different types of infrastructure (mixed traffic, dedicated bicycle paths and bicycle lanes), with a shopping area, school zone; in a total of five high crash risk areas (four locations, one was ridden two times). Figure 6.2 shows the route used for the field trials.

Participants were requested to ride the same route three times. During the first round, whichi served as a baseline ride, the set-up operated normally, but no information regarding road safety was given. This means the warning system was effectively turned off; only the speedometer was shown on the smartphone, as in the 'Approaching' situation in Figure 6.3. The function of this round was to 1) get participants familiar with the new e-bike and 2) to understand the perception and perceived safety of participants when riding this specific route with a "conventional e-bike". During the second and third ride, the warning system was turned on. Participants received warnings through either the audio or tactile modalities combined with visual information each time. In the third round, participants received warnings through the modality they had not experienced in round 2. In the high crash risk locations, participants were given an advisory speed of 20 km/h; this choice was based on pilot studies during which 18 km/h was found to be much too slow, matching the findings of Tollenaar and Plazier (2023), where participants indicated that advisory speeds of 10 or 15 km/h were generally too low. Navigation instructions were given to the participants through the Komoot (https://www.komoot.com/) on one of the smartphones.

In detail, participants rode the e-bike prototype in a predefined route. During the first ride, participants rode the prototype without receiving warnings, that is namely, as a “conventional e-bike”. However, additional sensors such as GPS were used to collect speed data without influencing their riding behaviour. After the first ride, participants filled out the first part of the survey, where they stated their perceived safety, perceived trust and experience. We repeated the survey about users' perceived safety, trust, and experience when they received notifications to reduce their speed. Participants rode the prototype for the second and third ride, receiving warnings from the context-aware prototype warning system based on different modalities. Through this, we investigated how users felt when receiving notifications from the warning system, if they were annoyed or comfortable, and their perceived safety for the context-aware warning system. Overall, we examined to what extent users were blissful, as well as their riding behaviour.

Furthermore, data was collected using GPS from the smartphone, and other sensors were incorporated into the e-bikes, adding valuable characteristics in understanding participants’ riding behaviour. The GPS, which was collected during the rides, allowed us to examine to what extent users followed the notifications and advice the context-aware prototype warning system provided.

#### 6.2.1.2. Crash density

Bicycle crashes have been studied widely in the literature, and there are different approaches to doing so. We aim to identify high crash risk locations in Enschede and develop a safety support system using bicycle crash data. Many studies have used Kernel Density Estimation (KDE) to identify traffic crash clusters (Abdulhafedh, 2017; Anderson, 2009; Ulak et al., 2017). KDE is a non-parametric approach to estimating the intensity of a spatial process, which focuses on clustering pattern distributions throughout an area study region and creates a density surface of spatial point events over a 2-dimensional geographic space (Xie & Yan, 2008). However, in traffic crashes, the events occur in a network; thus, the KDE may not be a good fit (Xie & Yan, 2008). To this end, we used the Network Kernel Density Estimation (NKDE) since road crashes occur along a network, and the density needs to be estimated in a 1-D linear space rather than the Euclidean distance commonly used by the KDE. The NKDE is an extension of the classical KDE.

We used the package spNetwork developed by Gelb (2021) in R (R Core Team, 2023) to proceed with the estimation, which is free and open-source software. We used the road network from the OSM (OpenStreetMap, 2023) and police crash report (BRON) data from 2016-2019. Figure 6.2 illustrates the bicycle crash patterns in the municipality of Enschede resulting from the NKDE; lines with red represent road segments with high crash density. In addition, we used OSM data in order to identify school zones and high street locations, which were found to have a significant impact on bicycle crashes (Kapousizis et al., 2021).

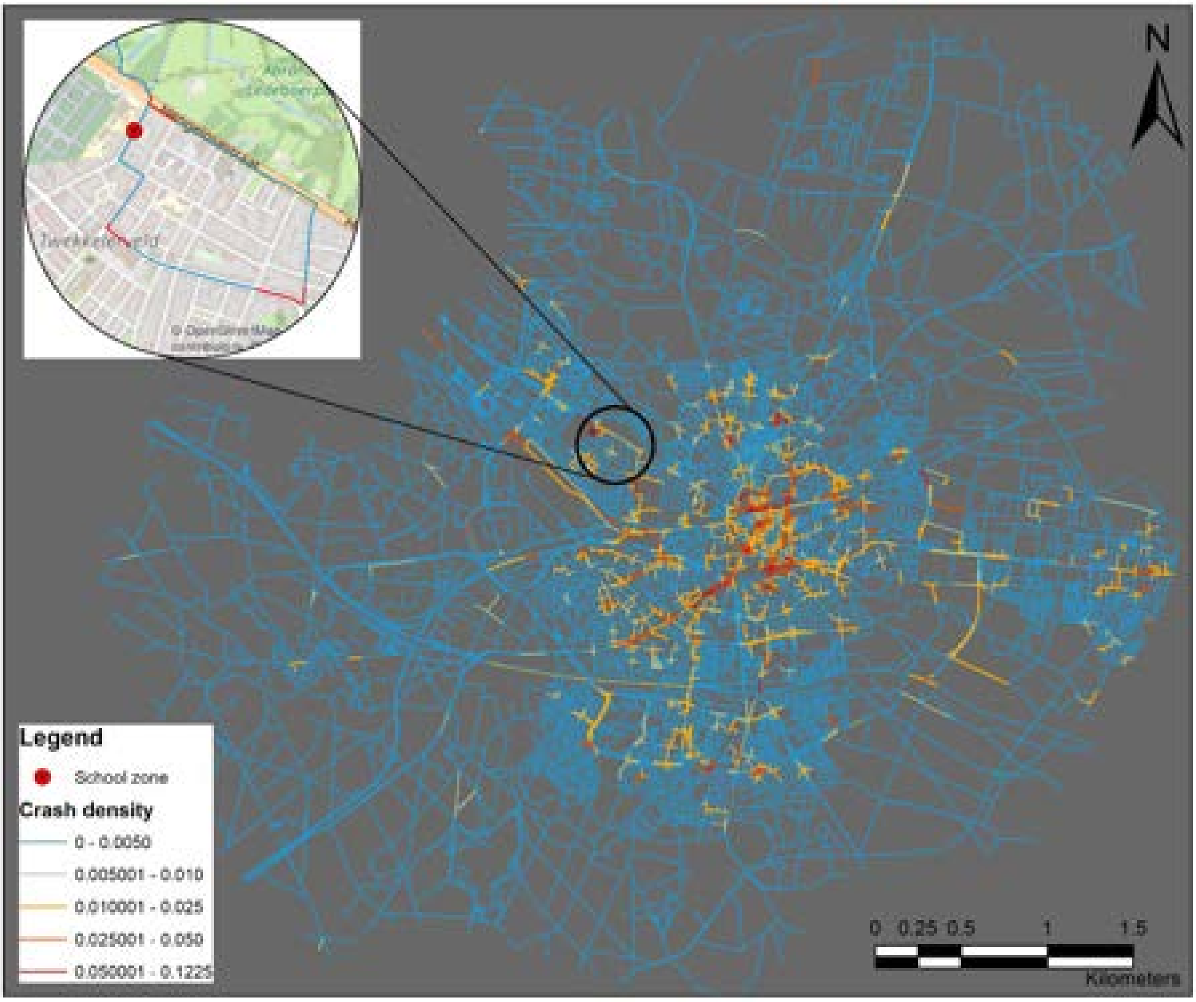


**Figure 6.2: Crash density map of the city of Enschede and location of the field route**

#### 6.2.1.3. Safety system design

The context-aware warning system proposed in this paper communicates the potentially dangerous locations to cyclists. The prototype of the warning system is created as a smartphone app using Android Studio. The context-aware warning system consists of two levels of communication: notifying and informing, similar to the set-up by Tollenaar and Plazier (2023).

The context-aware warning system comes into action when a ‘transition event’ occurs, and an overview of the event loop can be found in Figure 6.3. Four such events are identified: 1) entering: the cyclist enters a dangerous zone; 2) exiting: the cyclist exits a dangerous zone; 3) speeding up: the cyclist speeds up from below the advisory velocity to above; and 4) slowing down: the cyclist retains a ‘safe’ velocity. Additionally, the entering event is split up into two cases: the cyclist is going above or below the advisory velocity.

Notifications are either given as audio signals through bone-conducting headphones or tactile signals through haptic gloves. Bone-conducting headphones have been chosen since they do not block any environmental sounds. Haptic gloves were chosen due to their ease of implementation, as opposed to haptic handlebars (Baldanzini et al., 2011). To minimise distraction, notifications are only sent when potential danger to the cyclist increases during the entering and speeding up transition events.

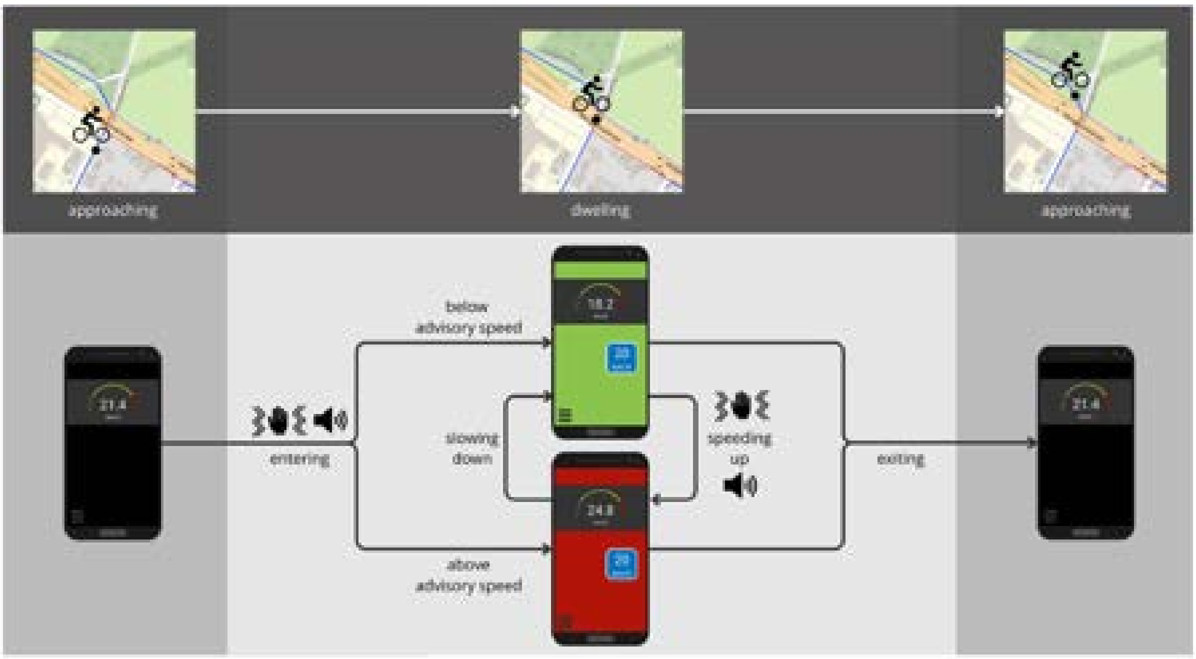


Figure 6.3: Interaction flow of the context-aware warning system prototype.

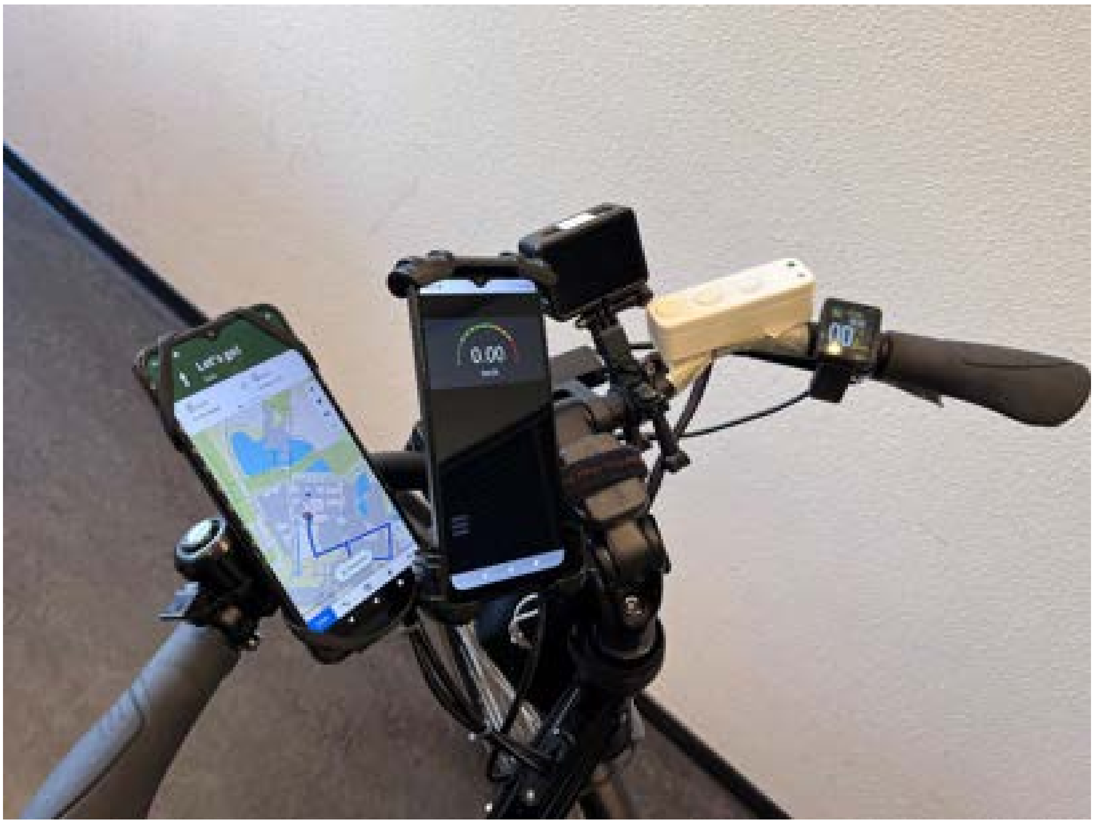


Figure 6.4: Bicycle set-up

Additionally, the system targets to supply less intrusive information that provides additional understanding for the notifications. The aim is to present this information in a way that is easily accessible and understandable without providing too much distraction. The information is given through a smartphone screen as shown in Figure 6.3, similar to the implementation of Tollenaar and Plazier (2023). The smartphone screen is set to red when the cyclist is going above the advisory speed and is set to green when the cyclist is going below the advisory speed. Only the speedometer is shown on normal segments without increased safety issues.

#### 6.2.1.4. Apparatus

Participants were riding a smart bicycle prototype on a predefined route starting at the University of Twente, the Netherlands. The field trial - set up/data collection/recruitment- was a joint work of PhD students as part of the Smart Connected Bikes project (https://www.smartconnectedbikes.nl/) Therefore, the prototype bike incorporated multiple sensors to collect data for different research projects. Including IMU sensors to measure road surface quality). Not all collected sensor data is used in this paper.

For this research, the bicycle was equipped with two Nokia C32 TA-1524 smartphones. One of the smartphones served as a prototype of the context-aware warning system and for GPS measurements; the other was used for navigation. Participants were asked to wear bHaptics TactGlove DK2 haptic gloves or Shokz OpenMove S661 bone conduction headphones for the warning system during the second or third round, as discussed in Section 6.3.4.

Additionally, for related research, one forward-facing GoPro 3 action camera and three Inertia ProMove Miniwere IMU sensors were mounted on the bicycle. Two of the three IMU sensors were attached to the bicycle frame, one to the pedal. In addition, participants were asked to wear a helmet to which another Inertia ProMove Miniwere IMU sensor was attached. Participants also wore an Empatica E4 wristband and a Polar H10 heart rate sensor. Finally, participants were also asked to use a button press system to indicate their experience during the rides.

The audio signal consists of two 780hz signals of 300ms with a 20ms pause. This is the same frequency is as used by Erdei (2020). They used two signals of 650 ms instead of 300ms. However, the shorter duration is chosen since it can be argued that an (unnecessarily) long signal can be more distracting. The phone volume was set to 50%. Following Erdei (2020), the tactile signal consists of two pulses of 250ms with a 400ms pause, however, it is not possible to extract the frequency from the bHaptics interface.

The bicycle was equipped with different hardware features, such as two smartphones, one to give directions to users and the other to communicate safety warning messages, as indicated in Figure 6.4.

#### 6.2.1.5. Participants recruitment

The field trial, along with a questionnaire, was conducted between April and May 2024 in Enschede, the Netherlands. The questionnaire was developed using Maptionnaire (Burnett et al., 2023) and was filled out by the participants during the field trials.

The target population were people 1) older than 18 years, 2) who have been cycling on average at least once per month in the past six months, 3) without the influence of illicit drugs, and 4) without medication that is issued with advice against, or prohibition against, participating in traffic. We used different channels to recruit participants, such as mailing lists of the University of Twente and Saxion University of Applied Sciences, advertisements in online press (U-

Today), local cycling unions in the city of Enschede, portal news of the municipality of Enschede, the Enschede Fiets app and personal social media. The field trials with the questionnaire had a completion time of around 1.5 hours. Each participant received a voucher worth €10 as a token of appreciation for their time. In total, 46 participants were recruited and participated in the field trials.

Before the field trials started, initial pilots with the instrumented e-bikes took place to test that all sensors worked properly, and that the set-up was feasible. In addition, we tested the survey; we first piloted it within the research group and later with some participants. Once the pilot of the field trials and the survey were successful, the survey was translated into Dutch by native speakers within the research group and tested once more to ensure the readability and consistency of the translation.

#### 6.2.1.6. Questionnaire

Enschede has a population of around 150 thousand inhabitants, with a dense cycling infrastructure as do most Dutch cities. The city of Enschede has international influences since the University of Twente is located there, and there are many international and high-tech companies. Thus, the survey was translated into Dutch and English to account for both native and foreign citizens. Note that the survey was developed in English, and two pilots were used to ensure the optimal structure and reliability of the questions. Thus, the questionnaire was distributed among researchers from our groups, and after two iterations, we translated the survey into Dutch. In total, 46 participants joined the field trials. After cleaning the data, 41 were analysed; two participants did not complete the rides due to rain, and three participants experienced technical issues, so we decided to exclude them. All participants completed three rounds: 25 completed the second round using audio warnings and the third round with the tactile, while 16 completed the second round with the tactile communication and the third round with audio warnings. The number of experiments that resulted from audio and tactile warnings was merely due to the availability of the equipment.

Questions in the survey for this research were divided into two parts: 1) questions related to sociodemographic statistics, participants' general mobility habits, and participants' perceived safety and experiences when they cycle in their daily lives; 2) questions about the participants' opinions on the context-aware warning system. Note that the second part was repeated three times, once after each ride. The questionnaire that was used can be found in Appendix F. Participants received a written information brief about the steps of the field trials as well as an oral explanation. Initially, participants were requested to fill out the first part of the survey, which consisted of sociodemographic information as mentioned above. Then, participants were requested to proceed by riding the bicycle. During this ride, no warnings were given through the prototype. Once the ride was completed, participants filled out the second part of the survey. Then, participants received an explanation of the safety support system and a set of 5-Likert scale questions about their expectations of the system.

The explanation of the context-aware warning system given to the participants during the survey was as follows:

*"In our research, we want to evaluate the design and effects of a warning system. The system warns you to avoid collisions with other road users. The warnings are given at hazardous locations, through visual, audio and/or vibration signals. We would like to ask you some questions about your expectations of this system."*

Then, participants continued with the second ride, during which warnings were given when entering critical locations. After the second ride, participants received another set of questions to evaluate the system based on their experience and perceptions. Participants rode the same route again in the third and last ride, during which signals were given through the modality not yet tested. They received the same set of questions as after the second round. Table 6.1 presents an overview of the questions we used in the survey.

**Table 6.1 Overview of the questions used**

| Category | Question | Source |
|---|---|---|
| Perceived safety | I would feel safe with the Warning System.<br>I think with the Warning System I can increase my safety<br>I think that riding with the Warning System can reduce the risk of me getting involved in a crash compared to a conventional bike<br>I think that there will be fewer crashes for users with the Warning System. | *(Jahanshahi et al., 2020; Kapousizis et al., 2024) and own investigation* |
| Perceived trust | I would trust the Warning System<br>I will ride with more stress using the Warning System.<br>I would like to use the Warning System.<br>I think the Warning System would be easy to use.<br>I expect that the capabilities of the Warning System will meet my requirements. | (Hinderks et al., 2018; Kapousizis et al., 2024; Nordhoff et al., 2020a; Venkatesh et al., 2012) |
| Perceived performance | Useful to useless<br>Assisting to worthless<br>Undesirable to desirable<br>Understandable to badly understandable<br>Raising alertness to reducing alertness<br>Noticeable to badly noticeable<br>Motivating to Very demotivating | (Hinderks et al., 2018) *and own investigation* |

### 6.2.2. Research methods

In this study, we had two main sources of collected data: 1) survey data and 2) GPS data, which was collected using smartphones. Participants' answers to the survey give us information about their perception of the context-aware warning system. At the same time, GPS data allows us to assess the effects of the system based on different modalities on participants' riding behaviour, specifically in speed reduction.

We calculated the average speed of the participants 5-seconds before and after the point they were supposed to receive a warning. The GPS used during the field trials had 1Hz accuracy, recording 1 point per second. After testing the context-aware support system, we used a 5-

second window as the proper time to allow participants to react after receiving a warning. Thus, we used 5-second windows before and after high crash risk locations.

Initially, we used t-tests to examine whether speed reductions in high crash risk locations differed by personal characteristics, such as gender, and usage of e-bike and conventional bicycle and if they were statistically significant. We used 299 speed points for the three rides for the "SlowDown" event to examine whether participants reduced their speed when initially receiving the warnings.

We further examined users' speed reduction after receiving system warnings by applying a Multinomial Logit model (MNL) to the collected data. We refer readers to the following study for more information about the MNL (McFadden, 1973). We estimated two MNLs to analyse participants' speed when they approached a high crash risk location and their speed when they received warnings to reduce their speed. For this part of the analysis, we used the "entering", "slow down", and "slowdown reminder" since these are the cases in which participants receive notifications. In total, we used 1560 warnings, 524 warning points for audio communication, and 592 for tactile communication. The remaining 444 data points are from the first ride (baseline) participants completed and were supposed to receive warnings. In order to perform the analysis, we used the five-second average speed before and after the warnings.

## 6.3. Results

### 6.3.1. Data statistics

As mentioned earlier, 41 participants were included in the analysis after the data cleaning. The mean age of participants was 42.1 (SD = 15.65) and ranged from 25 to 75 years of age; 73% were males (n = 30), and 63% (n = 26) earned a university degree. In addition, 73% (n = 30) of the participants use a bicycle weekly, more than four days a week, while only 22% (n = 9) use an e-bike weekly, meaning they have a quite good cycling experience. None of the participants used a Speed-Pedelec in a related question we asked. The sample distribution can be found in Table 6.2.

**Table 6.2 Sample composition**

| Variable | Sample | |
|---|---|---|
| | Count | Percentage |
| Number of respondents | 41 | 100% |
| **Gender** | | |
| Male | 30 | 73% |
| Female | 11 | 27% |
| **Age** | | |
| <25 | 4 | 10% |
| 25-35 | 18 | 44% |
| 36-45 | 2 | 5% |
| 46-55 | 7 | 17% |
| 56-65 | 5 | 12% |
| 66-75 | 4 | 10% |
| >75 | 1 | 2% |
| **Education** | | |
| Low (high school or lower) | 6 | 15% |
| Vocational (Technical) | 8 | 20% |
| High (university degree or higher) | 26 | 63% |
| Other | 1 | 2% |
| **Net monthly individual income** (€/month) | | |
| up to 3000 | 26 | 63% |
| More than 3000 | 15 | 37% |
| **E-bike usage** | | |
| Never or less than 1 day per year | 25 | 61% |
| 1 to 5 days per year | 6 | 15% |
| 6 to 11 days per year | 1 | 2% |
| 1 to 3 days per month | - | 0% |
| 1 to 3 days per week | 2 | 5% |
| 4 days or more per week | 7 | 17% |
| **Conventional bicycle usage** | | |
| Never or less than 1 day per year | 6 | 15% |
| 1 to 5 days per year | - | 0% |
| 6 to 11 days per year | 2 | 5% |
| 1 to 3 days per month | 3 | 7% |
| 1 to 3 days per week | 4 | 10% |
| 4 days or more per week | 26 | 63% |

### 6.3.2. Perceived safety and trust

Participants' scores for perceived safety and trust based on a 5-Likert scale of questions are shown in Figure 6.5 and 6.6 . Participants completed a repeated survey after every ride (without intervention-baseline, with audio and visual, and tactile and visual). Thus, we were able to capture participants' opinions about the context-aware warning system.

As shown in Figure 6.5, question Q1: *I would feel safe with the Warning System* indicated that participants felt safer with the warning system compared to the baseline, especially with tactile communication. The second question, Q2: *I think the Warning System I can increase my safety,* shows that participants had higher expectations since the score for the baseline has the highest value, while the audio and tactile come slightly after. In addition, we notice that while there was

22% “Neutral” in the baseline, later, after the rides, participants shifted to the negative side and felt less safe with the tactile warning.

Regarding Q3: *I think that riding with the Warning System can reduce the risk of me getting involved in a crash compared to a conventional bike*; we see that for the baseline, 44% of participants believed that the Warning System will decrease their risk of involvement in a crash, and 34% was neutral. However, after the rides, the neutral percentage shifted to the negative side since the percentages were 27% for the audio and 34% for the tactile. This means that participants were not fully convinced that the warning system could increase their safety compared to a conventional bicycle.

For the last question, Q4: *I think that there will be fewer crashes for users with the Warning System*; 49% of the participants had a neutral opinion, 44% positive and only 7% negative for the baseline. However, we see that after using the warning system, participants have a positive opinion in this regard, especially for the tactile warning. Overall, we see that during the first round of questions (before the participants experience the system) it seems that they keep a neutral attitude, while this changes after the rides. In addition, we see a shift from neutral to negative, implying that participants were less satisfied. However, we also found that participants had a positive opinion about the context-aware warning system for three out of the four questions.

Regarding participants’ trust for the context-aware warning system, as shown by Figure 6.6, participants’ scores for Q1: *I would trust/trusted the Warning System*, are in the middle, with 37% indicating a positive opinion for the baseline. After participants rode the e-bike with the warning system, their trust reduced to 23% for the audio warnings; for the tactile, their trust remained at 37%. However, most participants had a negative opinion in both audio and tactile settings, indicating a low trust in the system. Regarding Q2: *I will ride/rode with more stress using the Warning System;* for the baseline, the majority of the participants expected to feel lower stress. However, they mentioned that they felt higher stress using the Warning System, especially for the tactile.

About question 3, Q3: *I would (like to) use the Warning System,* most of the participants have a negative opinion, with only 21% and 28% having a positive opinion of the audio and tactile, correspondingly.

Q4: *I think the Warning System would be/was easy to use,* we see that the majority of the participants have a positive opinion, with 79% thinking that tactile is easy to use and 67% for the audio. It is important to mention that before the rides, 44% of the participants had a neutral opinion, which changed after the rides. Regarding the last question, Q5: *I (expect) that the capabilities of the Warning System will meet/met my requirements,* the positive answers have remained similar between the baseline and the rides; however, half of the participants initially had a neutral opinion (before they try out the e-bike), they shifted to negative ones.

### 6.3.3. Perceived performance

During the survey and field trials, participants were also asked to evaluate the warnings they received on a number of scales. The resulting scores the participants gave can be found in Figure 6.7 and Figure 6.8. Participants were asked for this evaluation after rides 2 and 3.

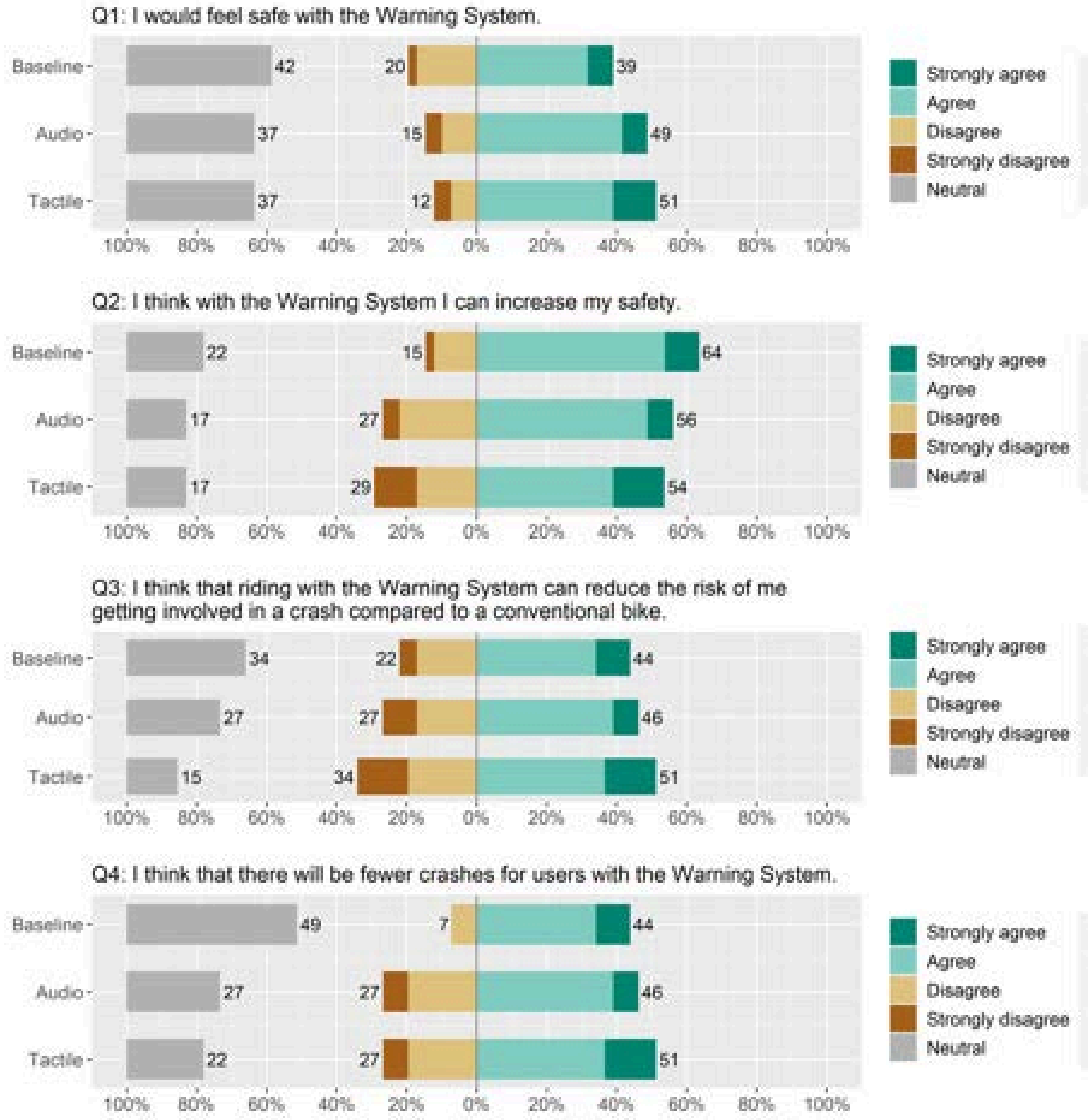
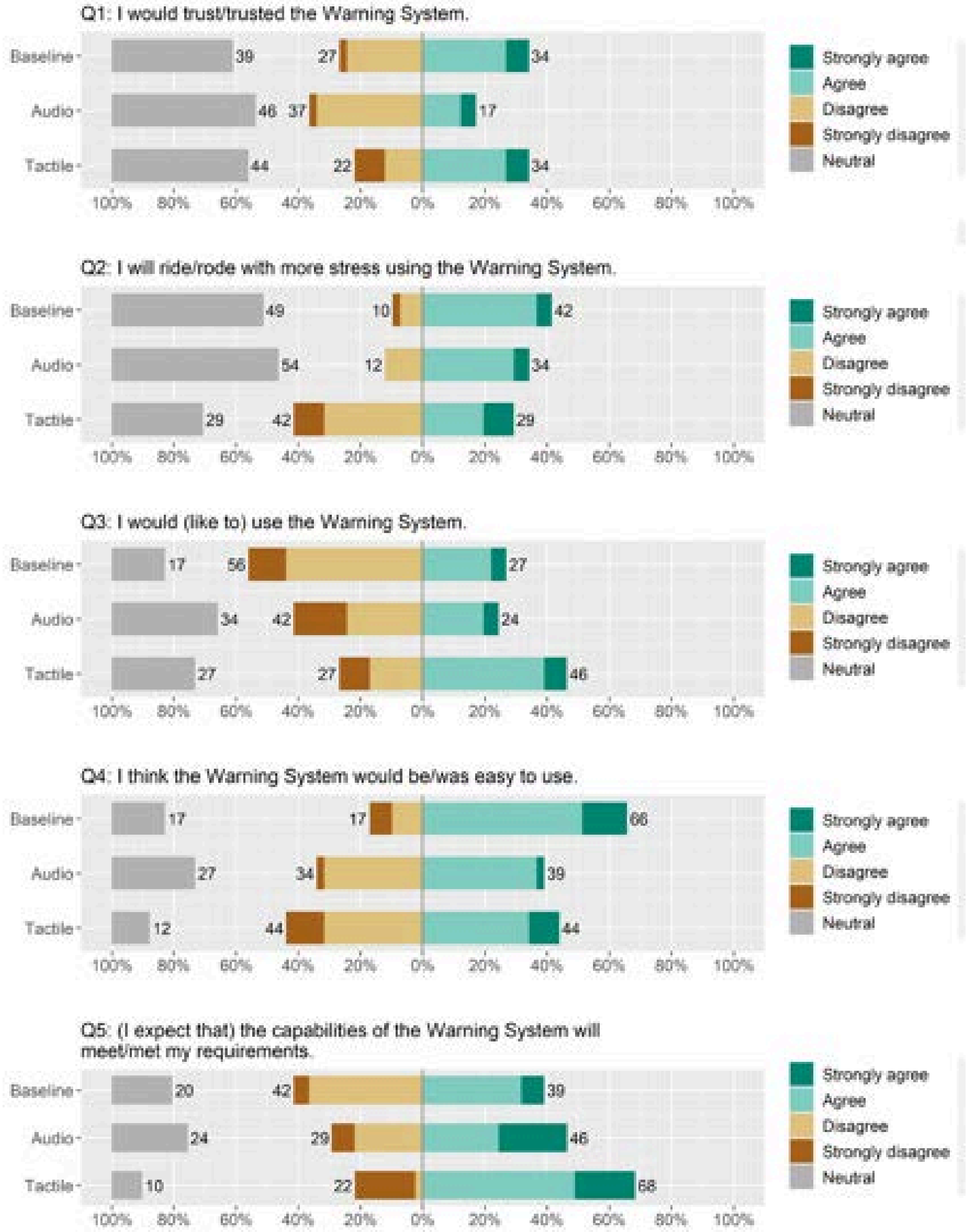


Figure 6.5: 5-point Likert scale questions related to perceived safety


Q1: I would trust/trusted the Warning System.

Q2: I will ride/rode with more stress using the Warning System.

Q3: I would (like to) use the Warning System.

Q4: I think the Warning System would be/was easy to use.

Q5: (I expect that) the capabilities of the Warning System will meet/met my requirements.

Figure 6.6: 5-point Likert scale questions related to trust.

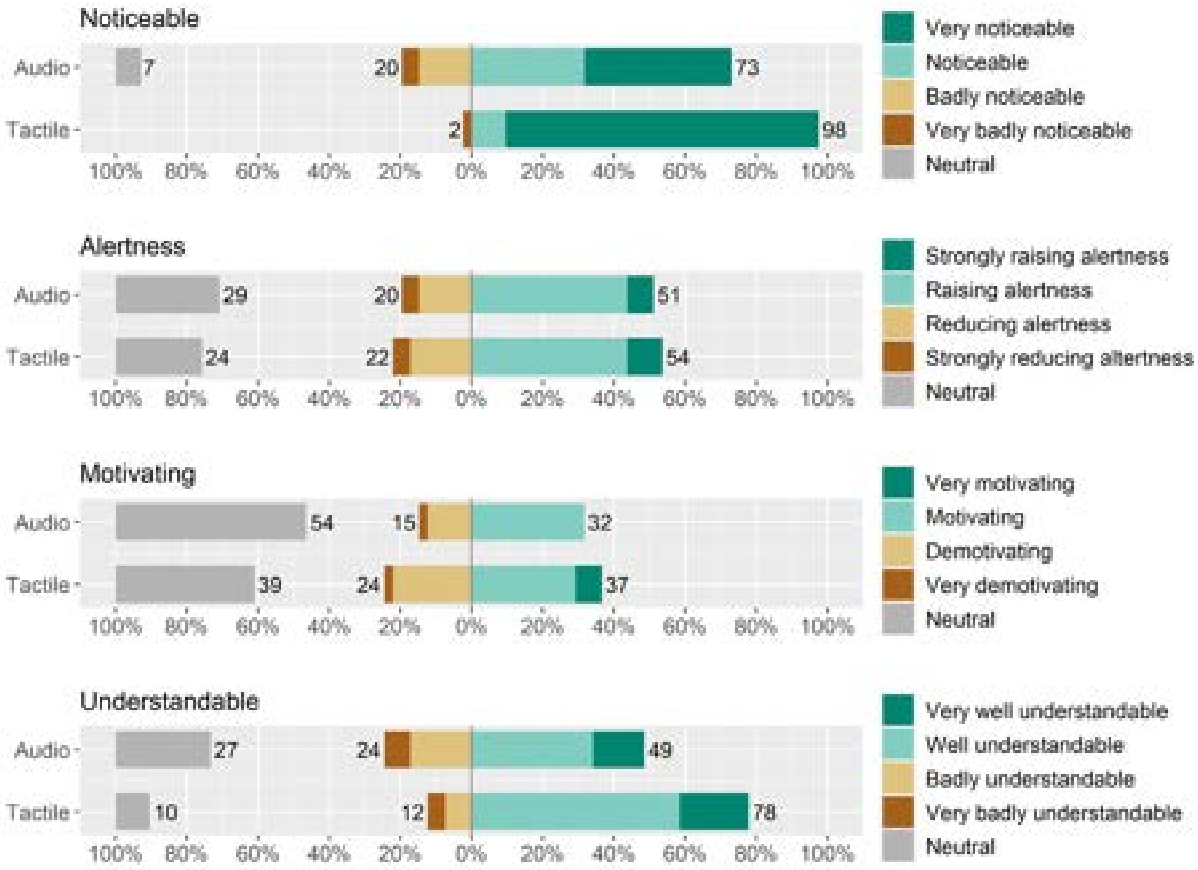


**Figure 6.7: 5-point Likert scale evaluation of the warning system for different scales related to the perceived performance.**

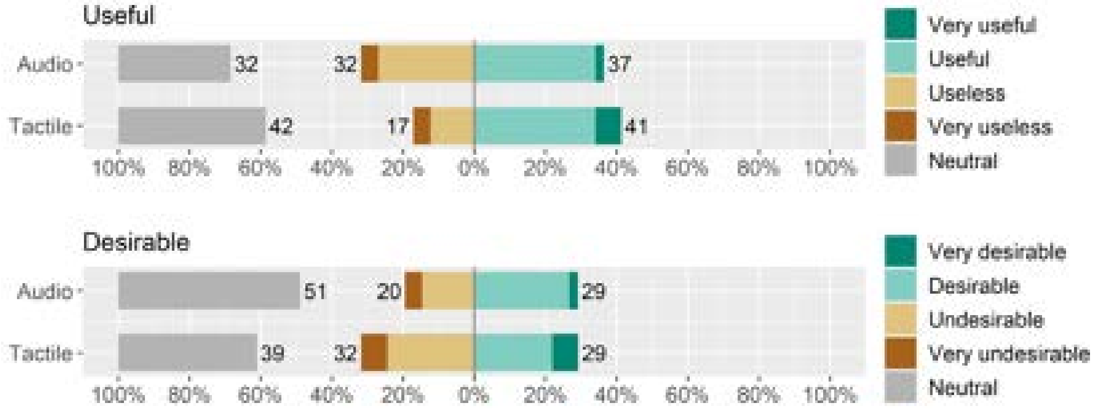


**Figure 6.8: 5-point Likert scale evaluation of the context-aware warning system for different scales related to the perceived usefulness and desirability of the system.**

As can be found in Figure 6.7, most participants indicated that they found both the audio and tactile warnings noticeable. As many as 97% of the participants found the tactile warnings noticeable, while 73% found the audio warning noticeable. The scores for alertness are mostly towards raising alertness, although some participants did feel like the system reduced their alertness (51% for audio and 53% for tactile). A possible explanation for this might have to do with the behavioural adaptation of the participants (Smiley, 2000). Regarding the scores for motivating the system, most participants had a neutral attitude, while only 32% had a positive opinion for the audio and 36% for the tactile. Lastly, participants evaluated to what extent the warnings were understandable, with most participants (78%) indicating that they found the tactile clear, while the audio was only 49%.

Participants' opinions on the context-aware warning system's usefulness and desirability varied (Figure 6.8). In detail, 36% of the participants found the tactile warning useful, and 41% found the audio useful. Regarding the system's desirableness, 29% of the participants gave a positive score for the audio and tactile aspects. However, we noticed that a high proportion of the participants had a neutral opinion for both questions.

### 6.3.4. Riding behaviour changes

Besides the survey data, GPS data was also collected using the smartphones. We used this data to estimate the actual change in cyclists' speed behaviour. For 38 participants, measurements from all three rounds are available and included in these results. The participants who were not included had a GPS failure during one of the rounds.

We calculated the average speed of the participants 5-seconds before and after the point they were supposed to receive a warning. The GPS used during the field trials had 1Hz accuracy, meaning it was recorded 1 point per second. After testing the context-aware support system, we ended up using a 5-second window as the proper time to allow participants to react after they received a warning. Thus, we used 5-second windows before and after high crash risk locations.

First, we compared participants' speed for the baseline ride (without intervention) against the rides with the intervention. We applied the same for the rides with the interventions. We calculated the average speed for all the locations, before and after warnings, and found that participants reduced their speed by 1.3 kilometres per hour after intervention.

In addition, we ran t-tests in order to examine the difference in average speed between the two groups. In detail, we used the ride without intervention as a baseline and compared it with the audio and tactile interventions (Table 6.3). It The average speed for all three rides was almost the same before a warning was communicated to the users (baseline: 22.9km/h, audio: 23.1km/h and tactile: 23.0km/h). After the warning, users-reduced their speed on average by 1.2km/h and 1.4 km/h for audio and tactile, correspondingly.

**Table 6.3 T-test for speed differences (baseline, audio and tactile)**

| Type | Mean before | Mean after | Mean diff | SD before | SD after | p-value | t value | df |
|---|---|---|---|---|---|---|---|---|
| Baseline | 22.94 | 22.50 | 0.44 | 2.62 | 2.12 | 0.222 | 1.22 | 166.73 |
| Audio | 23.17 | 21.95 | 1.22 | 1.97 | 2.52 | 0.001 | 3.91 | 196.62 |
| Tactile | 23.03 | 21.61 | 1.42 | 1.98 | 2.33 | 0.001 | 4.78 | 204.81 |

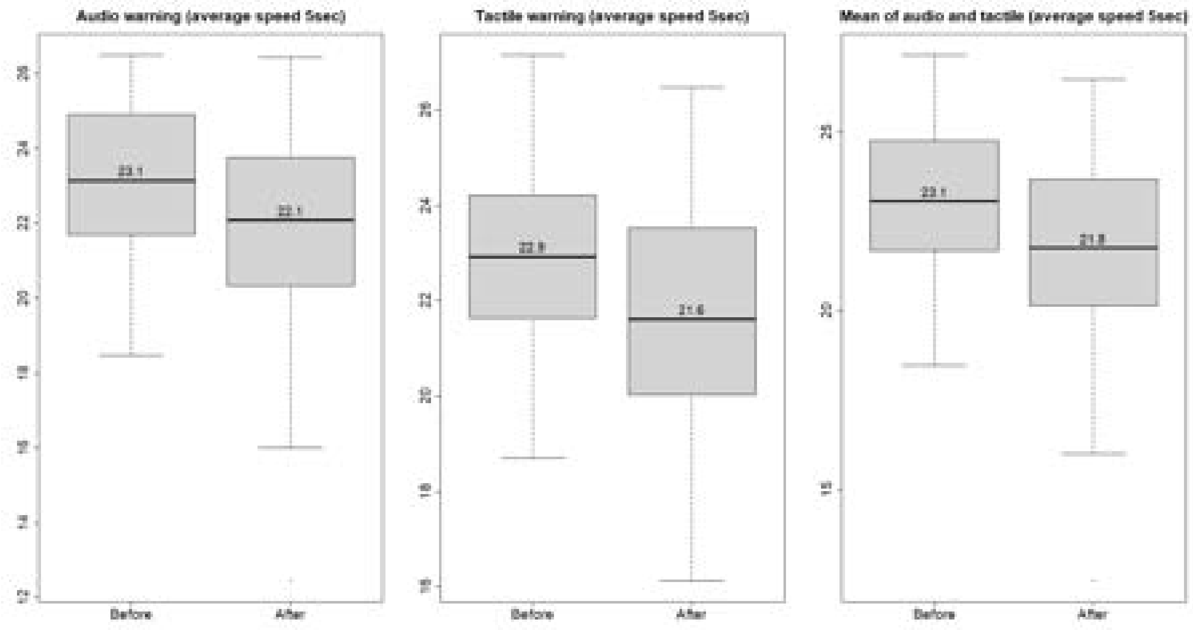


**Figure 6.9: Average speed before and after warnings based on different modalities**

Figure 6.9 shows the average speeds before and after the warnings for the individual modalities, audio and tactile, in the average 5-second windows before and after participants enter a high crash risk location, and the average speeds for both modalities.

Furthermore, as mentioned earlier (Section 6.2), in our experiment, we used a route with five different high crash risk locations (one was a school location), where participants were receiving warnings. Thus, we also compared participants' speeds before and after warnings in the different locations. We compared the participants' speeds when entering a location without and with the context-aware warning system, and we found that participants had lower speeds after receiving warnings when they entered high crash risk locations, and the speed reduction was almost equal in all locations.

### 6.3.5. Factors affecting speed reduction

Table 6.4 presents the test results based on different types of warnings and the different variables that were used. Males were found to have a higher speed reduction than females in both types of warnings. For the audio, males had a reduction of 1.2km/h (p-value < 0.001) and females only 0.6km/h; similar rates were found for the tactile 1.3km/h (p-value < 0.001) for males and 0.9km/h for females after they received the warnings. The differences in speed reduction were not significant for female participants. Females were found to cycle with an average speed of 21.8km/h before receiving a warning, while males 23.5km/h, females used to cycle 1.7km/h slower than males. Therefore, males and females reduced their speed, however the speed reduction for the males was more significant since they approached a high-speed location with a higher speed.

**Table 6.4 t-test for different sociodemographic groups and warning types**

| | Type | Mean before | Mean after | Mean diff | SD before | SD after | p-value | t value | df |
|---|---|---|---|---|---|---|---|---|---|
| Audio | Males | 23.67 | 22.43 | 1.25 | 1.87 | 2.61 | 0.001 | 3.385 | 136.070 |
| | Females | 22.00 | 21.44 | 0.56 | 1.65 | 1.73 | 0.423 | 0.817 | 21.947 |
| | e-bike weekly | 23.29 | 22.18 | 1.11 | 1.88 | 2.35 | 0.261 | 1.162 | 17.165 |
| | No e-bike weekly | 23.46 | 22.31 | 1.15 | 1.94 | 2.55 | 0.002 | 3.191 | 143.570 |
| | Bicycle weekly | 23.49 | 22.61 | 0.88 | 1.86 | 2.19 | 0.010 | 2.592 | 136.350 |
| | No bicycle weekly | 23.24 | 20.97 | 2.27 | 2.19 | 3.33 | 0.027 | 2.338 | 27.705 |
| Tactile | Males | 23.37 | 21.99 | 1.38 | 2.10 | 2.52 | 0.001 | 3.76 | 153.140 |
| | Females | 21.68 | 20.77 | 0.91 | 1.74 | 1.54 | 0.207 | 1.304 | 19.708 |
| | e-bike weekly | 22.33 | 20.77 | 1.56 | 1.98 | 1.95 | 0.114 | 1.674 | 15.997 |
| | No e-bike weekly | 23.26 | 21.96 | 1.3 | 2.13 | 2.48 | 0.001 | 3.594 | 158.520 |
| | Bicycle weekly | 23.23 | 21.93 | 1.3 | 2.11 | 2.41 | 0.001 | 3.55 | 149.330 |
| | No bicycle weekly | 22.83 | 21.37 | 1.46 | 2.27 | 2.66 | 0.133 | 1.554 | 25.347 |

***: p-value < 0.001, **: p-value < 0.05, *: p-value < 0.1.

The last variables we tested were the usage of bicycles weekly or not, and types, such as e-bikes and conventional bicycles. We tested participants using an e-bike on a weekly base (more than one time per week) against those who do not use an e-bike weekly. We found that both groups reduced their speed by 1.1km/h after receiving audio and 1.4km/h when receiving tactile warnings. However, only the non-weekly e-bike users were found to have a significant difference. This is probably due to the small number of weekly e-bike users. For the conventional bicycle users using a bicycle weekly, it was found that a speed reduction of 0.9km/h for audio and 1.3km/h for tactile warnings were both significant with a p-value < 0.05. However, for the other group, participants using a bicycle less than once a week, were found to have non-significant differences again due to the small number of participants in this group.

Furthermore, we estimated a MNL and used the following categories:

- 0: participants did not follow the recommendation;
- 1: participants reduced their speed up to 1km/h;
- 2: participants reduced their speed between 1 and 2km/h;
- 3: participants reduced their speed by more than 2km/h.

Finally, we estimated two models, one for the audio warnings and one for the tactile. Table 6.5 and Table 6.6 present the results correspondingly. During the model estimation, we used the category "0: no speed reduction" as a reference category and the comparison made against it.

**Audio:** The results of the rest of the categories are as follows: gender (males) has negative betas in the first two reduction categories (0–1 and 1–2 km/h reduction)($\beta = -0.276$ $\beta = -0.198$), while for the third category (more than 2km/h reduction) it was found that to be a positive beta ($\beta = 0.687$), meaning that males are less likely to reduce their speed by 0–2km/h than the females. Also, males are more likely to reduce their speed by two kilometres than females. Age was used as a dummy variable here and the comparison between participants older than 55 against the rest of the age groups. A positive beta was found only for the last category (reduction of more than 2km/h), but still no significant difference with the base category (participants younger than 55). Participants using an e-bike weekly are more likely to reduce their speed by 0–1 km/h or 1–2km/h, compared to participants not using an e-bike weekly. With the category 1–2km/h reduction to be significant (p-value = 0.042). Regarding the last variable, participants who use a conventional bicycle weekly, it was found that they are less likely to reduce their speed by more than 2km/h compared to participants using a bicycle less often; (β = -1.438, p-value = 0.003).

**Tactile:** Regarding the model results for the tactile warnings, we found that, again, males are more likely to reduce their speed by more than 2km/h compared to females. Additionally, we found that participants of the age group older than 56 have negative estimates, for the first two categories (0-1km/h and 1-2km/h reduction), meaning that they are less likely to reduce their speed compared to females. However, they are more likely to reduce their speed by more than 2km/h compared to females. Participants who use an e-bike weekly are more likely to reduce their speed up to 2km/h (β = 1.247, p-value = 0.04) compared to participants using an e-bike less. Finally, participants using a conventional bicycle weekly are more likely to reduce their speed in all categories than those using a conventional bicycle a few times a month or less.

Furthermore, the first model for audio indicates that frequent bicycle users have negative estimates in the last speed category (more than 2km/h reduction) and at a significant confidence level, while we do not find similar results for the tactile warning. Overall, we did not find statistically significant differences for most of the variables in both warnings, audio and tactile, probably due to the small number of participants and data points. These results, therefore, need to be interpreted with caution.

## 6.4. Discussion of the results

### 6.4.1. Explaining users' perceived safety and trust

Participants in this study evaluated the safety support system. In detail, we see that participants have a higher perceived safety for the system in questions Q1: I would feel safe with the Warning System, Q2: I think the Warning System I can increase my safety, and Q4: I think that there will be fewer crashes for users with the Warning System compared to the baseline before they ride the instrumented e-bike. Only in question, Q2: I think the Warning System I can increase my safety participants scored higher for the baseline than the audio and tactile scenarios. What stands out in this analysis is that more than half of the participants have a positive opinion of the safety support system. In addition, we notice a higher preference towards tactile communication since it gives them a higher perceived safety compared to the audio; however, this difference is small. Thus, we can see that the system increased participants' perceived safety. Perceived safety was found to be a significant factor in user acceptance of the behavioural intention of a smart e-bike (Kapousizis et al., 2024).

Interestingly, the effect of trust in the system is lower compared to the perceived safety. We found that participants had higher expectations based on what they got, which is reflected in their scores regarding their trust in the safety support system. Less than half of the participants trust the system, and only in question Q4: I think that there will be fewer crashes for users with the Warning System did around 70% state that the system is easy to use. In other words, we found that participants in this study found the system easy to use, which was also found to be a significant factor in accepting smart bicycle technologies by Kapousizis et al. (2024). While participants show a high perceived safety for the system, potential users of this system need to be convinced and trust the system as well. Thus, we believe that a system with fewer devices in the handlebar will be more trustworthy than the current one (Figure 6.3). Overall, improvements in the system's set-up are suggested to improve the system's trust since it also affects user acceptance in other studies (Kapser & Abdelrahman, 2020; Kim et al., 2024).

**Table 6.5 Model results for audio warnings**

**Audio**

| **Reference Class: No speed reduction** | **0-1 km/h reduction** | | **1-2 km/h reduction** | | **More than 2 km/h reduction** | |
|---|---|---|---|---|---|---|
| Variables | Beta | St.Error | Beta | St.Error | Beta | St.Error |
| (Intercept) | -0.960 | 0.595 | -3.827 | 1.219 | -1.333* | 0.750 |
| gender (male) | -0.276 | 0.403 | -0.198 | 0.613 | 0.687 | 0.654 |
| Age group ≥56 | -0.265 | 0.446 | -0.899 | 0.806 | 0.688 | 0.497 |
| E-bike (weekly) | 0.055 | 0.684 | 2.163** | 1.063 | -1.102 | 0.825 |
| Bicycle (weekly) | -0.194 | 0.509 | 1.769 | 1.170 | -1.438*** | 0.493 |

***: p-value < 0.001, **: p-value < 0.05, *: p-value < 0.1.

**Table 6.6 Model results for Tactile warnings**

**Tactile**

| **Reference Class: No speed reduction** | **0-1 km/h reduction** | | **1–2 km/h reduction** | | **More than 2 km/h reduction** | |
|---|---|---|---|---|---|---|
| Variables | Beta | St.Error | Beta | St.Error | Beta | St.Error |
| (Intercept) | -0.543 | 0.493 | -2.463*** | 0.7223 | -2.405** | 0.783 |
| gender (male) | -0.568 | 0.359 | -0.107 | 0.503 | 0.66 | 0.647 |
| Age group ≥56 | -0.517 | 0.396 | -0.004 | 0.471 | 0.604 | 0.446 |
| E-bike (weekly) | 0.631 | 0.503 | 1.247** | 0.607 | -0.235 | 0.705 |
| Bicycle (weekly) | 0.147 | 0.417 | 0.930 | 0.637 | 0.032 | 0.554 |

***: p-value < 0.001, **: p-value < 0.05, *: p-value < 0.1.

### 6.4.2. Explaining users' riding behaviour changes

The average speed of the participants during the first round was found to be higher compared to the rounds with the speed interventions. In detail, we estimated the average speed before and after a participant received a warning. For the baseline round, we found that participants did not change their speed when approaching a high crash risk location; however, they did reduce their speed by almost 2km/h during the second and third rounds when they received warnings. This means that the intervention was effective, which may result in reducing crash risk due to the high speed, which was found to be a significant factor associated with e-bike crashes (Kapousizis et al., 2024; Stelling et al., 2021). A similar study using a bicycle simulator also found that warning messages influenced participants to reduce their speed (Linder et al., 2024).

Furthermore, regarding the effectiveness of the two different nudging systems, we found that the average speed with the tactile warnings was slightly lower than the audio (0.2km/h difference). This might be because some participants mentioned that they did not always hear the audio communication since the bone-conducting headphones were sometimes shifted due to the helmet.

### 6.4.3. Explaining speed reduction

We explained the speed reduction by comparing participants with different sociodemographic characteristics and mobility habits using t-test group differences and MNL model. The information on sociodemographic characteristics and mobility habits was collected from the survey, as explained in Section 6.2.

As indicated in Section 6.4.5, and based on the t-test we estimated, we found that both males and females reduced their speed when approaching a high crash risk location, meaning they followed the warnings from both audio and tactile communication channels. However, we found that speed reduction for males was higher than for females since males were found to ride at a higher speed compared to females in our field experiment. These results are in line with the results from the MNL model since we found that males are more likely to reduce their speed by 2km/h, in both communication channels as well. Even though males had a higher speed reduction after receiving a warning, their speed was still higher than the females' speed (22.4km/h vs 21.4km/h for audio warnings and 22.0km/h vs 20.8km/h for tactile).

We also found that participants who use e-bikes weekly showed no significant difference again, probably due to this group's low number of members. Positive speed reduction was also found in the MNL model, with only a statistically significant difference for the group 1–2km/h reduction. Participants using a conventional bicycle weekly were found to have a significant difference before and after the warnings in both communication types (audio and tactile) since, on average, they reduced their speed by almost 2km/h. Regarding the MNL model, we found that participants who use a conventional bicycle weekly were less likely to reduce their speed by more than 2km/h than non-conventional bicycle users. The findings align with a recent study by Soro et al. (2024), which found that participants using a bicycle weekly were more likely to use an intersection system alert than those cycling less. Lastly, participants older 55 were found to be more likely to reduce their speed by 2km/h in the MNL model, but this result is not statistically significant. Overall, no significant effects were observed in both models.

### 6.4.4. Policy and practical implications of the study

This study proved the usefulness and effectiveness of an early safety support system for e-bike users since it positively influences the perceived safety of the users and riding behaviour. Bicycle manufacturers and system designers could consider integrating such a warning system on the e-bikes since we found that 1) a significant number of participants felt safer using this system and 2) the potential of reducing the crash risk is high due to the significant speed reduction. Due to the low scores for trust in this system, we recommend that bicycle manufacturers and designers improve the system quality to reach a higher technology readiness level before they consider further field trials (Kapousizis et al., 2022). This can be done by implementing the system on the bicycle rather than using smartphones, which happened during the field trials. Policymakers may consider creating new policies to promote the context-aware warning system or similar to a specific group of more vulnerable e-bike users, such as elderly cyclists. Integrating such warning systems into fast e-bikes might help reduce the probability of e-bike users being involved in crashes, especially due to the high speed.

### 6.4.5. Limitations and future work

A limitation of this study is that participants used the prototype along a predefined route under a structured field trial, which may influence their riding behaviour. Thus, we recommend that future studies run long-term field trials to assess the effects of a warning system under natural conditions and how participants cycle in everyday life. In addition, the industry could use smart e-bike prototypes and let potential buyers try them out in their test centres. The benefits of such experiments will be twofold: on the one hand, to promote smart bicycle technologies and, on the other hand, to get better insights into potential consumers' preferences on different technologies on e-bikes.

Furthermore, in this study, we did not consider the reason for each user trip, i.e., travelling for leisure or on a commute trip home-to-work, since people may react differently based on the trip characteristics. Another point for attention is the small number of participants, which may affect the validity and generalizability of the findings. Also, the gender and age discrepancy in the sample may have affected the findings. Thus, future studies can focus on collected balanced population data to better segment the population.

The effectiveness of the on-bicycle communication heavily depends on the implementation. The bone-conducting headphones were difficult to combine with the helmets at times. This might have caused the headphones to shift, decreasing the audibility. For ease of implementation, haptic gloves were used rather than, for example, haptic handlebars (Baldanzini et al., 2011). The aim was to evaluate the feasibility of haptic feedback rather than this exact implementation. Participants in this field trial were asked to cycle using the Komoot navigation app. Exploring other options, such as using physical signs, is recommended for future research. In this research, it turned out that participants found it difficult to navigate along the route. Another point for attention is the unbalanced number of participants over the order of conditions due to the equipment's availability. Hence, we recommend future studies to monitor this better.

The survey had open questions where participants could indicate their opinions about the context-aware prototype warning system. Some participants liked the audio volume, while others indicated the audio was barely audible. The current set-up worked with a fixed volume, and in the final product, it should be adjustable to the user's hearing. Additionally, the combination of headphones and the helmet may have shifted the headphones a little, making the signal less audible. Furthermore, multiple participants indicated that "the sound could not be heard when there was wind.” This raises questions about the suitability of the headphones. Therefore, in the future, the system may benefit from further finetuning.

In this study, we used BRON dataset, which underrepresents cycling crashes compared to ambulance datasets, however, the latter is not available for the whole country yet (Piljic, 2024). In addition, crash data also do not necessarily match with perceived safety levels (Uijtdewilligen, 2024), which might also affect trust in user support systems. In addition, we used a spatial analysis approach (KDE) to identify high crash risk locations. However, crash specific factors such as the time, date (of the bicycle crashes), age, and gender (of cyclists in those crashes) were not taken into account to identify user and time specific crash risks. We recommend further research to create risk profiles for different user groups, i.e., elderly users, since different ages have a different probability of being involved in a crash and provide personalised safety warnings. Also, we believe that developing a dynamic model that considers all the above information, including weather conditions, and sends real-time updates will also be of interest.

A further study is suggested to focus on different types of communication, such as helmets with integrated audio or lights that warn users when they approach a high crash risk location. Another potentially fruitful research would be to investigate users’ perceived safety and trust of a speed adaptation system, which would reduce the assistance of the e-bike or decelerate when approaching high crash risk locations rather than the context-aware warning system we examined in this paper.

## 6.5. Conclusion

E-bikes have the potential to reduce car usage by replacing cars for short to medium distance trips. Nonetheless, as it is easier to ride e-bikes faster than conventional bicycles, they are riskier, especially for those unfamiliar with the high speed (Schleinitz & Petzoldt, 2023). Cycling safety has been a persistent issue in many countries, including the Netherlands, especially in the last few years with e-bikes.

In this study, we showed that integrating a safety support system into e-bikes can be instrumental in reducing crash risks. To do so, we tested the effects of the designed safety support system on users’ perceived safety, trust, and riding behaviour. We verified that the designed system could influence cyclist riding behaviour and perceived safety. The key findings are summarised below as follow:

- Participants were found to have a higher perceived safety for the e-bike equipped with a safety support system than a conventional e-bike.
- Although participants found the system easy to use, positively influencing their acceptance, their general trust was low.
- The mean speed of the participants during the rides, baseline and with intervention, was found to be lower for the rides with the intervention. This proves that the system positively influences users’ riding behaviour for speed reduction.

- Males were found to have a higher speed reduction after the advice from the system to reduce their speed compared to females. However, females entered a high crash location with a lower speed than males.
- Participants who use an e-bike or conventional bicycle weekly are more likely to reduce their speed with audio warnings than tactile warnings.

To conclude, the results of this study prove that the context-aware warning system positively influences users' perceived safety and perceived performance. Furthermore, we found that participants' riding behaviour changed when they rode with the context-aware warning prototype system. In this study, we examined a potential smart bike technology corresponding to smartness level 2; however, there is room for further investigation of other smart bicycle technologies with higher bicycle smartness levels (Kapousizis et al., 2022). Our study showed that there is potential for adopting similar and more advanced systems waiting to be unlocked by researchers and bicycle manufacturers.

# Chapter 7

# Conclusion and discussion

This thesis investigated smart bicycle technologies that enhance cyclists' safety by 1) conducting a systematic literature review, 2) examining the factors influencing users' acceptance and willingness to pay for smart bicycle technologies, and 3) investigating the impact of smart bicycle technologies on the behaviour and safety of users. For this purpose, we collected and analysed survey data from five European countries. Lastly, 4) it evaluated users' experiences, including perceived safety, trust, and perceptions, using a context-aware prototype warning system in a real-world field trial experiment.

E-bikes help individuals to travel more comfortably since they are less physically demanding than conventional bicycles (Fishman & Cherry, 2016). Thus, e-bike users can travel longer distances with less effort, which is one reason that e-cycling has become popular in many countries. Furthermore, e-bike sales are increasing globally, which can increase sustainability and reduce transport emissions, noise, and traffic congestion in urban and peri-urban areas. In addition, e-bikes, as is cycling in general, can have various benefits for users' physical and psychological health, especially when people switch to e-bikes from motor vehicles (Bourne et al., 2018; de Haas et al., 2021a; Van Cauwenberg et al., 2019).

Evidence shows that despite the numerous benefits of e-bikes in terms of users' health and environment, the number of e-bike crashes is also increasing (Haustein & Møller, 2016; Panwinkler & Holz-Rau, 2021; Schleinitz & Petzoldt, 2023; VeiligheidNL, 2023). This can mainly be due to their high speed and unfamiliarity of e-bike users with (e-)cycling (Haustein & Møller, 2016; Huertas-Leyva et al., 2018; Stelling et al., 2021). Although high-quality cycling infrastructure is essential to promote cycling, there is evidence that improving cycling infrastructure alone is not enough to tackle e-bike crashes. Therefore, the potential benefits of introducing smart technologies in cycling safety could also be crucial. However, this subject has not been investigated yet. Bridging this gap, this thesis 1) identified technologies that can be used on e-bikes affecting cyclists' safety, 2) introduced a topology for bicycle smartness levels, 3) determined factors affecting individuals' intention to use and pay for smart bicycle technologies in Europe, and also in more details in the Dutch context, and 4) tested the traffic safety impact and users' perception of smart bicycle technologies in a field study.

## 7.1. Main findings and conclusions

This chapter summarises the main methodological contribution and the findings derived from this thesis. It provides an overview of the answers given to cover the research gaps as formulated in Chapter 1.

**What smart bicycle technologies can be implemented on smart connected bikes to enhance cycling safety? (Chapter 2)**

Smart bicycle technologies aim to, among others, decrease bicycle crashes and increase comfort for people while cycling. There is a high interest in cycling technologies, which is reflected in the high number of recent academic studies focusing on smart bicycle technologies to assist cyclists and improve cyclists' safety. Hence, in the literature, there has been a steep increase in studies investigating smart bicycle technologies during the last two decades, confirming the growing interest in technologies in cycling. Despite this, a complete picture of such technologies and their influence on cycling safety was not available. In addition, a clear consensus about the term "smart" bicycle among researchers, industry, and stakeholders was lacking. To this end, a comprehensive literature review was conducted in the context of this thesis, adopting a systematic literature review framework.

Significant results emerged in three major aspects, and we shed light on the current landscape of smart bicycle technologies that affect cyclists' safety. First, emerging "smart" bicycle technologies implemented on bicycles that affect cycling safety were identified. This provided insights concerning current and proposed systems that can influence cyclists' safety. Second, a topology of bicycle smartness levels was proposed, providing a common language for all concerned actors to ease the implementation of smart bicycle technologies. Third, the technology readiness levels were assessed. This allowed the classification of technologies based on their maturity, creating in turn a road map of the different technologies belonging to different bicycle smartness levels. According to these, the available technologies currently found in the literature fall into "Level 2: Warning assistance" of the bicycle smartness levels. Therefore, this level was used as a hypothetical scenario introduced in the survey in Chapter 3.

**What are the factors affecting user acceptance of the Smart e-bike? The impact of respondents from different European countries. (Chapter 3)**

Even though smart bicycle technologies are gaining ground, and many researchers and safety institutes have indicated their potential to influence cyclists' safety, less is known about people's intention to use and accept such technologies (Kapousizis et al., 2022; Oliveira et al., 2021; SWOV, 2023). Thus, this chapter investigated the factors influencing users' intention towards smart bicycle technologies. In the literature, factors associated with user acceptance of technology are categorised as follows: "usefulness", "ease of use", "peer pressure", and "enjoyment". In addition to those categories, we also identified "perceived safety" and "social status" as factors that might influence users' intention towards smart bicycle technologies. We also considered additional variables that potentially influence users' intentions, such as gender, age, and education level. Specifically in the context of smart bicycle technologies, we further extended the variables taken into account by including the digital skills of a user since we believe that this variable influences individuals' intention to accept (and even could make them prone towards) new technologies. Together with "perceived safety", we considered the cycling infrastructure, population density and city size, since we believe these variables influence individuals' intention to use the smart e-bike and act as pulling measures towards cycling. On top of that, we know various differences exist among countries, especially in cycling culture and infrastructure; hence, the country is also a potentially significant variable we took into account. All the factors mentioned above were analysed using structural equation modelling under the UTAUT framework. For this, we introduced a hypothetical scenario of a smart e-bike, employing a specific set of technologies as mentioned in Chapter 2, to test individuals' behavioural intentions. This analysis allowed us to better understand the factors influencing users' intention to use the smart e-bike, in the context of both Pedelecs and Speed-Pedelecs, in different countries.

A significant positive relationship was found between performance expectancy, hedonic motivation, perceived safety, and effort expectancy to behavioural intention. Performance expectancy, hedonic motivation, and perceived safety appeared to be the strongest factors in determining the behavioural intention of users to use the new technologies on e-bikes. Social influence also showed an important positive role to user intention, while effort expectancy showed a small positive significant role. In contrast, no significant relationship was found between social status and behavioural intention. When investigating cross-country differences, performance expectancy strongly and positively impacted user intention across all countries, while hedonic motivation showed no significant impact in the Austrian sample. Perceived safety positively influenced users' intention in Belgium, Germany, and the Netherlands. Social influence showed a stronger relationship and was significant among the Dutch and Austrian responders. Among the controlled variables, increased age, respondents with high digital skills and respondents involved in bicycle crashes, positively affected the behavioural intention towards the smart e-bike. In contrast, high education negatively impacted the behavioural intention towards the smart e-bike.

The measurement invariance was investigated to confirm the validity of the results of the multigroup analyses for the five countries and between Pedelec and Speed Pedelec groups. Measurement invariance allows us to determine whether a factor is equivalently perceived across groups, in our case: countries and groups of e-bikes, and to draw meaningful conclusions about the group comparison. Measurement invariance demonstrated sufficient levels in our analyses, proving no significant difference between groups. The cross country analysis indicated that the factors influencing behavioural intention on smart bicycle technologies vary among countries, meaning that there is heterogeneity across the five countries. Thus, different factors influence users' intentions among countries. The analysis regarding the different types of e-bikes showed that users' intentions differ between Pedelec and speed Pedelec (potential) users, with the former having higher behavioural intention towards smart bicycle technologies in all factors. Performance expectancy and hedonic motivation were dominant positive factors in both types of e-bikes.

**Which variables influence potential users' preferences and willingness to pay for smart bicycle technologies across European countries? Providing a classification of individuals according to their choices. (Chapter 4)**

One specific service never fits everywhere and everyone. This is because different individuals have different needs, but individuals with similar characteristics might also have different needs, especially from countries with varying cycling infrastructure and cycling culture. With this in mind, we carried out a stated choice experiment in five European countries and asked respondents to choose among different types of smart bicycle technologies. The collected data was analysed employing a latent class choice model. To better understand individuals' preferences and account for heterogeneity in participants' choices, we used sociodemographic variables, attitudinal questions and experience with similar smart technologies for bicycles.

The results identified two distinct types of potential users in Europe, according to their approach towards bicycle technologies. Therefore, the following two classes were formulated; on the one hand, **Class 1: "Technology-cautious"** there is a higher concentration of respondents with below-average country income, highly educated, above 40 years old, and those living in areas with dense cycling infrastructure. On the other hand, in **Class 2: "Technology-prone"** there is a higher concentration of respondents with above-average country income, technology-friendly, younger than 39 years old, those living in areas with an absence of cycling infrastructure and respondents from Greece. In general, the distribution of the respondents into the two classes is almost equal, with 52% of the respondents falling in **Class 1** and 48% in **Class 2**. On the one hand, **Class 1: "Technology-cautious"** comprised individuals who have a preference for simple types of technologies and are cost sensitive, and on the other hand, **Class 2: "Technology-prone"** comprised participants who have a preference for advanced technologies and are less cost sensitive than the former class. Significant heterogeneity was found in preferences among participants, which can partially be explained by a number of variables, such as sociodemographic characteristics, geographical characteristics such as countries, respondents' technology friendliness and safety-related questions (cycling). **Class 2** consists of respondents living in areas lacking cycling infrastructure, who are technologically savvy and have an above-average monthly income, have higher preferences for smart bicycle technologies and are more likely to use advanced bicycle technologies. They are less sensitive to cost and have a higher willingness to pay. Finally, the marginal rate of substitution reveals significant differences between the willingness to pay for smart bicycle technologies of individuals who fall into two classes. Individuals falling in **Class 1**, **Technology-cautious** are willing to pay up to €100, while participants falling in **Class 2**, **Technology-prone** are willing to pay an additional price of up to €200 for advanced bicycle technologies to increase their safety, compared to the reference categories. Overall, respondents with high income (above average), technologically savvy, and those living in areas with low cycling infrastructure are more likely to opt for more advanced "collision avoidance systems" that can warn against potential collisions.

### What are the preferences of Dutch e-bike users regarding smart bicycle technologies and to what extend are they willing to pay for such technologies? Explaining the existing heterogeneity in preferences and WTP. (Chapter 5)

Heterogeneity can hold within individuals from the same country, even for those with very similar characteristics. To examine these facts, we used a mixed logit model using stated choice survey data from the Netherlands and sought for random heterogeneity. Hence, we allowed random parameters during the model estimation in order to capture heterogeneity in preferences. In addition, used negative lognormal distribution for the cost attribute and normal distribution for the rest of the attributes. This allowed us to estimate a more realistic willingness to pay values since nobody likes to pay, and normal distribution usually leads to misleading results. We also examined deterministic heterogeneity in our data by including interaction with sociodemographic characteristics, such as age and gender. While we also used other variables, we could not capture significant differences and thus dropped from the final estimated model. This approach allowed us to estimate a superior model and revealed ample results. In addition to this approach, we segmented our sample into groups to better understand the data and respondents' choices. We estimated the willingness to pay for specific population segments.

The findings illustrate that respondents are relatively open towards smart bicycle technologies affecting cycling safety. We found random heterogeneity in all random coefficients in our results, meaning that there is variation in respondents' choices. In addition, we found a negative utility for the cost attribute, indicating a cost sensitivity in respondents. We explained the random heterogeneity and found that young respondents aged between 25–44 have a higher preference for speed adjustment systems. In addition, we also found that males are less likely to use a speed adaptation system, as well as participants falling in the age group older than 60. Regarding respondents' willingness to pay, overall, they are willing to spend up to €200 for assistance with smart bicycle technologies, €200 for assistance with smart routes, and €170 for emergency call systems. Also, respondents showed that they were willing to pay a significant amount for advanced smart bicycle technologies, up to €160. Generally speaking, it was found that respondents are willing to pay around 10% on top of the price of the new e-bike to use smart bicycle technologies. Lastly, considering the market segmentation, we found differences in willingness to pay for respondents with income higher than the average income, gender (females) and participants who own an e-bike in the Netherlands towards smart bicycle technologies since they are more likely to pay for advanced bicycle technologies. Education also seems to influence respondents since there is a difference in the willingness to pay. High educated respondents have a preference for assistance systems and automatic speed adjustment rather than collision avoidance systems. We can conclude that sociodemographic characteristics can explain heterogeneity and differentiate sensitivities in the WTP for smart bicycle technologies.

**What are the effects of a safety support system on cyclist's riding behaviour and perceived safety? (Chapter 6)**

In the Netherlands, the number of bicycle crashes has increased in recent years, and almost one-third of all cyclist fatalities are e-bike users (Statistics Netherlands (CBS), 2021). In addition, new types of e-bikes emerged, such as the fat-bike, which can travel up to 45km/h and are mainly used by young people. Recent studies show that high speed is one of the major causes of the high number of e-bike crashes and municipalities in the country are trying to improve cyclists' safety in different ways. Concerns about e-bikes and the different speeds on bicycle paths between e-bikes and conventional bicycles are widespread and also being scrutinized by public agencies such as in the city of Amsterdam. Therefore, we examined the potential impact of an early wearing system for e-bike users in a field study. We identified high crash risk locations for bicycle crashes in Enschede, the Netherlands and developed a smartphone application which warns cyclists to reduce their speed.

The results have identified that participants have a higher perceived safety for the safety support system than a conventional e-bike without such a system. This means that participants felt safer with the use of such technology. In addition, participants indicated that they found the system easy to use, which might influence their acceptance, as found earlier in Chapter 3. Furthermore, we found that during the field trials, participants reduced their speed when approaching a high crash risk location, and hence, they followed the speed recommendation by the application. In detail, based on the GPS data collected during the rides of the participants, we found that participants reduced their speed when approaching a high crash risk location and received warnings from the context-aware safety support system. This proves that the system positively influences users' riding behaviour for speed reduction. With this last chapter, we proved the effectiveness of such a system on cyclist's riding behaviour and perceived safety.

## 7.2. Synthesis and reflection of the findings

This section synthesises and reflects upon the findings from this thesis. It discusses how the findings from each chapter are linked to each other to draw solid research results. It also discusses the key factors that influence user acceptance, the effect of different countries with different cycling cultures and infrastructure on user preferences and WTP, and the impact of smart bicycle technologies on traffic safety. Based on the data collected from the European-based survey and field trials with the follow-up survey, some interesting conclusions about the impact of smart bicycle technologies on cycling safety can be drawn. The above serves as a solid understanding of this research.

This thesis provided empirical evidence from e-bike users from European countries and factors influencing their intention for smart bicycle technologies. It tested e-bike users' preferences for smart bicycle technologies and took advantage of comparing survey data from five European countries: Austria, Belgium, Germany, Greece and the Netherlands. The collected data came from individuals who own or are willing to buy an e-bike. This allows us to investigate the preferences of individuals interested in e-bikes rather than random people. Each of the countries mentioned above differs in cycling infrastructure, cycling culture and perception of cycling. On the one hand, the Netherlands is heaven for cycling, with more than 35,000 km of separated cycle tracks and around 24 million bicycles, meaning that cycling is an integral part of everyday life in the country. On the other hand, Greece lacks cycling infrastructure and cycling policies. The rest of the countries have a medium level of cycling culture. Austria, Germany and Belgium have relatively good cycling infrastructures, with many citizens using bicycles daily, especially in the Flemish part of Belgium. These differences were tested in this research in two Chapters 3 and 4.

The comparison between the five European countries allowed us to investigate the factors influencing respondents' intentions and preferences towards smart bicycle technologies. It aimed to test the extent to which safety-related factors, such as the absence of cycling infrastructure and cultural differences, affect respondents' opinions. Thus, Chapter 3 proves that the perceived usefulness of the system plays a key role in behavioural intention for all the respondents from all countries. It is the only factor important to all five countries, meaning that respondents believe the smart e-bike will be useful for their daily routines and help them achieve their goals. What emerges from the results reported in Chapter 3 is that different factors influence behavioural intention for the smart e-bike, meaning there is heterogeneity among respondents' factors.

Different factors influence behavioural intention for smart bicycle technologies for respondents from different countries. This is because they have different needs and can see different benefits from use of the smart e-bike. For instance, the factor Perceived safety is low among the Greek participants, probably since there is no cycling infrastructure there, so they believe they cannot benefit from the smart e-bike since cycling infrastructure is needed. In contrast, perceived safety is also a key factor in Belgium, Germany and the Netherlands, countries with a substantial-good quality of infrastructure for the formers and high quality for the latter. Most of the factors tested have the same direction between the countries, except for social influence and social status in Germany and the Netherlands, which differ; however, they are not significantly different (-0.054 and -0.001), correspondingly. Overall, we found that the lack of cycling infrastructure negatively influences the behavioural intention for the smart e-bike. These findings might further indicate that these factors should be considered to improve these smart e-bike domains before promoting them in the market. This also means that there is not one package that fits everyone and everywhere. These outcomes could be used as a foundation by policymakers and stakeholders to help implement smart bicycle technologies in different areas and prioritise and promote different systems that might benefit potential users.

Willingness to pay shows that respondents can be separated into two groups, as was found in Chapter 4: 1) individuals tend to prefer less advanced smart bicycle technologies, and they are cost-sensitive, and 2) individuals who have a higher preference for advanced smart bicycle technologies and are less cost sensitive. WTP indicates that respondents in this research are willing to pay up to €200 for advanced smart bicycle technologies for those who are less cost-sensitive, while for the cost-sensitive, we found they are willing to pay up to €100 for less advanced technologies. This raises the question of who the individuals who have a higher preference for advanced bicycle technologies are and who the rest are. Findings indicate that respondents who earn above the average income per country, are technology friendly, are young and come from Greece are more likely to prefer advanced smart bicycle technologies and are less cost-sensitive. However, highly educated respondents prefer less advanced smart bicycle technologies and are more cost-sensitive. The difference between individual preferences shows that individuals will pursue different types of smart bicycle technologies when these technologies are introduced to the market.

Focusing on the Dutch studies, Chapters 5 and 6, it was found that respondents are open to smart bicycle technologies and willing to pay for them in order to have one on their bicycles. Nonetheless, we found heterogeneity in respondents' preferences for smart bicycle technologies, which also influenced the WTP estimates. In detail, Chapter 5 found a gender effect on preferences; males are less likely to use automatic speed adjustment technologies on their bicycles than females. Males have a higher preference for less advanced systems, such as assistance and collision avoidance systems. On the other hand, females are more likely to use automatic speed adjustment technologies since they have higher utilities and WTP for them. For instance, males have a negative utility for automatic speed adjustment in risk areas with a negative mean value for the WTP of €-52, while females are willing to pay €35 on average. In addition, Chapter 5 shows that respondents below 44 years old from the Netherlands have a higher utility for the automatic speed adjustment system for risk areas than the rest of the age groups.

Taking into account the results from Chapter 6, it was found that there is a correlation between these findings. Chapter 6 proves that both males and females are likely to follow the warning from the safety support system during the field trials. Males had a higher speed reduction since they used to cycle faster than females. In the WTP study (Chapter 5), it was found that the males were less likely willing to pay for a similar system. However, in Chapter 6, it was found that they followed the warnings and reduced their speed. Of course, in the field trials, an automatic adjustment system for risk areas was not tested; rather, it was tested using an early warning system, which is the closest; hence, a comparison with the previous chapters is not direct. However, it turned out that males and participants older than 56 were found less likely to pay for such systems during the field trials was found that they reduced their speed. The advantages of an early warning system are twofold: 1) participants tend to follow the warnings and change their riding behaviour by reducing their speed by 2km/h, which is a significant reduction, and 2) participants have a higher perceived safety using such the safety support system, proving that they believe that it will influence their safety. Taken together, these findings suggest a significant role for perceived safety as found in Chapter 3 in promoting smart bicycle technologies.

## 7.3. Practical implications

Road safety is an important domain, and many parties, at high levels, such as the European Commission, as well as at local levels, such as governments, municipalities and traffic authorities, focus on reducing road fatalities with “Vision Zero”, zero or close to zero fatalities in roads, by 2050 (Commission, 2023; SWOV, 2019). In addition, as discussed in this thesis, many governments in countries with low cycling rates, and countries with established cycling cultures, such as the Netherlands, are promoting bicycles and e-bikes since the latter can replace car trips and reduce transport externalities. For instance, the Dutch government has announced the “Tour de force” program, which seeks to increase the number of kilometres ridden by 20% until 2027 in the Netherlands (Government of the Netherlands, 2018). This will help to increase sustainability and contribute to more liveable and healthy cities. However, to promote cycling, among other things, it is important to improve cyclists’ safety. This section discusses and provides recommendations and possible policy implications of our findings. Policymakers, bicycle manufacturers, and related parties should consider the following recommendations.

### 7.3.1. Implications for policymakers

Smart bicycle technologies could reduce crashes and go hand in hand with other measures such as safe cycling infrastructure, vehicle safety systems, educational programs, and campaigns. Thus, we recommend that policymakers be involved in further research with field trials to test the effectiveness of these technologies. Also, they might consider including smart bicycle technologies as one of the safety measures to increase cyclists' safety. In addition, road authorities and traffic safety institutions can consider smart bicycle technologies as an additional measure to improve cyclist safety and may want to promote them to local authorities.

The findings of this study show different factors affecting users' intention for the smart e-bike among countries (Chapter 3), and different age groups are inclined to accept it. Thus, we suggest policymakers promote the smart e-bike considering the influential factors per country.

Individuals need to see the benefits of the smart e-bike before accepting it, hence, specific campaigns and actions are needed per country to promote the smart e-bike. Furthermore, Chapters 4 show that individuals living in areas with low cycling infrastructure are more likely to accept advanced smart bicycle technologies. So, promoting different types of smart bicycle technologies based on the users' local needs will be beneficial. Hence, policymakers may want to promote smart bicycle technologies to a specific group of e-bike users prone to crashes, as indicated in Chapters 3 and 4.

Policymakers, governments, and bicycle manufacturers can use this study’s insights to promote such technologies. In detail, stakeholders and bicycle manufacturers can work together to test the efficiency of such technologies and tackle specific bicycle crashes. The synergy of such a union is needed in order for the advanced smart bicycle technologies to be tested in a real environment when they reach the proper technology readiness levels. This will help, on the one hand, test to what extent such technologies can be incorporated into the different congestion levels in urban and rural environments and improve cycling safety. On the other hand, policymakers could focus on the potential benefits of smart bicycle technologies and may promote them in specific areas and groups of people.

To uptake a higher level of bicycle smartness level technologies (Chapter 2), policymakers and stakeholders should focus on developing the digital infrastructure needed to deploy smart bicycle technologies. This is an important step forward, and specific actions are needed to secure safe communications between Bicycle to Infrastructure and Bicycle to Everything, avoiding cyber-attacks and leaking of private information.

### 7.3.2. Implementation for bicycle manufacturers

The findings of this thesis might also help bicycle manufacturers promote and prioritise the development of specific smart bicycle technologies with specific functionalities. Bicycle manufacturers and system designers should further examine the effectiveness of these technologies on safety and operation, especially when more than one functionality is embedded in the bicycle since one device may affect the functionality of the others (Chapter 2). In addition, system designers should develop the technologies and make them user-friendly since the factor of Effort expectancy was found to be an important indicator of user acceptance (Chapter 3). Besides, bicycle manufacturers should consider the other factors in Chapter 3 to promote smart bicycle technologies, such as social influence and exert pressure on potential users. Also, system designers should develop the systems in a way that can be pleasurable to users since the factor of Hedonic motivation was found to have a significant influence on behavioural intention.

Furthermore, results show that individuals from different countries as well as from the same country have different preferences and willingness to pay for smart bicycle technologies (Chapters 3 and 4). Hence, we recommend that bicycle manufacturers promote specific bicycle technologies rather than specific packages of smart bicycle technologies. In addition, on average, individuals are willing to pay for smart bicycle technologies and their evidence that different population segments, such as males vs females, and young vs older individuals, have significantly different WTP for smart bicycle technologies (Chapters 4 and 5). It is wise for bicycle manufacturers to market their products around this price; otherwise, individuals will not be willing to pay for smart bicycle technologies.

Lastly, the results of this study suggest that further investigation is needed before deploying smart bicycle technologies (Chapters 2, 3 and 6). This will offer multiple benefits to bicycle manufacturers. They will be able to examine the efficacy of their systems and reach the needed maturity and technology readiness level for their products (Chapters 2 and 3). This research tested a safety support prototype system and not a fully smart connected bicycle or advanced smart bicycle technologies as examined in the survey. Thus, we recommend that bicycle manufacturers conduct more field trials, with more participants, advanced bicycle technologies, and longer testing periods for these systems. On the one hand, they should further examine participants' intentions by testing different technologies, and on the other hand, they could use the field trials as an opportunity to advertise smart bicycle technologies since citizens will see smart e-bikes running around (Chapter 3). Future field trials should focus on test systems that will have a better appearance for users since it affects their trust in the system as well (Chapter 6); thus, testing improved versions rather than prototypes will be beneficial.

### 7.3.3. General recommendation

Several recommendations arose from this thesis. Literature review (Chapter 2) shows that further work is needed to establish the implementation and safety assessment of the smart bicycle technologies in simulation, laboratories and field trials. Another point of attention is the human-machine interaction and the possible speed intervention of bicycles with smart technologies. Communication should be smooth and to the point, minimizing users' distraction and providing crucial information on time to allow sufficient reaction time and minimise stress. Lastly, as the bicycle smartness level increases in the proposed topology, the collaboration between policymakers, traffic authorities, bicycle manufacturers, and the automotive industry becomes imminent to develop communication protocols to allow bicycles to be connected with infrastructure and other motor vehicles. Also, the digital infrastructure is a key factor for deploying full connectivity and intervention ecosystem, as indicated in Chapter 2.

Chapter 3 offers new insights into deploying new technologies on e-bikes to increase cycling safety, which can benefit different stakeholders, such as bicycle manufacturers and cities. More specifically, bicycle manufacturers and designers of such innovative systems can integrate these insights to optimise and better develop the systems and features to be brought into the market. Also, cities can develop and implement new policies, fostering a smooth transition for these emerging technologies.

Considering the results derived from Chapter 4 about user preferences and willingness to pay for smart bicycle technologies gives insights to governments and policymakers. Results can help governments and policymakers promote such systems in the interest of cyclists to reduce the number of bicycle crashes. However, it should not be forgotten that individuals from different countries and even from the same country have different preferences for smart bicycle technologies and different willingness to pay. Thus, bicycle manufacturers can prioritise specific technologies in different countries and align product prices with individual preferences and overall circumstances.

Chapter 5 serves interesting results for governments and policymakers in the Netherlands. It shows that the Dutch are open to smart bicycle technologies, and thus, deploying such technologies could be a success. However, considering the results and focusing on specific potential user groups for promoting smart bicycle technologies would be ideal. For instance, we found significant differences in the WTP among different population groups; hence, targeting specific systems for specific groups would help the market penetration of such systems.

Chapter 6 shows that a safety support system can influence users’ riding behaviour and might have a positive impact on cyclists' safety. Thus, we strongly recommend that the field trial experiment continue and incorporate more advanced bicycle technologies with a broader audience of participants. Additionally, we recommend that bicycle manufacturers align their development plans with the aims of the focus areas and go hand in hand with governments. For instance, agreements with governments to modernise traffic lights and digital infrastructure are needed for some of the technologies.

## 7.4. Further research

This thesis has covered many gaps that were identified earlier in Chapter 1; however, since it also introduces new research on cycling safety with the use of smart bicycle technologies and user acceptance and willingness to pay, many new recommendations have been derived. This chapter provides several avenues for further research, new research gaps, and potential ideas. In this thesis, we mainly used behavioural modes in order to examine respondents’ opinions based on empirical data for different hypothetical scenarios such as UTAUT and SC. In fact, they are powerful tools to capture behavioural intention, user preferences, and WTP, and different approaches might help estimate the above further.

### 7.4.1. New research topic insights

This thesis provides new research insights and makes space for new research avenues. The entire thesis investigates a new research topic from scratch; we first investigated the new smart bicycle technologies, examined users’ preferences, acceptance, and WTP, and later, we implemented specific technologies and tested them in real experiments. We applied survey data, Likert scale questions based on the UTAUT framework and perceived safety and trust, stated preference data, and GPS data to assess users’ behaviours. Safety is of interest to many stakeholders and actors in the transportation domain. Generally speaking, bicycle traffic safety is a multi-agent problem that can be approached from different perspectives. We approached this from a technological point of view, and the insights apply to this aspect.

Within this thesis, we touched upon different aspects of users’ behaviour by examining behavioural intention, preferences, and cyclists’ riding behaviour changes, however more research is needed with different approaches and data collection to get a solid idea of people’s behaviour. This is due to the fact that there is an outbreak of e-bike users, and more e-bikes come with new technologies, so people are more familiar with bicycle technologies. Also, bicycle crashes continue to increase (SWOV, 2024), so e-bike users may consider different options to increase their safety.

This thesis examined users’ acceptance of smart bicycle technologies in European countries. Since it was the first time such a topic was introduced and tested, we used a specific set of smart bicycle technologies. At the same time, it gave us important insights into users’ acceptance.

More in-depth research would be important to capture users’ acceptance of different types of technologies individually rather than as a package of specific technologies. For instance, in countries with low-quality or absence of cycling infrastructure and without dedicated traffic lights for cyclists, examining the smart traffic lights that can give priority to cyclists, it might seem futuristic for the respondents. Thus, testing specific technologies can help capture better users’ acceptance. In addition, another possible research topic is the investigation of Bicycle-to-everything communication and what will be the users’ acceptance and preferences.

To better understand individuals’ preferences towards smart bicycle technologies, we focused on e-bike users and those interested in buying one, in other words, people interested in e-bikes. While this is an appropriate approach given that the focus was to get insights for this specific group of users, we recommend further research to focus on a wider audience and with a representation of the population to examine individuals' intentions for smart bicycle technologies. Research investigating the opinion of a wider audience would determine the importance of smart bicycle technologies since more and more people are switching to e-bikes. Hence, it will help capture the opinions of people unfamiliar with cycling and might also influence people to feel unsafe to cycle or use an e-bike with smart bicycle technologies since we found that such technologies can increase the perceived safety of the users.

Another avenue for further research is the validation of these findings through real-world studies. Ultimately, longitudinal studies might be necessary to go to the next level. Thus, future research could consider long-term field trials investigating user intention towards smart bicycle technologies and following up with a stated choice experiment to examine WTP. In addition, conducting such studies with individuals who are in the process to buy an e-bike and testing different systems will help to better assess consumers' preferences and WTP. Such field trials can take place at bicycle manufacturing test centres, where potential customers can test different bicycle prototypes. Also, further work is needed to test more advanced smart bicycle technologies, which were included in the stated choice experiment survey of this study, and smart bicycle levels with higher technology readiness levels in field trial experiments. This will help to better explore users’ perceptions of these technologies since, in this thesis, we only examined users’ perceptions of safety support systems. On the one hand, it can allow to capture the experienced behavioural intention of individuals towards a smart e-bike and, on the other hand, would allow investigating the experienced utility of an individual for smart bicycle technologies rather than the expected utility, was examined. This way, the WTP will be calculated after an individual has experienced smart bicycle technologies.

A natural progression of this work is to analyse the objective safety of smart bicycle technologies. This thesis could not investigate this due to the lack of data. However, in the future, when more e-bikes will run with smart bicycle technologies, we recommend examining to what extent such a system can improve cyclists’ safety by reducing the probability of a collision. In addition, it would be beneficial to incorporate feedback from users’ riding behaviour changes into the support system to improve it based on users’ needs and improve the smart bicycle technologies.

Several questions still remain unanswered regarding the challenges of human-machine interaction. We investigated different types of modalities for communication with the user and found much more to be examined. Thus, we suggest further research investigating and analysing human-machine interaction and perceived performance for smart bicycle technologies and other communication channels, such as helmets with integrated audio or lights that warn users when approaching a high crash risk location. This way, the benefits would be twofold: 1) bicycle users will tend to use a helmet, which is useful in the case of a crash since one-third of bicycle crashes affect the head of the victims, and 2) users will probably have less distracting interaction with the bicycle. Overall, other research should examine the potential distractions of such communication and, of course, the behavioural adaptation of the users. Perhaps users might rely more on the system and pay less attention when cycling around, which may increase crash risk, which is not the aim.

This study focused only on individual e-bike users; however, shared e-bikes would also be an interesting topic for research. As mentioned in the literature, the high number of e-bike crashes is due to the high speed and the users' unfamiliarity. Considering this, people who use shared e-bikes might be less familiar with and, so they probably have a higher likelihood of being involved in a crash compared to the owners of e-bikes. Thus, we see room for further research on this area.

Delivery bicycles and new e-bikes, such as fat e-bikes, are also interesting topics for further investigation. In many cities in the Netherlands, there are huge problems with fast-delivery bicycles, which overrun cities at high speed to deliver on time and are at high risk for crashes with other bicycles, pedestrians and motor vehicles. In addition, the fat e-bikes recently introduced to the market can speed up to 45 km/h and are mainly used by teenagers unfamiliar with high speed; hence, the number of crashes involving these groups of people increases. Thus, investigating the probability of integrating specific smart bicycle technologies, such as automatic speed adaptation, will be interesting.

Another potentially fruitful avenue for future research is to investigate the willingness to pay of citizens and not e-bike users, perhaps in a city or a country, for specific smart bicycle technologies, e.g., speed limitation, on other bicycles, such as fast e-bikes or delivery bicycles. This way, the cost is shifted to a different group of people who can benefit from the technologies indirectly since e-bikes will be ridden at a low speed, and this will probably reduce crashes. Another point for investigation could be the potential societal benefits citizens can receive from using smart bicycle technologies by promoting their use for specific groups of people. For instance, a cost-benefit analysis of the potential use of such technologies might turn to societal benefits due to the fewer fatalities and health benefits due to the more users. Thus, the investigation of government subsidies for smart bicycle technologies would be a great point for further research.

To develop a full picture of the willingness to pay for smart bicycle technologies, additional studies investigating different ranges for the cost will be needed. We used a realistic price range. However, we found that respondents in this research are willing to pay less than the boundary prices we used. Thus, a different price range, including zero, would be of interest in future investigations as we did not include it. In addition, it is also important that future studies can also compare WTP with and without a specific technology, rather than WTP for alternative technologies. This way, the actual WTP for a technology can be found. Furthermore, in relation to the WTP, further research might be possible to examine the “pay as a service” for smart bicycle technologies. This means that users will not buy the system; instead, they will pay a subscription to use advanced bicycle technologies.

Lastly, in this study, we used a static model based on the historical bicycle crashes. However, a dynamic model taking into account time variation in crash occurrences and sociodemographic characteristics and riding style of the victims would be worth investigating. Such a dynamic model could provide personalised safety risk information to different bicycle users, by creating risk profiles for different user groups, i.e., elderly users, since different ages have a different probability of being involved in a crash. In future investigations, it might also be possible to use real-time information to update cyclists on traffic, weather conditions and road situations such as black ice and black spots.

# Appendices

## Appendix A: Cycling infrastructure density per country

Figure A1: Buffer zones in Austria

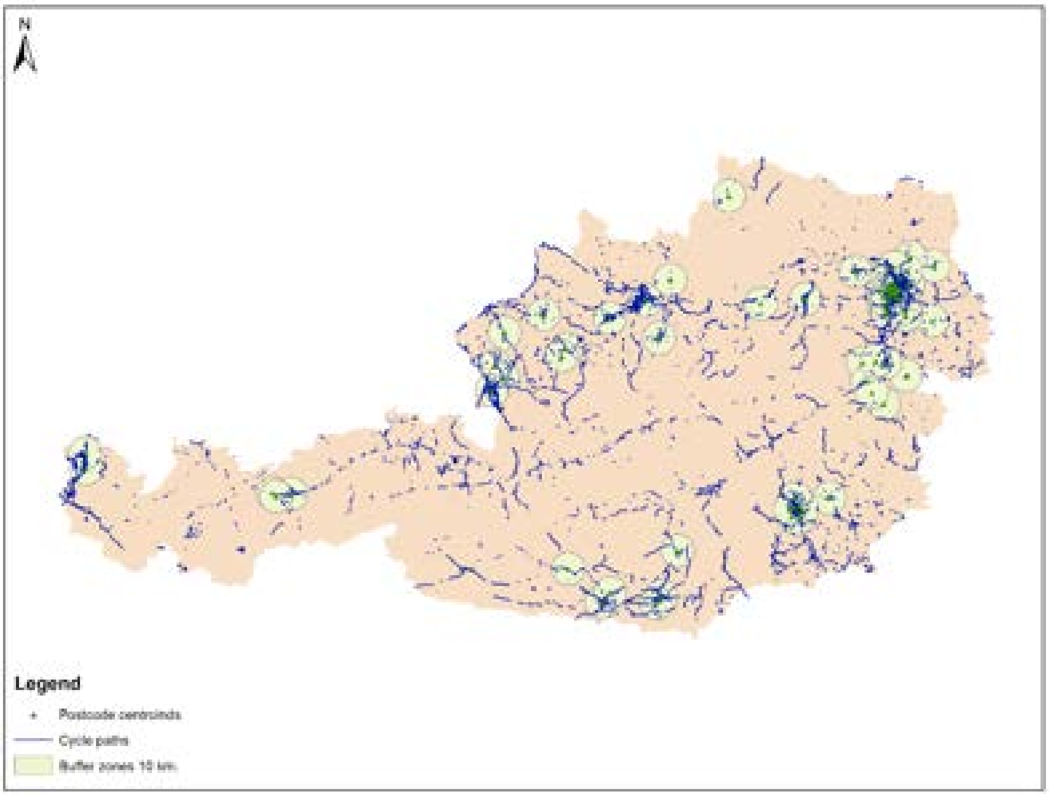


Figure A2: Buffer zones in Belgium

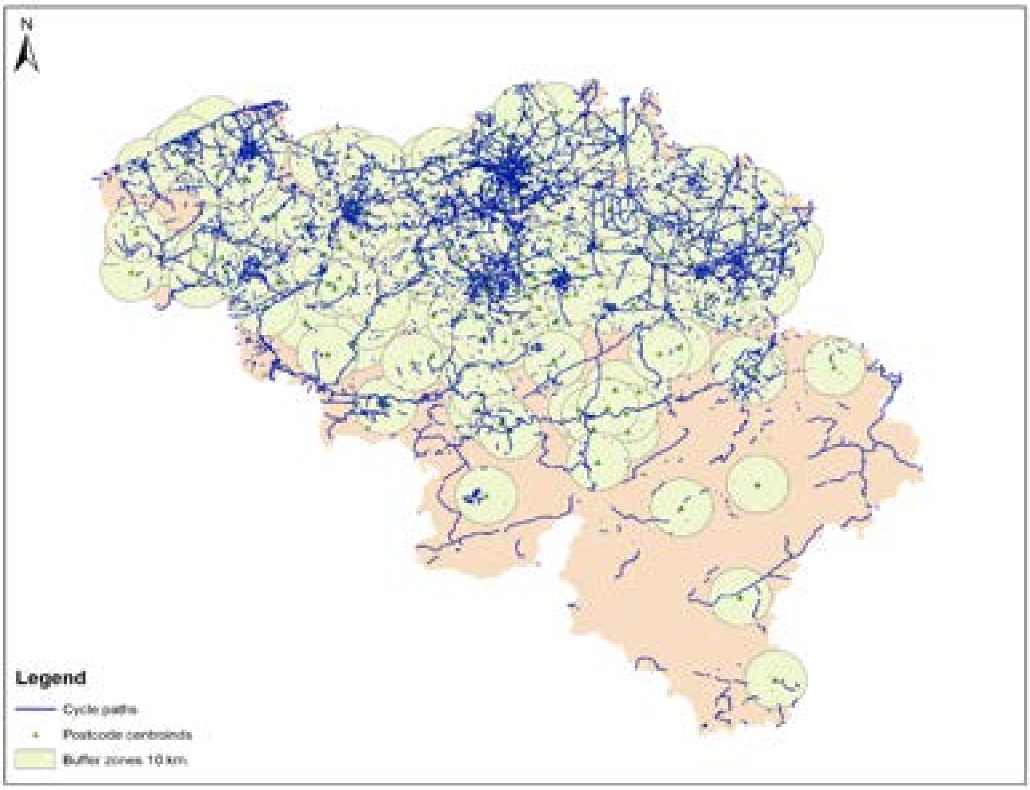


Figure A3: Buffer zones in Germany

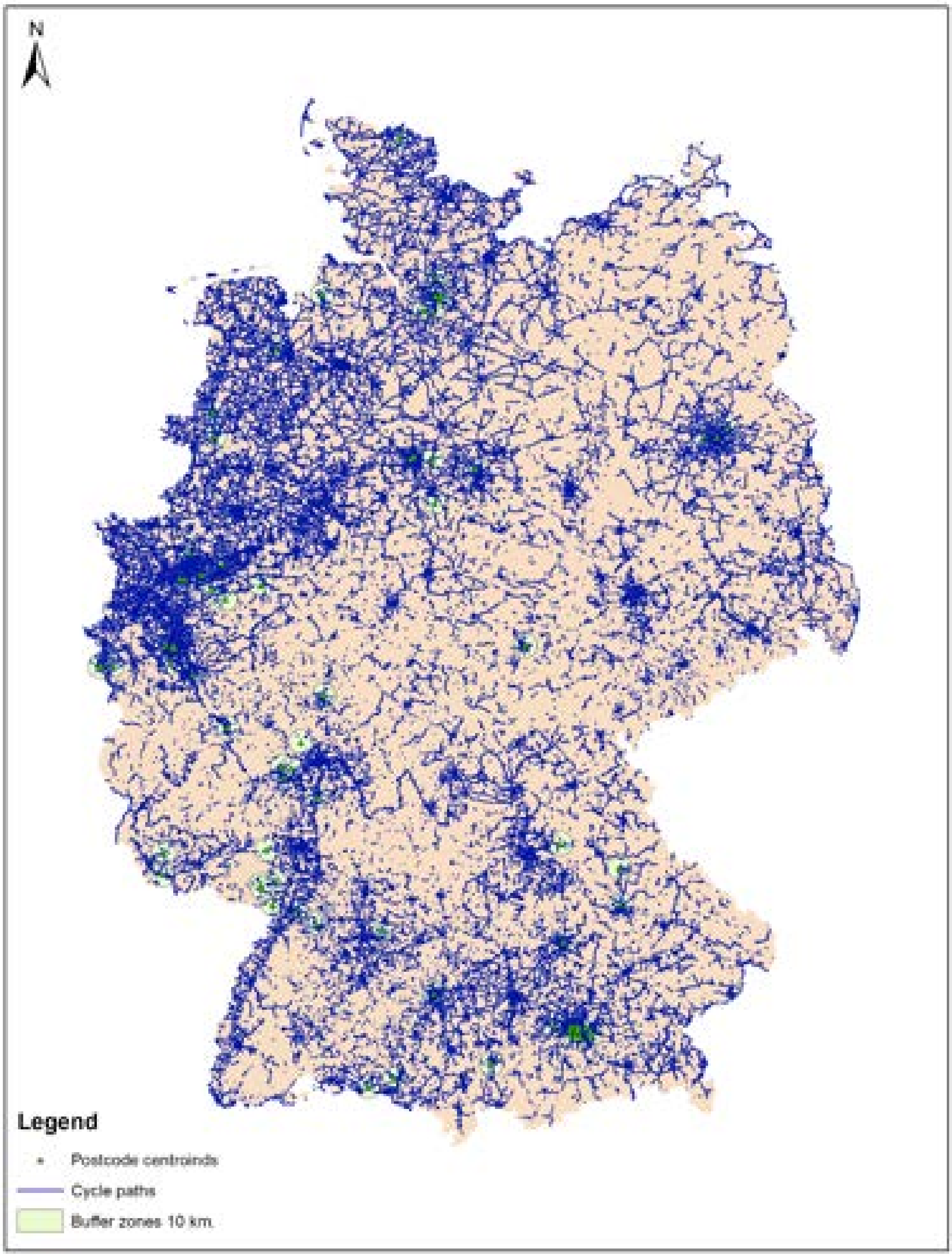


Figure A4: Buffer zones in Greece

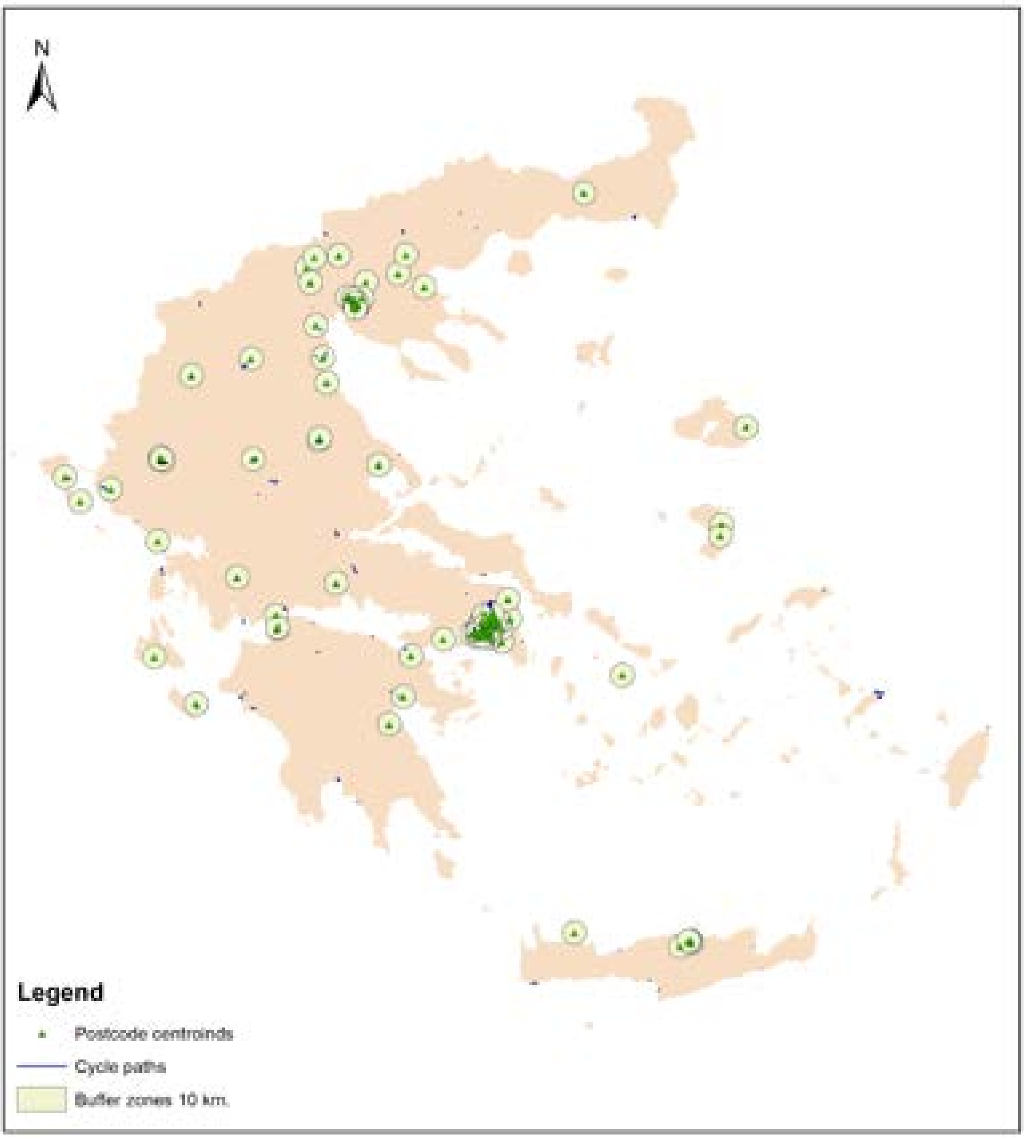
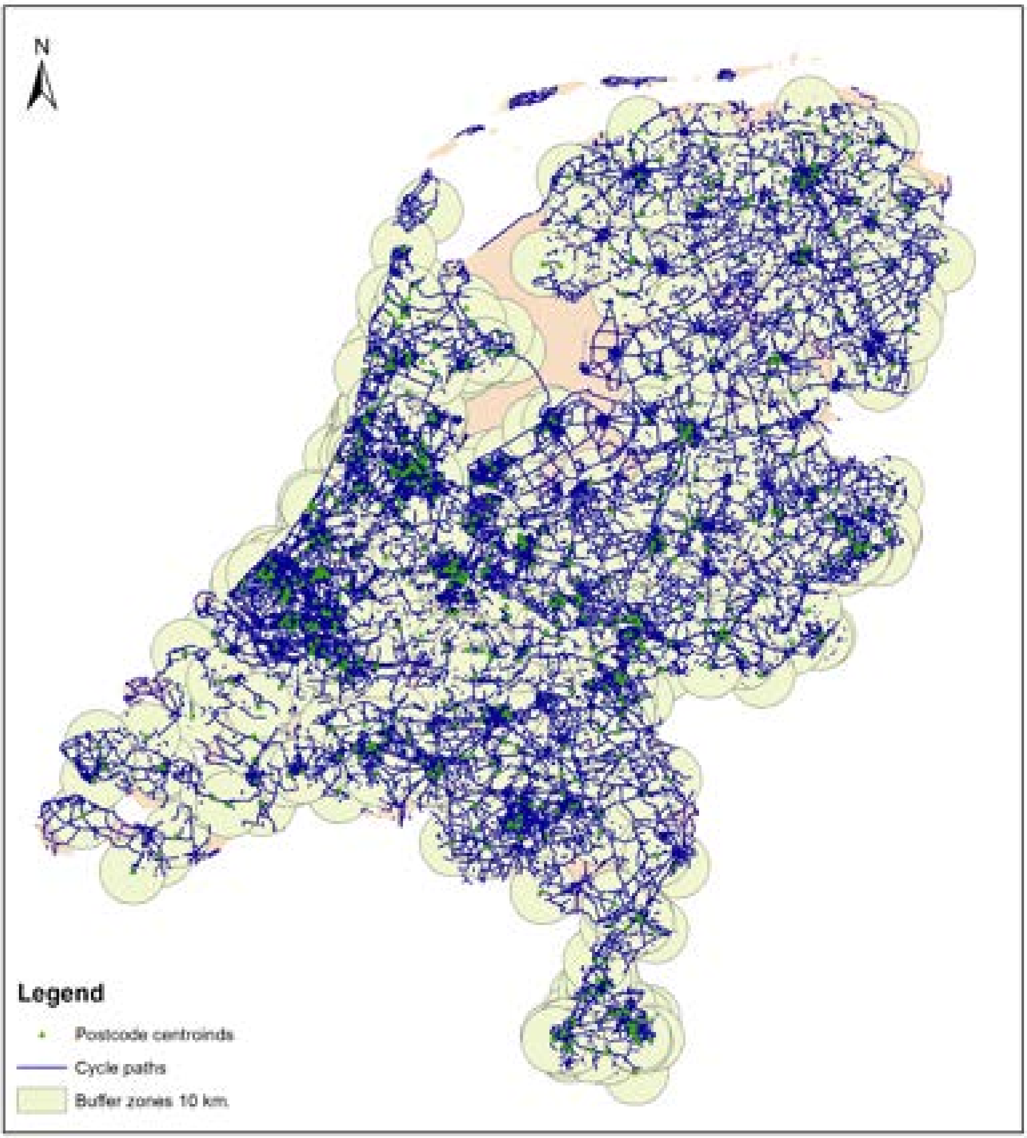


Figure A5: Buffer zones in the Netherlands



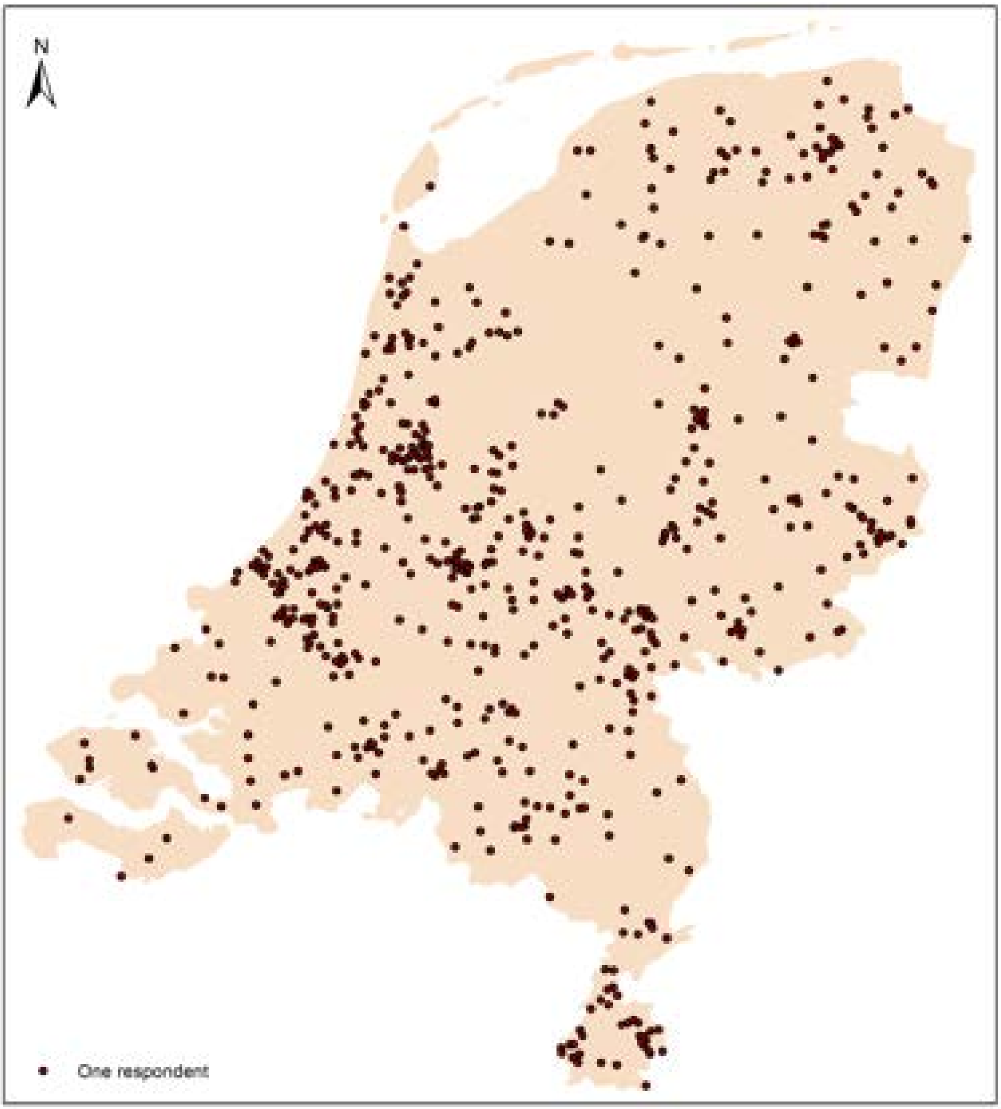
## Appendix B: Explanatory Factor Analysis result

| **Factors** | **KMO** | **Factor loadings** | **Communalities** |
|---|---|---|---|
| PE1 | 0.961 | 0.687 | 0.779 |
| PE2 | 0.959 | 0.689 | 0.720 |
| PE3 | 0.961 | 0.665 | 0.780 |
| EE1 | 0.880 | 0.726 | 0.431 |
| EE2 | 0.873 | 0.638 | 0.559 |
| EE3 | 0.919 | 0.619 | 0.467 |
| SI1 | 0.938 | 0.790 | 0.811 |
| SI2 | 0.918 | 0.826 | 0.899 |
| SI3 | 0.939 | 0.781 | 0.823 |
| HM1 | 0.962 | 0.561 | 0.554 |
| HM2 | 0.942 | 0.611 | 0.558 |
| HM3 | 0.937 | 0.603 | 0.745 |
| SS1 | 0.968 | 0.597 | 0.770 |
| SS2 | 0.962 | 0.678 | 0.704 |
| SS3 | 0.957 | 0.753 | 0.773 |
| PS1 | 0.963 | 0.624 | 0.710 |
| PS2 | 0.925 | 0.806 | 0.830 |
| PS2 | 0.938 | 0.624 | 0.679 |
| BI1 | 0.951 | 0.516 | 0.863 |
| BI2 | 0.952 | 0.530 | 0.716 |

## Appendix C: Heterotrait-Monotrait ratio correlation

| | **PE** | **EE** | **SI** | **ST** | **HM** | **PS** | **BI** |
|---|---|---|---|---|---|---|---|
| **PE** | | | | | | | |
| **EE** | 0.363 | | | | | | |
| **SI** | 0.644 | 0.231 | | | | | |
| **ST** | 0.565 | 0.208 | 0.597 | | | | |
| **HM** | 0.733 | 0.421 | 0.594 | 0.615 | | | |
| **PS** | 0.637 | 0.394 | 0.552 | 0.499 | 0.654 | | |
| **BI** | 0.750 | 0.401 | 0.634 | 0.579 | 0.744 | 0.670 | |

## Appendix D: Distribution of respondents in the Netherlands



## Appendix E: Questionnaire 1 (European-based survey)

Please select a language to continue.
Selecteer een taal om door te gaan.
Bitte wählen Sie eine Sprache aus, um fortzufahren.
Veuillez sélectionner une langue pour continuer.
Παρακαλώ επιλέξτε μια γλώσσα για να συνεχίστε.

○ English
○ Nederlands
○ Deutsch
○ French
○ Ελληνικά

→

**Welcome,**

Cycling is one of the most sustainable and green transportation modes. It helps people to increase their physical activities, travel faster (avoiding traffic) and decrease commuting costs.
What do you think about e-bikes that help you e.g., to avoid collisions and detect dangerous situations? We would appreciate your opinion

By answering the survey, you will help us to improve cycling safety. The survey will take approximately 10-15 min.

This research is conducted at the University of Twente, in The Netherlands. For any information, please feel free to contact g.kapousizis@utwente.nl

Data gathered from this questionnaire will be used by the University of Twente and will be stored anonymously and according to the General Data Protection Regulation (GDPR).

Thank you for helping us make cycling safer!

← →

0% 100%

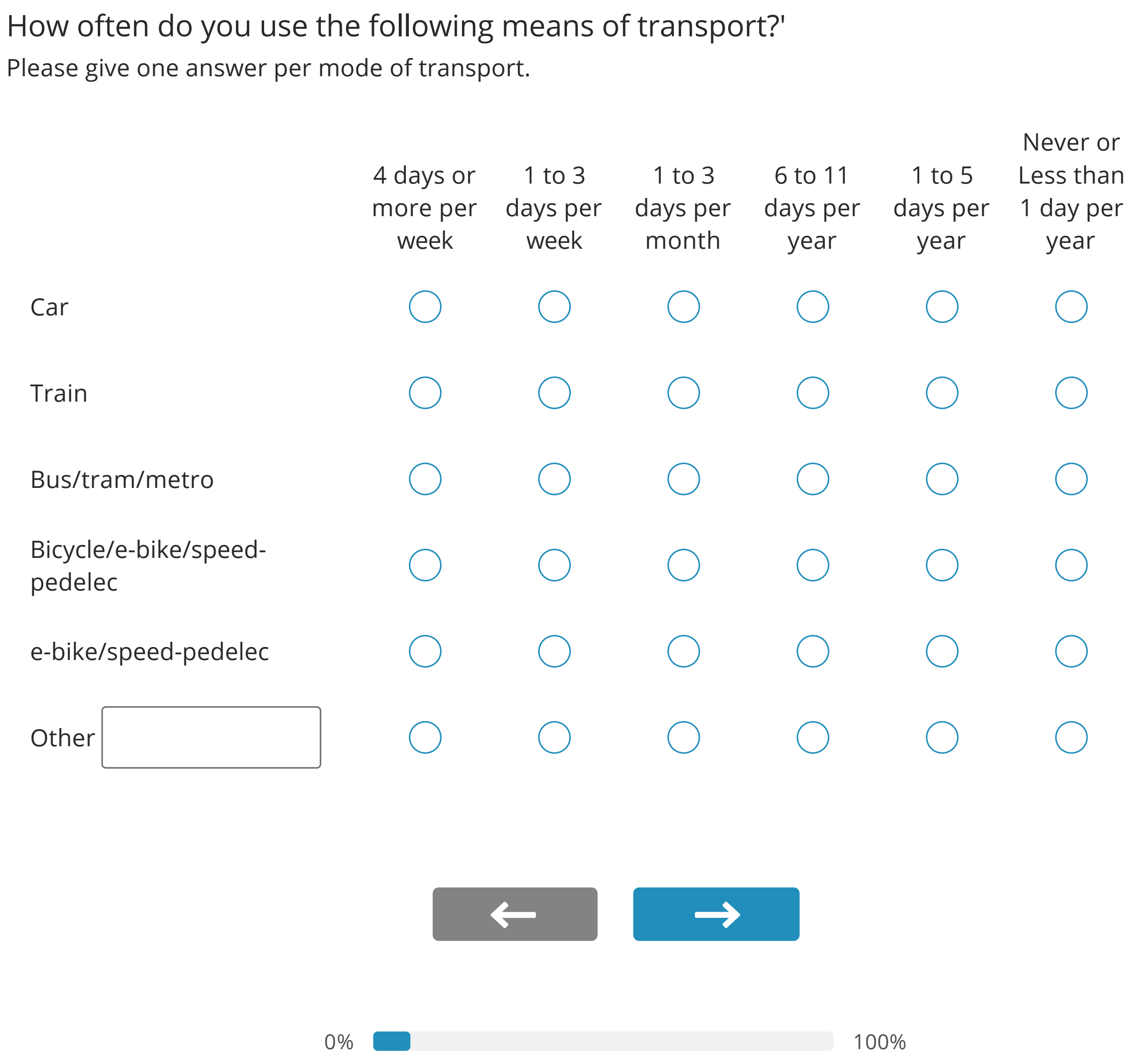
This research is conducted at the University of Twente, in The Netherlands. For any information, please feel free to contact Georgios Kapousizis g.kapousizis@utwente.nl

Data gathered from this questionnaire will be used by the University of Twente and will be stored anonymously and according to the General Data Protection Regulation (GDPR).

Thank you for helping us make cycling safer!

← →

0% 100%



How often do you use the following means of transport?'

Please give one answer per mode of transport.

| | 4 days or more per week | 1 to 3 days per week | 1 to 3 days per month | 6 to 11 days per year | 1 to 5 days per year | Never or Less than 1 day per year |
|---|---|---|---|---|---|---|
| Car | ○ | ○ | ○ | ○ | ○ | ○ |
| Train | ○ | ○ | ○ | ○ | ○ | ○ |
| Bus/tram/metro | ○ | ○ | ○ | ○ | ○ | ○ |
| Bicycle/e-bike/speed-pedelec | ○ | ○ | ○ | ○ | ○ | ○ |
| e-bike/speed-pedelec | ○ | ○ | ○ | ○ | ○ | ○ |
| Other ☐ | ○ | ○ | ○ | ○ | ○ | ○ |

How often have you used a smartphone in the past year...

Please skip 2-4 if 1 is never

| | Very often | Often | Sometimes | Rarely | Never |
|---|---|---|---|---|---|
| 1. to connect to the internet? | ○ | ○ | ○ | ○ | ○ |
| 2. to plan a trip by car or bicycle, using travel apps (e.g. Google Maps)? | ○ | ○ | ○ | ○ | ○ |
| 3. to pay (tapping) in a shop and/or supermarket? | ○ | ○ | ○ | ○ | ○ |

Some modern cars employ Advanced Driving Assistance Systems (ADAS), e.g. collision avoidance, automatic emergency braking, lane keeping assistance. Have you ever used such systems?

○ Yes

○ No

Please indicate to what extent you agree or disagree with the following statements, ranging from strongly disagree to strongly agree.

| | strongly disagree -- | 'disagree - | neutral . | agree + | strongly agree ++ | I don't know |
|---|---|---|---|---|---|---|
| There is a lot of traffic on my city/town/village | ○ | ○ | ○ | ○ | ○ | ○ |
| Cycling is safe in my city/town/village | ○ | ○ | ○ | ○ | ○ | ○ |
| Cyclists share the road with motor vehicles, in my city/town/village | ○ | ○ | ○ | ○ | ○ | ○ |
| There is a lack of bicycle lanes/paths in my city/town/village | ○ | ○ | ○ | ○ | ○ | ○ |
| Children can safely ride a bike to their school in my city/town/village | ○ | ○ | ○ | ○ | ○ | ○ |
| Cycling is considered an important transport mode in my country | ○ | ○ | ○ | ○ | ○ | ○ |

← →

0% 100%

## What type of the following bicycles do you use?

Multiple answers are possible.

- ☐ bicycle (conventional)
- ☐ e-bike (pedelec 15,5mph or 25kmh)
- ☐ fast e-bike (speed-pedelec 28mph or 45kmh)
- ☐ cargo
- ☐ e-cargo
- ☐ none of the above? Please indicate ________

← →

0% ▬ 100%

Do you own the bicycle/s you mentioned above?

| | Yes | No, it is a shared bicycle | No, I borrow it from a relative/friend | Other |
|---|---|---|---|---|
| bicycle (conventional) | ○ | ○ | ○ | ○ |
| e-bike (pedelec 15,5mph or 25kmh) | ○ | ○ | ○ | ○ |
| fast e-bike (speed-pedelec 28mph or 45kmh) | ○ | ○ | ○ | ○ |
| cargo | ○ | ○ | ○ | ○ |
| e-cargo | ○ | ○ | ○ | ○ |
| none of the above? Please indicate ☐ | ○ | ○ | ○ | ○ |

Please select which of the following statements fits best to you.

○ I fully enjoy cycling without any stress in my city/village

○ I enjoy cycling in my city/village, but I am cautious

○ I always feel stressed when I am cycling in my city/village

○ I don't know

Please indicate to what extent you agree or disagree with the following statements, ranging from strongly disagree to strongly agree.

| | strongly disagree | disagree | neutral | agree | strongly agree | I do not know |
|---|---|---|---|---|---|---|
| I feel safe when I cycle in my city/town/village | ○ | ○ | ○ | ○ | ○ | ○ |
| I get nervous easily when I cycle | ○ | ○ | ○ | ○ | ○ | ○ |

In how many accidents have you been involved in the past 3 years while riding a bicycle?

Please do not consider accidents that happened during training e.g. mountain or racing bikes, etc.

○ 0

○ 1

○ 2

○ 3

○ 4 or more

Fell down (single crash, e.g., potholes, grooves, tram tracks) in the past 3 years. Times?

Please indicate.

← →

0% 100%

You mentioned that you do not use a bicycle as a transportation mode. What is the reason for this? Please select from the following. Multiple answers are possible.

- ☐ I can not cover my distance
- ☐ It is too slow
- ☐ It is too demanding
- ☐ I do not feel safe
- ☐ Topology (hilliness, etc.) in my area
- ☐ None of the above? Please indicate ______

You can overcome these issues by using an e-bike, would you buy one?

- ○ Yes, an e-bike (pedelec) that travels up to **15,5mph (25km/h)**
- ○ Yes, a fast e-bike (Speed-Pedelec) that travels up to **28mph (45km/h)** (it requires a motor scooter license, plates and insurance. You are not allowed to ride on bike lanes with an Speed-Pedelec)
- ○ No
- ○ I do not know

← →

0% ▬ 100%

Please indicate to what extent the following statements affect your choice of not buying an e-bike?

| | strongly disagree | disagree | neutral | agree | strongly agree | I do not know |
|---|---|---|---|---|---|---|
| I do not know how to cycle | ○ | ○ | ○ | ○ | ○ | ○ |
| It is too expensive | ○ | ○ | ○ | ○ | ○ | ○ |
| Lack of safe parking spot | ○ | ○ | ○ | ○ | ○ | ○ |
| Lack of bicycle infrastructure | ○ | ○ | ○ | ○ | ○ | ○ |
| Lack of facilities when you arrive at your work (e.g., for showering) | ○ | ○ | ○ | ○ | ○ | ○ |
| I can not carry my child/children | ○ | ○ | ○ | ○ | ○ | ○ |
| Busy streets | ○ | ○ | ○ | ○ | ○ | ○ |
| Not suitable weather conditions in my area (e.g. rain, heat) | ○ | ○ | ○ | ○ | ○ | ○ |
| | strongly disagree | disagree | neutral | agree | strongly agree | I do not know |
| It is heavy | ○ | ○ | ○ | ○ | ○ | ○ |
| I do not like cycling | ○ | ○ | ○ | ○ | ○ | ○ |
| It is not in line with my social class | ○ | ○ | ○ | ○ | ○ | ○ |
| It is not in my culture | ○ | ○ | ○ | ○ | ○ | ○ |
| I cannot ride an e-bike longer than 43-75mph (70-120 km) without recharging | ○ | ○ | ○ | ○ | ○ | ○ |
| I cannot charge it easily (lack of charging stations) | ○ | ○ | ○ | ○ | ○ | ○ |
| Battery life | ○ | ○ | ○ | ○ | ○ | ○ |

Do you have further ideas or remarks, that you would like to share with us, on how to improve cycling?

← →

0% 100%

Would you like to use a bicycle for everyday transportation if there was a cycling infrastructure (e.g. bicycle paths) in your country?

- ○ Yes
- ○ No
- ○ I do not know

← →

0% 100%

Please indicate to what extent the following statements affect your choice of not buying an e-bike?

| | strongly disagree | disagree | neutral | agree | strongly agree | I do not know |
|---|---|---|---|---|---|---|
| It is too expensive | ○ | ○ | ○ | ○ | ○ | ○ |
| Lack of safe parking spot | ○ | ○ | ○ | ○ | ○ | ○ |
| It is heavy | ○ | ○ | ○ | ○ | ○ | ○ |
| I cannot ride an e-bike longer than 43-75mph (70-120 km) without recharging | ○ | ○ | ○ | ○ | ○ | ○ |
| I can not charge it easily (lack of charging stations) | ○ | ○ | ○ | ○ | ○ | ○ |
| It enables less physical exercise than a conventional bike | ○ | ○ | ○ | ○ | ○ | ○ |
| In case of an accident, there is a higher chance of getting severely injured with an e-bike than a conventional bike | ○ | ○ | ○ | ○ | ○ | ○ |
| I do not need it | ○ | ○ | ○ | ○ | ○ | ○ |
| I do not need it | ○ | ○ | ○ | ○ | ○ | ○ |
| Battery life | ○ | ○ | ○ | ○ | ○ | ○ |

← →

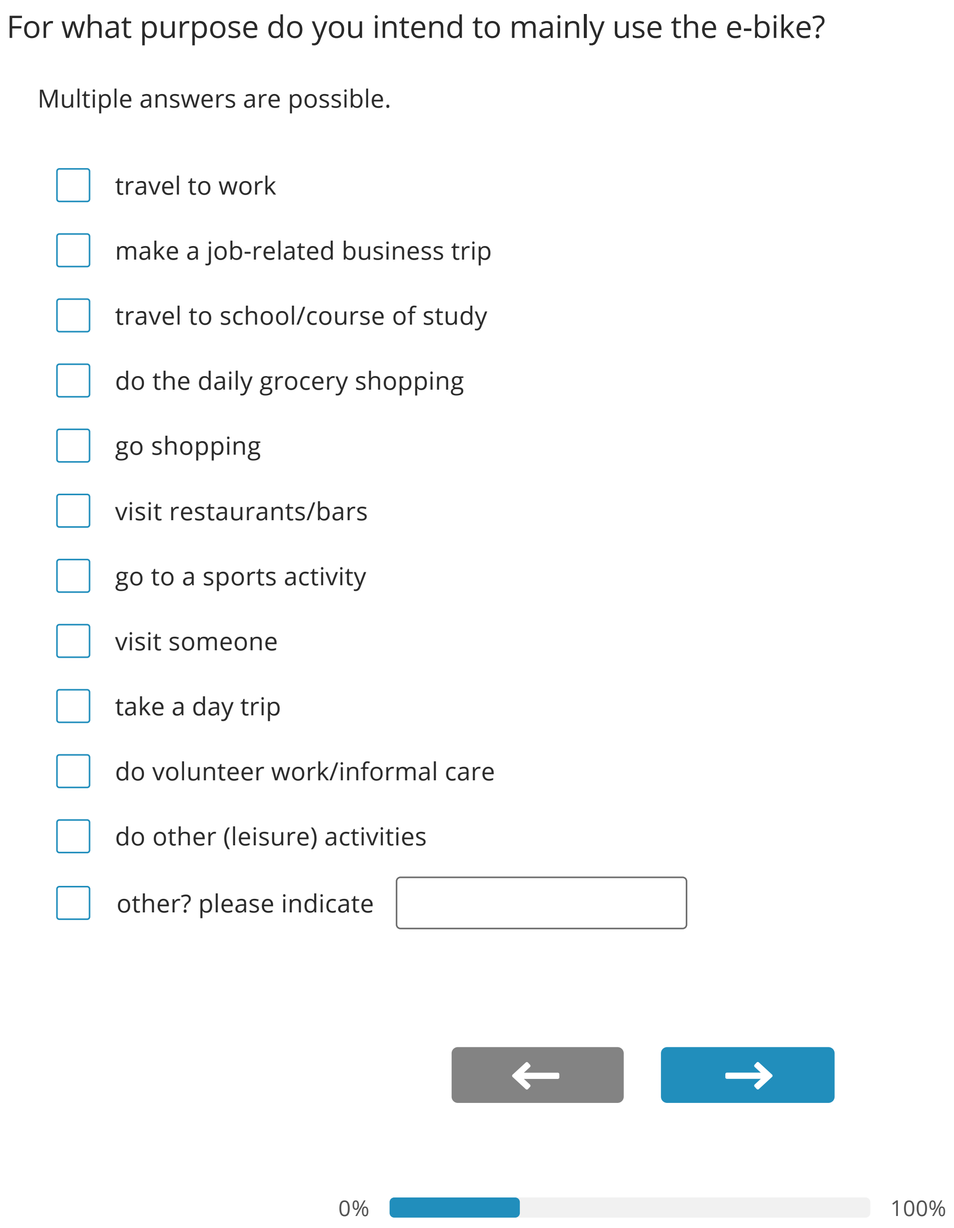
0% 100%

Are you considering buying an e-bike within the next 5 years?

- ○ Yes, an e-bike (pedelec) that travels up to **15,5mph (25km/h)**
- ○ Yes, a fast e-bike (Speed-Pedelec) that travels up to **28mph (45km/h)** (it requires a motor scooter license, plates and insurance. You are not allowed to ride on bike lanes with an Speed-Pedelec)
- ○ No, I already own an e-bike (pedelec)
- ○ No, I already own a speed-pedelec
- ○ No
- ○ I do not know

← →

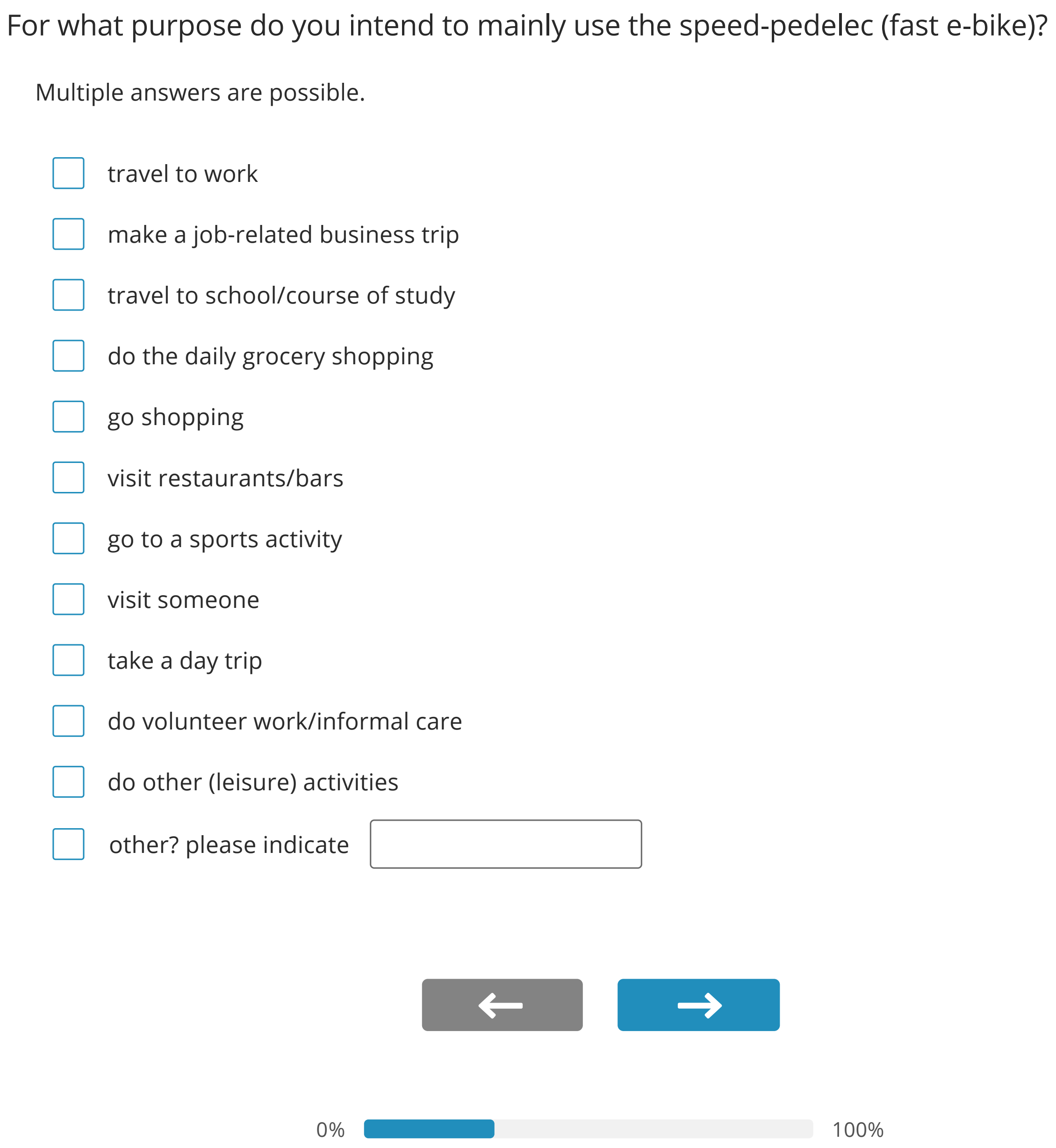
0% 100%



For what purpose do you intend to mainly use the e-bike?

Multiple answers are possible.

- ☐ travel to work
- ☐ make a job-related business trip
- ☐ travel to school/course of study
- ☐ do the daily grocery shopping
- ☐ go shopping
- ☐ visit restaurants/bars
- ☐ go to a sports activity
- ☐ visit someone
- ☐ take a day trip
- ☐ do volunteer work/informal care
- ☐ do other (leisure) activities
- ☐ other? please indicate



For what purpose do you intend to mainly use the speed-pedelec (fast e-bike)?

Multiple answers are possible.

- ☐ travel to work
- ☐ make a job-related business trip
- ☐ travel to school/course of study
- ☐ do the daily grocery shopping
- ☐ go shopping
- ☐ visit restaurants/bars
- ☐ go to a sports activity
- ☐ visit someone
- ☐ take a day trip
- ☐ do volunteer work/informal care
- ☐ do other (leisure) activities
- ☐ other? please indicate

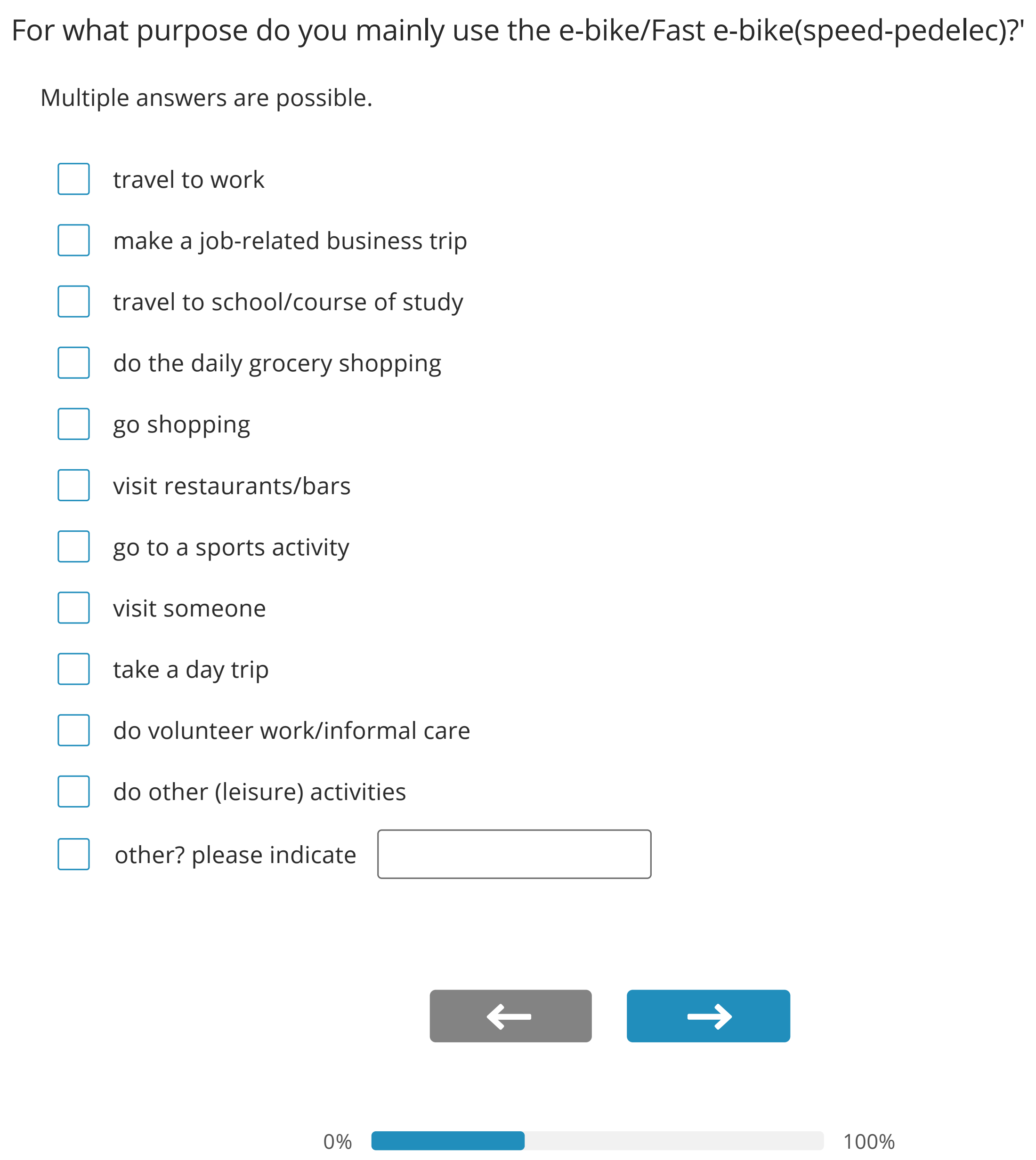
You mentioned that you do not know if you would like to buy a new bicycle. Please in the following questions imagine that you are about to buy an e-bike.
For what purpose do you intend to mainly use the e-bike?

Multiple answers are possible.

☐ travel to work
☐ make a job-related business trip
☐ travel to school/course of study
☐ do the daily grocery shopping
☐ go shopping
☐ visit restaurants/bars
☐ go to a sports activity
☐ visit someone
☐ take a day trip
☐ do volunteer work/informal care
☐ do other (leisure) activities
☐ other? please indicate ________

← →

0% 100%



For what purpose do you mainly use the e-bike/Fast e-bike(speed-pedelec)?'

Multiple answers are possible.

- ☐ travel to work
- ☐ make a job-related business trip
- ☐ travel to school/course of study
- ☐ do the daily grocery shopping
- ☐ go shopping
- ☐ visit restaurants/bars
- ☐ go to a sports activity
- ☐ visit someone
- ☐ take a day trip
- ☐ do volunteer work/informal care
- ☐ do other (leisure) activities
- ☐ other? please indicate ____________

Please imagine that you could use the following systems in your new e-bike. Please rate to what extent you think each system will increase your safety, ranging from 1= "low effect" to 5 = "high effect".

| | low effect | 2 | 3 | 4 | High effect | I don't know |
|---|---|---|---|---|---|---|
| **Safe cycling information (warning assistance):** A system that can warn you when you approach high-risk locations or on busy streets | ○ | ○ | ○ | ○ | ○ | ○ |
| **Collision avoidance system:** A system that provides you warnings for potential collision with the vehicles in front, rear and to the side | ○ | ○ | ○ | ○ | ○ | ○ |
| **Safe adjust speed:** A system that can adjust the speed of the bike automatically when you approach high-risk locations or on busy streets | ○ | ○ | ○ | ○ | ○ | ○ |
| **Smart navigation system (safer routes):** A system that can plan the safest route for you | ○ | ○ | ○ | ○ | ○ | ○ |
| **Intervention ecosystem:** A system in which traffic authorities could notify you (e.g. to change route, stop) and/or automatically adjust the speed of your bicycle based on real-time data e.g., emergency, traffic situation, road accident, weather condition. | ○ | ○ | ○ | ○ | ○ | ○ |
| **Accident notification system:** A system that can automatically make a call or send an SMS to your emergency contact person or to the emergency unit | ○ | ○ | ○ | ○ | ○ | ○ |
| **Cooperative-Cruise control:** A system that automatically adjusts the speed of your bicycle in order to be in line with other bicycles\' speeds and ride as a group. You join and leave the group at any time | ○ | ○ | ○ | ○ | ○ | ○ |

Would you be interested in having one or more of the following systems on your new e-bike to increase your safety?

Multiple answers are possible.

- ☐ **Safe cycling information (warning assistance):** A system that can adjust the speed of the bike automatically when you approach high-risk locations or on busy streets to increase your safety to avoid collisions
- ☐ **Collision avoidance system:** A system that provides you warnings for potential collision with the vehicles in front, rear and to the side
- ☐ **Safe adjust speed:** A system that can adjust the speed of the bike automatically when you approach high-risk locations or on busy streets to increase your safety to avoid collisions
- ☐ **Smart navigation system (safer routes):** A system that can plan the safest route for you
- ☐ **Intervention ecosystem:** A system that can automatically adjust the speed of your bicycle based on the traffic situation, road accident, weather condition in order to increase your safety.
- ☐ **Accident notification system:** A system that can automatically make a call or send an SMS to your emergency contact person or to the emergency unit
- ☐ **Cooperative-Cruise control:** A system that automatically adjusts the speed of your bicycle in order to be in line with other bicycles\' speeds and ride as a group. You join and leave the group at any time
- ☐ **None of the above**

← →

0% ▬▬▬ 100%

Please imagine that you could use the following systems in your new your new Speed-Pedelec. Please rate to what extent you think each system will increase your safety, ranging from low effect to high effect.

| | low effect 1 | 2 | 3 | 4 | high effect 5 | I don't know |
|---|---|---|---|---|---|---|
| **Safe cycling information (warning assistance):** A system that can warn you when you approach high-risk locations or on busy streets | ○ | ○ | ○ | ○ | ○ | ○ |
| **Collision avoidance system:** A system that provides you warnings for potential collision with the vehicles in front, rear and to the side | ○ | ○ | ○ | ○ | ○ | ○ |
| **Safe adjust speed:** A system that can adjust the speed of the bike automatically when you approach high-risk locations or on busy streets | ○ | ○ | ○ | ○ | ○ | ○ |
| **Smart navigation system (safer routes):** A system that can plan the safest route for you | ○ | ○ | ○ | ○ | ○ | ○ |
| **Intelligent speed adaptation system:** A system that can automatically adjust the speed, allows you to ride the speed-pedelec in bike paths (e.g., 15,5mph or 25kmh on bike-paths within city limits, 28mph or 45kmh on bike-paths outside city limits) | ○ | ○ | ○ | ○ | ○ | ○ |
| **Intervention ecosystem:** A system in which traffic authorities could notify you (e.g. to change route, stop) and/or automatically adjust the speed of your bicycle based on real-time data e.g., emergency, traffic situation, road accident, weather condition. | ○ | ○ | ○ | ○ | ○ | ○ |
| **Accident notification system:** A system that can automatically make a call or send an SMS to your contact person or to the emergency unit | ○ | ○ | ○ | ○ | ○ | ○ |
| **Cooperative-Cruise control:** A system that automatically adjusts the speed of your bicycle in order to be in line with other bicycles\' speeds and ride as a group. You join and leave the group at any time | ○ | ○ | ○ | ○ | ○ | ○ |

[Script]

Would you be interested in having one or more of the following systems on your new speed-pedelec (fast e-bike) to increase your safety?

'Multiple answers are possible.

**Safe cycling information (warning assistance):** A system that can adjust the

☐ speed of the bike automatically when you approach high-risk locations or on busy streets to increase your safety to avoid collisions

☐ **Collision avoidance system:** A system that provides you warnings for potential collision with the vehicles in front, rear and to the side

☐ **Safe adjust speed:** A system that can adjust the speed of the bike automatically when you approach high-risk locations or on busy streets to increase your safety to avoid collisions

☐ **Smart navigation system (safer routes):** A system that can plan the safest route for you

☐ **Intelligent speed adaptation system:** A system that can automatically adjust the speed, allows you to ride the speed-pedelec in bike paths (e.g., 15,5mph or 25kmh on bike-paths within city limits, 28mph or 45kmh on bike-paths outside city limits)

☐ **Intervention ecosystem:** A system that can automatically adjust the speed of your bike based on the traffic situation, road accident, weather condition in order to increase your safety.

☐ '**Accident notification system:** A system that can automatically make a call or send an SMS to your contact person or to the emergency unit

☐ **Cooperative-Cruise control:** A system that automatically adjusts the speed of your bicycle in order to be in line with other bicycles\' speeds and ride as a group. You join and leave the group at any time

☐ **None of the above**

← →

0% 100%

Please imagine that you could use the following systems in your e-bike. Please rate to what extent you think each system will increase your safety, ranging from low effect to high effect.

| | low effect 1 | 2 | 3 | 4 | high effect 5 | I don't know |
|---|---|---|---|---|---|---|
| **Safe cycling information (warning assistance):** A system that can warn you when you approach high-risk locations or on busy streets to increase your safety to avoid collisions | ○ | ○ | ○ | ○ | ○ | ○ |
| **Collision avoidance system:** A system that provides you warnings for potential collision with the vehicles in front, rear and to the side | ○ | ○ | ○ | ○ | ○ | ○ |
| **Safe adjust speed:** A system that can adjust the speed of the bike automatically when you approach high-risk locations or on busy streets | ○ | ○ | ○ | ○ | ○ | ○ |
| **Smart navigation system (safer routes):** A system that can plan the safest route for you | ○ | ○ | ○ | ○ | ○ | ○ |
| **Intervention ecosystem:** A system in which traffic authorities could notify you (e.g. to change route, stop) and/or automatically adjust the speed of your bicycle based on real-time data e.g., emergency, traffic situation, road accident, weather condition. | ○ | ○ | ○ | ○ | ○ | ○ |
| **Accident notification system:** A system that can automatically make a call or send an SMS to your emergency contact person or to the emergency unit | ○ | ○ | ○ | ○ | ○ | ○ |
| **Cooperative-Cruise control:** A system that automatically adjusts the speed of your bicycle in order to be in line with other bicycles\' speeds and ride as a group. You join and leave the group at any time | ○ | ○ | ○ | ○ | ○ | ○ |

Would you be interested in having one or more of the following systems on your e-bike to increase your safety?

Multiple answers are possible.

- ☐ **Safe cycling information (warning assistance):** A system that can adjust the speed of the bike automatically when you approach high-risk locations or on busy streets to increase your safety to avoid collisions
- ☐ **Collision avoidance system:** A system that provides you warnings for potential collision with the vehicles in front, rear and to the side
- ☐ **Safe adjust speed:** A system that can adjust the speed of the bike automatically when you approach high-risk locations or on busy streets to increase your safety to avoid collisions
- ☐ **Smart navigation system (safer routes):** A system that can plan the safest route for you
- ☐ **Intervention ecosystem:** A system that can automatically adjust the speed of your bike based on the traffic situation, road accident, weather condition in order to increase your safety.
- ☐ **Accident notification system:** A system that can automatically make a call or send an SMS to your contact person or to the emergency unit
- ☐ **Cooperative-Cruise control:** A system that automatically adjusts the speed of your bicycle in order to be in line with other bicycles\' speeds and ride as a group. You join and leave the group at any time
- ☐ **None of the above**

← →

0% 100%

Please imagine that you could use the following systems in your Speed-Pedelec. Please rate to what extent you think each system will increase your safety, ranging from low effect to high effect.

| | low effect 1 | 2 | 3 | 4 | high effect 5 | I don't know |
|---|---|---|---|---|---|---|
| **Safe cycling information (warning assistance):** A system that can warn you when you approach high-risk locations or on busy streets | ○ | ○ | ○ | ○ | ○ | ○ |
| **Collision avoidance system:** A system that provides you warnings for potential collision with the vehicles in front, rear and to the side | ○ | ○ | ○ | ○ | ○ | ○ |
| **Safe adjust speed:** A system that can adjust the speed of the bike automatically when you approach high-risk locations or on busy streets | ○ | ○ | ○ | ○ | ○ | ○ |
| **Smart navigation system (safer routes):** A system that can plan the safest route for you | ○ | ○ | ○ | ○ | ○ | ○ |
| **Intelligent speed adaptation system:** A system that can automatically adjust the speed, <u>allows you to ride the speed-pedelec in bike paths (e.g., 15,5mph or 25kmh on bike-paths within city limits, 28mph or 45kmh on bike-paths outside city limits)</u> | ○ | ○ | ○ | ○ | ○ | ○ |
| **Intervention ecosystem:** A system in which traffic authorities could notify you (e.g. to change route, stop) and/or automatically adjust the speed of your bicycle based on real-time data e.g., emergency, traffic situation, road accident, weather condition. | ○ | ○ | ○ | ○ | ○ | ○ |
| **Accident notification system:** A system that can automatically make a call or send an SMS to your contact person or to the emergency unit | ○ | ○ | ○ | ○ | ○ | ○ |
| **Cooperative-Cruise control:** A system that automatically adjusts the speed of your bicycle in order to be in line with other bicycles\' speeds and ride as a group. You join and leave the group at any time | ○ | ○ | ○ | ○ | ○ | ○ |

Would you be interested in having one or more of the following systems on your new Fast e-bike (Speed-Pedelec) to increase your safety?

Multiple answers are possible.

- ☐ **Safe cycling information (warning assistance):** A system that can adjust the speed of the bike automatically when you approach high-risk locations or on busy streets to increase your safety to avoid collisions
- ☐ **Collision avoidance system:** A system that provides you warnings for potential collision with the vehicles in front, rear and to the side
- ☐ **Safe adjust speed:** A system that can adjust the speed of the bike automatically when you approach high-risk locations or on busy streets to increase your safety to avoid collisions
- ☐ **Smart navigation system (safer routes):** A system that can plan the safest route for you
- ☐ **Intelligent speed adaptation system:** A system that can automatically adjust the speed, allows you to ride the speed-pedelec in bike paths (e.g., 15,5mph or 25kmh on bike-paths within city limits, 28mph or 45kmh on bike-paths outside city limits)
- ☐ **Intervention ecosystem:** A system that can automatically adjust the speed of your bike based on the traffic situation, road accident, weather condition in order to increase your safety.
- ☐ **Accident notification system:** A system that can automatically make a call or send an SMS to your contact person or to the emergency unit
- ☐ **Cooperative-Cruise control:** A system that automatically adjusts the speed of your bicycle in order to be in line with other bicycles\' speeds and ride as a group. You join and leave the group at any time
- ☐ **None of the above**

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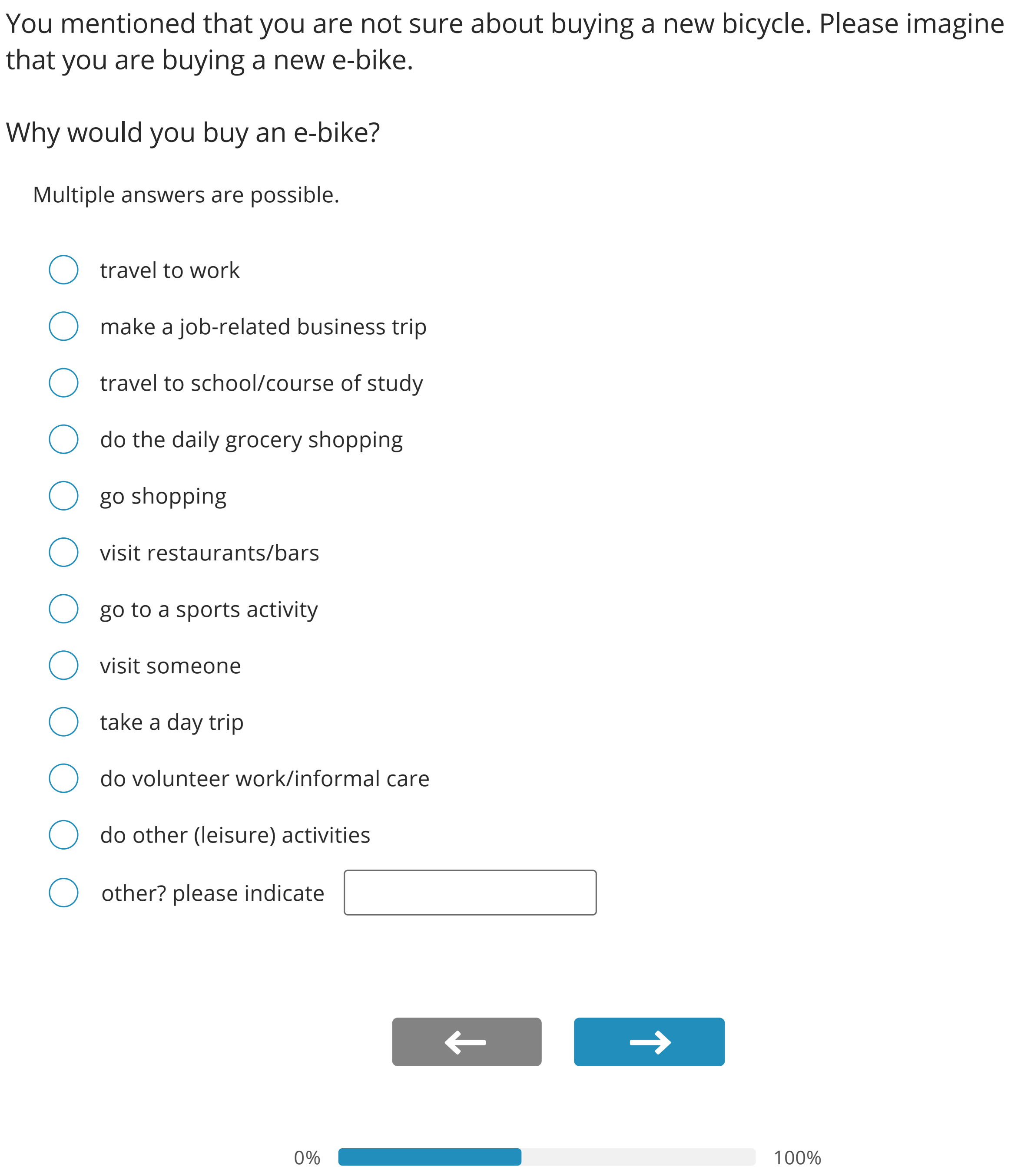

You mentioned that you are not sure about buying a new bicycle. Please imagine that you are buying a new e-bike.

Why would you buy an e-bike?

Multiple answers are possible.

○ travel to work
○ make a job-related business trip
○ travel to school/course of study
○ do the daily grocery shopping
○ go shopping
○ visit restaurants/bars
○ go to a sports activity
○ visit someone
○ take a day trip
○ do volunteer work/informal care
○ do other (leisure) activities
○ other? please indicate ☐

In the following questions, you will be asked to give your opinion about new technologies on a bicycle, namely a **Smart Bike.**

A Smart Bike is an e-bike (pedelec) that will assist you with pedal power and reduce the risk of an imminent collision.
- The Smart Bike will warn you and/or automatically reduce its speed in order to avoid a collision with other bikes, vehicles or pedestrians.
- The Smart Bike will assist you to get green traffic lights and thus, help decreasing your travel time.
- The Smart Bike will automatically send an SMS to emergency units in case you have involved in a severe accident.
- With the Smart Bike, you will be able to ride longer distances with less effort, comfortably and safely. Also, it will recommend the safer route for you.
- When riding the Smart Bike, you still maintain the steering control of the bicycle.

Below you can see a representation of how a Smart Bike would look like:

← →

0% 100%

In the following questions, you will be asked to give your opinion about new technologies on a bicycle, namely a **Smart Bike.**

A Smart Bike is an e-bike that will assist you with pedal power and reduce the risk of an imminent collision.
- The Smart Bike will warn you and/or automatically reduce its speed in order to avoid a collision with other bikes, vehicles or pedestrians.
- The Smart Bike will assist you to get green traffic lights and thus, help decreasing your travel time.
- The Smart Bike will automatically send an SMS to emergency units in case you have involved in a severe accident.
- With the Smart Bike, you will be able to ride longer distances with less effort, comfortably and safely. Also, it will recommend the safer route for you.
- When riding the Smart Bike, you still maintain the steering control of the bicycle.

Below you can see a representation of how a Smart Bike would look like:

← →

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In the following questions, you will be asked to give your opinion about new technologies on a bicycle, namely a **Smart Bike.**

A Smart Bike is a speed-pedelec (fast e-bike) that will assist you with pedal power and reduce the risk of an imminent collision.
- The Smart Bike will warn you and/or automatically reduce its speed in order to avoid a collision with other bikes, vehicles or pedestrians.
- The Smart Bike will assist you to get green traffic lights and thus, help decreasing your travel time.
- The Smart Bike will automatically send an SMS to emergency units in case you have involved in a severe accident.
- With the Smart Bike, you will be able to ride longer distances with less effort, comfortably and safely. Also, it will recommend the safer route for you.
- When riding the Smart Bike, you still maintain the steering control of the bicycle.

Below you can see a representation of how a Smart Bike would look like:

← →

0% 100%

Please indicate to what extent you agree or disagree with the following statements, ranging from strongly disagree to strongly agree.

Do you think that a Smart Bike would be useful to you?

| | strongly disagree -- | disagree - | neutral . | agree + | strongly agree ++ |
|---|---|---|---|---|---|
| I expect that a Smart Bike would be useful for me | ○ | ○ | ○ | ○ | ○ |
| Using a Smart Bike would help me reach my destination, within a city, more comfortably | ○ | ○ | ○ | ○ | ○ |
| Using a Smart Bike would help me reach longer destinations, outside a city, more comfortably | ○ | ○ | ○ | ○ | ○ |
| I expect that a Smart Bike would be useful for achieving my daily mobility needs | ○ | ○ | ○ | ○ | ○ |

What do you think about the ease of use of the Smart Bike?

| | strongly disagree -- | disagree - | neutral . | agree + | strongly agree ++ |
|---|---|---|---|---|---|
| I think a Smart Bike would be easy to use | ○ | ○ | ○ | ○ | ○ |
| It would be too much effort for me to pay attention to the systems of a Smart Bike | ○ | ○ | ○ | ○ | ○ |
| A Smart Bike would be as easy as a conventional bike to use | ○ | ○ | ○ | ○ | ○ |
| It would be too time consuming for me to learn how to use a Smart Bike | ○ | ○ | ○ | ○ | ○ |
| I could acquire the necessary knowledge to use a Smart Bike | ○ | ○ | ○ | ○ | ○ |
| I can get help from others when I have difficulties using a Smart Bike | ○ | ○ | ○ | ○ | ○ |

What do you think the opinion of others would be about the Smart Bike?

| | strongly disagree -- | disagree - | neutral . | agree + | strongly agree ++ |
|---|---|---|---|---|---|
| I believe that people who are important to me think that I should use a Smart Bike | ○ | ○ | ○ | ○ | ○ |

| | | | | | |
|---|---|---|---|---|---|
| I expect that people who are important to me would encourage me to use a Smart Bike | ○ | ○ | ○ | ○ | ○ |
| I expect that people whose opinions I value would prefer that I use a Smart Bike | ○ | ○ | ○ | ○ | ○ |

← →

0% 100%

## To what extent do you agree or disagree with the following statements

| | strongly disagree -- | disagree - | neutral . | agree + | strongly agree ++ |
|---|---|---|---|---|---|
| I would feel part of a group/community using a Smart Bike | ○ | ○ | ○ | ○ | ○ |
| I would recommend a Smart Bike to others | ○ | ○ | ○ | ○ | ○ |
| Riding a Smart Bike will be in line with my social class | ○ | ○ | ○ | ○ | ○ |
| I would be proud if people saw me owning a Smart Bike | ○ | ○ | ○ | ○ | ○ |

## To what extent do you think that the Smart Bike will be pleasurable?

| | strongly disagree -- | disagree - | neutral . | agree + | strongly agree ++ |
|---|---|---|---|---|---|
| Riding a Smart Bike would be enjoyable for me | ○ | ○ | ○ | ○ | ○ |
| Riding a Smart Bike would be much more enjoyable than a conventional bike for me | ○ | ○ | ○ | ○ | ○ |
| Riding a Smart Bike would be cool | ○ | ○ | ○ | ○ | ○ |

## Do you think that the Smart Bike will be safe?

| | strongly disagree -- | disagree - | neutral . | agree + | strongly agree ++ |
|---|---|---|---|---|---|
| I believe that a Smart Bike will increase my safety (when riding) compared to a conventional bike | ○ | ○ | ○ | ○ | ○ |
| I will ride with more stress using a Smart Bike | ○ | ○ | ○ | ○ | ○ |
| I think that riding a Smart Bike can reduce the risk of me getting involved in a crash/collision compared to a conventional bike | ○ | ○ | ○ | ○ | ○ |
| I think that there will be fewer severe crashes for the Smart Bike users | ○ | ○ | ○ | ○ | ○ |

You are doing great! We appreciate your effort!

← →

0% 100%

Would you like to buy a Smart Bike when it will be available on the market?

| | strongly disagree -- | disagree - | neutral . | agree + | strongly agree ++ |
|---|---|---|---|---|---|
| I would like to buy a Smart Bike when it will be on the market in the future | ○ | ○ | ○ | ○ | ○ |
| I would like to choose a Smart Bike even though it is more expensive | ○ | ○ | ○ | ○ | ○ |

An e-bike costs around 2000€, how much more money would you like to pay for a Smart Bike?

○ 0€

○ 200€

○ 400€

○ 600€

○ 800€

○ >1000€

Would you be willing to receive/share the following information with others to increase your safety?

| | Receiving information | Sharing information | Receiving & Sharing information | No |
|---|---|---|---|---|
| Road quality (e.g., road damages, construction sites) to/from the Municipality/Traffic Authorities | ○ | ○ | ○ | ○ |
| Real-time information to/from other road users for the road condition (e.g., congestion, accidents) End Unverified %] | ○ | ○ | ○ | ○ |
| Data that the Smart Bike produces to/from its manufacturers | ○ | ○ | ○ | ○ |

← →

Would you like to buy a Smart Bike when it will be available on the market?

| | strongly disagree<br>-- | disagree<br>- | neutral<br>. | agree<br>+ | strongly agree<br>++ |
|---|---|---|---|---|---|
| I would like to buy a Smart Bike when it will be on the market in the future | ○ | ○ | ○ | ○ | ○ |
| I would like to choose a Smart Bike even though it is more expensive | ○ | ○ | ○ | ○ | ○ |

A speed-pedelec (fast e-bike) costs around 5000€, how much more money would you like to pay for a Smart Bike?

○ 0€

○ 200€

○ 400€

○ 600€

○ 800€

○ >1000€

Would you be willing to receive/share the following information with others to increase your safety?

| | Receiving information | Sharing information | Receiving & Sharing information | No |
|---|---|---|---|---|
| Road quality (e.g., road damages, construction sites) to/from the Municipality/Traffic Authorities | ○ | ○ | ○ | ○ |
| Real-time information to/from other road users for the road condition (e.g., congestion, accidents) End Unverified %] | ○ | ○ | ○ | ○ |
| Data that the Smart Bike produces to/from its manufacturers | ○ | ○ | ○ | ○ |

← →

0% 100%

You mentioned that you are considering buying an e-bike or that you already own one.

In this part of the survey, you have to imagine that you are about to buy a new **e-bike** which costs around 2000€.

← →

0% 100%

You mentioned that you are considering buying a speed-pedelec (fast e-bike) or that you already own one.

In this part of the survey, you have to imagine that you are about to buy a new **speed-pedelec** which costs around 5000€.

← →

0% 100%

You mentioned that you are not sure about buying a new bicycle.

In this part of the survey, please imagine that you are buying a new **e-bike** which costs around 2000€.

← →

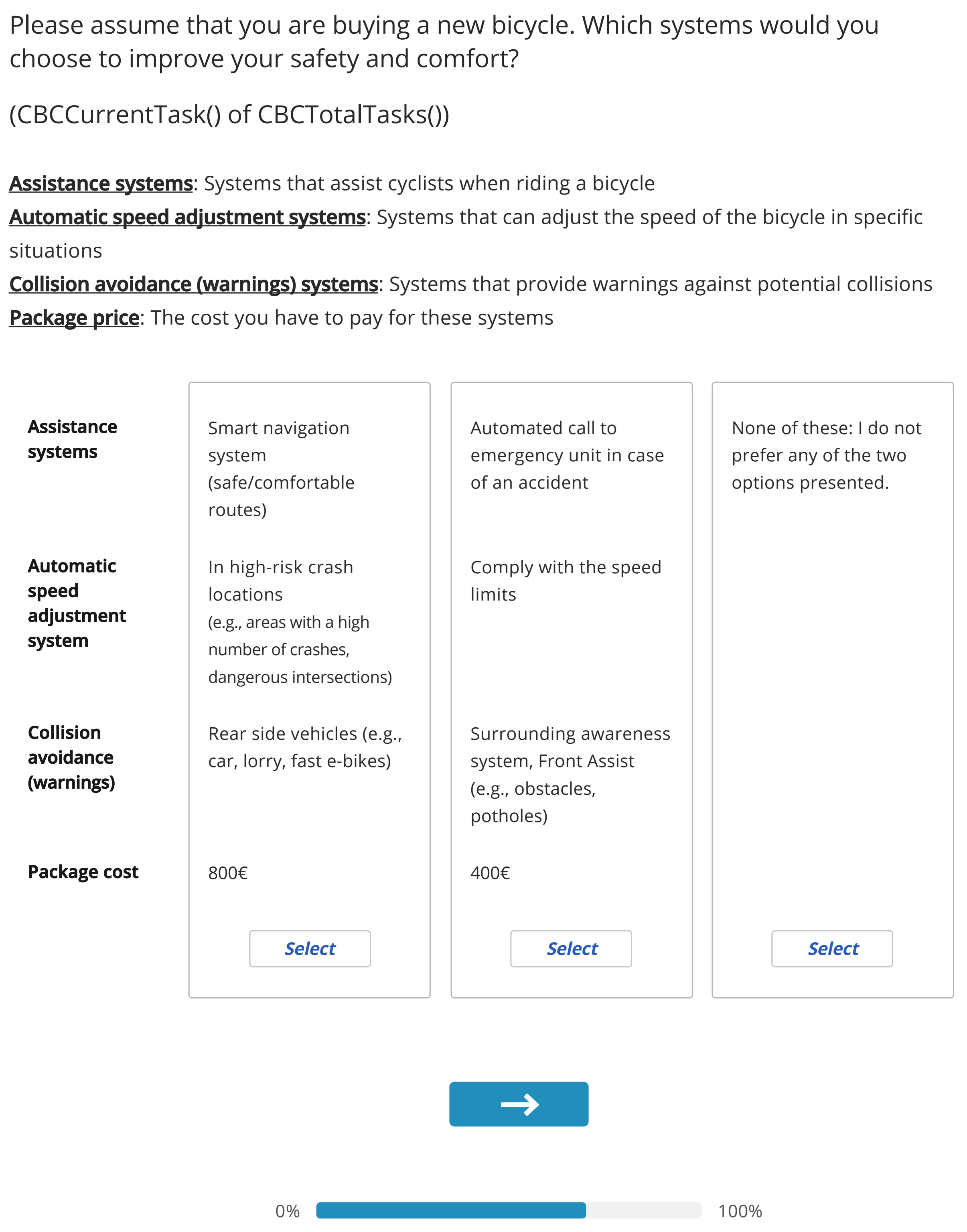
0% 100%

We will present 6 different scenarios of bicycles to you, which vary in the safety level, functionalities and price. Please mark the bicycle that best fulfils your expectations by ticking the "select" bottom below.

You almost made it!

← →

0% 100%



Please assume that you are buying a new bicycle. Which systems would you choose to improve your safety and comfort?

(CBCCurrentTask() of CBCTotalTasks())

**Assistance systems**: Systems that assist cyclists when riding a bicycle
**Automatic speed adjustment systems**: Systems that can adjust the speed of the bicycle in specific situations
**Collision avoidance (warnings) systems**: Systems that provide warnings against potential collisions
**Package price**: The cost you have to pay for these systems

| | | | |
|---|---|---|---|
| **Assistance systems** | Smart navigation system (safe/comfortable routes) | Automated call to emergency unit in case of an accident | None of these: I do not prefer any of the two options presented. |
| **Automatic speed adjustment system** | In high-risk crash locations<br>(e.g., areas with a high number of crashes, dangerous intersections) | Comply with the speed limits | |
| **Collision avoidance (warnings)** | Rear side vehicles (e.g., car, lorry, fast e-bikes) | Surrounding awareness system, Front Assist (e.g., obstacles, potholes) | |
| **Package cost** | 800€ | 400€ | |
| | Select | Select | Select |

Please assume that you are buying a new bicycle. Which systems would you choose to improve your safety and comfort?

(CBCCurrentTask() of CBCTotalTasks())

**Assistance systems**: Systems that assist cyclists when riding a bicycle
**Automatic speed adjustment systems**: Systems that can adjust the speed of the bicycle in specific situations
**Collision avoidance (warnings) systems**: Systems that provide warnings against potential collisions
**Package price**: The cost you have to pay for these systems

| | | | |
|---|---|---|---|
| **Assistance systems** | Automated call to your emergency contacts in case of an accident | Automated call to emergency unit in case of an accident | None of these: I do not prefer any of the two options presented. |
| **Automatic speed adjustment system** | To keep safe distance from a vehicle ahead (Cooperative Adaptive Cruise Control) | In high-risk crash locations (e.g., areas with a high number of crashes, dangerous intersections) | |
| **Collision avoidance (warnings)** | Blind Spot detector (left and right assist) | Rear side vehicles (e.g., car, lorry, fast e-bikes) | |
| **Package cost** | 1000€ | 600€ | |
| | *Select* | *Select* | *Select* |

→

0% 100%

Please assume that you are buying a new bicycle. Which systems would you choose to improve your safety and comfort?

(CBCCurrentTask() of CBCTotalTasks())

**Assistance systems**: Systems that assist cyclists when riding a bicycle
**Automatic speed adjustment systems**: Systems that can adjust the speed of the bicycle in specific situations
**Collision avoidance (warnings) systems**: Systems that provide warnings against potential collisions
**Package price**: The cost you have to pay for these systems

| | | | |
|---|---|---|---|
| **Assistance systems** | Automated call to your emergency contacts in case of an accident | Smart navigation system (safe/comfortable routes) | None of these: I do not prefer any of the two options presented. |
| **Automatic speed adjustment system** | To keep safe distance from a vehicle ahead (Cooperative Adaptive Cruise Control) | Comply with the speed limits | |
| **Collision avoidance (warnings)** | Surrounding awareness system, Front Assist (e.g., obstacles, potholes) | Blind Spot detector (left and right assist) | |
| **Package cost** | 800€ | 600€ | |
| | *Select* | *Select* | *Select* |

You almost made it!

→

0% 100%

Please assume that you are buying a new bicycle. Which systems would you choose to improve your safety and comfort?

(CBCCurrentTask() of CBCTotalTasks())

**Assistance systems**: Systems that assist cyclists when riding a bicycle
**Automatic speed adjustment systems**: Systems that can adjust the speed of the bicycle in specific situations
**Collision avoidance (warnings) systems**: Systems that provide warnings against potential collisions
**Package price**: The cost you have to pay for these systems

| | | | |
|---|---|---|---|
| **Assistance systems** | Automated call to your emergency contacts in case of an accident | Smart navigation system (safe/comfortable routes) | None of these: I do not prefer any of the two options presented. |
| **Automatic speed adjustment system** | Comply with the speed limits | In high-risk crash locations<br>(e.g., areas with a high number of crashes, dangerous intersections) | |
| **Collision avoidance (warnings)** | Rear side vehicles (e.g., car, lorry, fast e-bikes) | Surrounding awareness system, Front Assist (e.g., obstacles, potholes) | |
| **Package cost** | 400€ | 1000€ | |
| | *Select* | *Select* | *Select* |

→

0% 100%

Please assume that you are buying a new bicycle. Which systems would you choose to improve your safety and comfort?

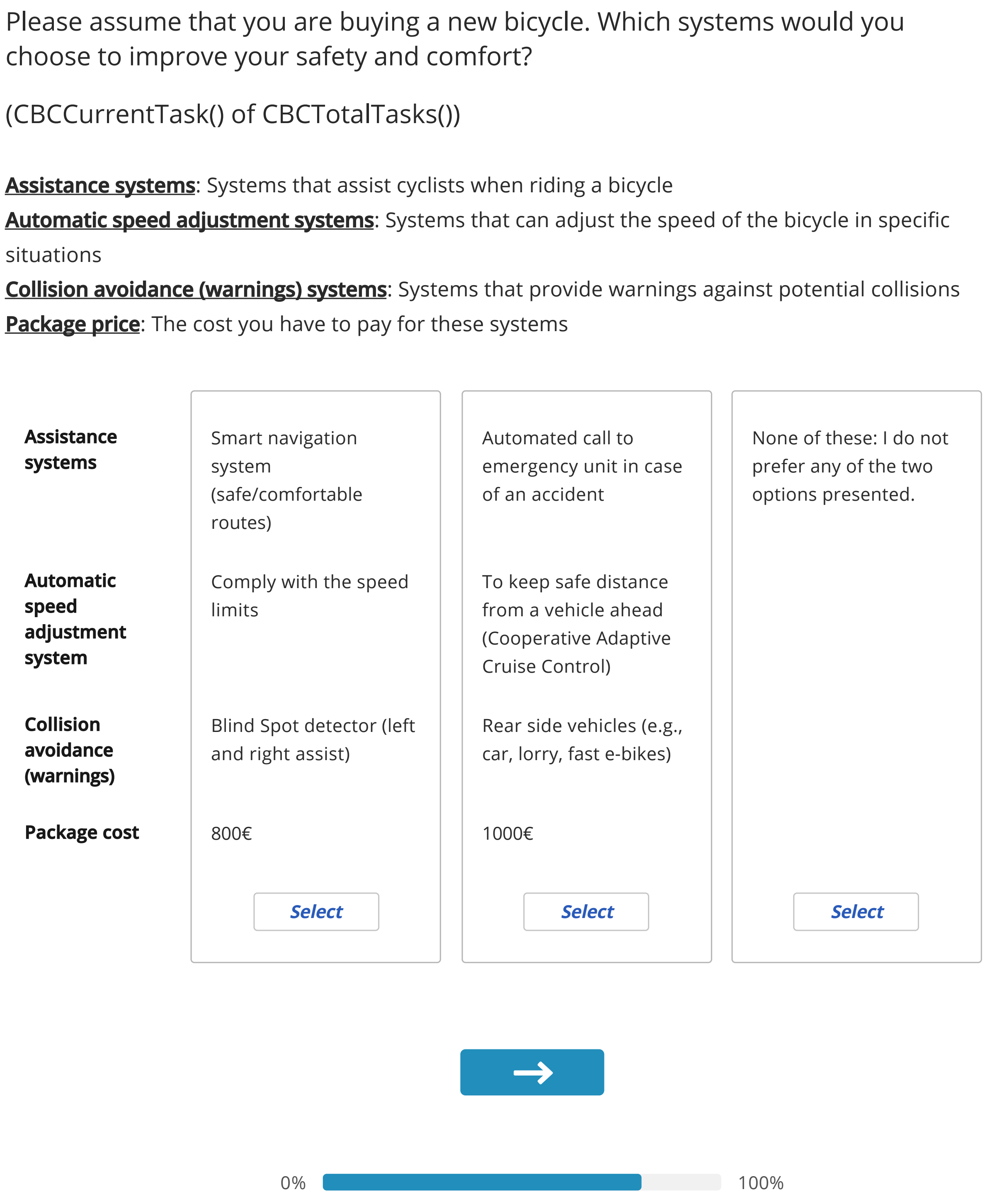
(CBCCurrentTask() of CBCTotalTasks())

**Assistance systems**: Systems that assist cyclists when riding a bicycle
**Automatic speed adjustment systems**: Systems that can adjust the speed of the bicycle in specific situations
**Collision avoidance (warnings) systems**: Systems that provide warnings against potential collisions
**Package price**: The cost you have to pay for these systems

| | | | |
|---|---|---|---|
| **Assistance systems** | Automated call to your emergency contacts in case of an accident | Automated call to emergency unit in case of an accident | None of these: I do not prefer any of the two options presented. |
| **Automatic speed adjustment system** | In high-risk crash locations<br>(e.g., areas with a high number of crashes, dangerous intersections) | To keep safe distance from a vehicle ahead (Cooperative Adaptive Cruise Control) | |
| **Collision avoidance (warnings)** | Surrounding awareness system, Front Assist (e.g., obstacles, potholes) | Blind Spot detector (left and right assist) | |
| **Package cost** | 600€ | 800€ | |
| | *Select* | *Select* | *Select* |

→

0% 100%



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(CBCCurrentTask() of CBCTotalTasks())

**Assistance systems**: Systems that assist cyclists when riding a bicycle
**Automatic speed adjustment systems**: Systems that can adjust the speed of the bicycle in specific situations
**Collision avoidance (warnings) systems**: Systems that provide warnings against potential collisions
**Package price**: The cost you have to pay for these systems

| | | | |
|---|---|---|---|
| **Assistance systems** | Smart navigation system (safe/comfortable routes) | Automated call to emergency unit in case of an accident | None of these: I do not prefer any of the two options presented. |
| **Automatic speed adjustment system** | Comply with the speed limits | To keep safe distance from a vehicle ahead (Cooperative Adaptive Cruise Control) | |
| **Collision avoidance (warnings)** | Blind Spot detector (left and right assist) | Rear side vehicles (e.g., car, lorry, fast e-bikes) | |
| **Package cost** | 800€ | 1000€ | |

How do you travel to the following places?

If you use multiple transportation modes to travel (e.g., a bicycle, then the train), please select the one you travel the longest distance in the trip.

| | Work/education | Other activities (e.g., grocery/shopping) | Leisure activities (e.g., sports/restaurants) |
|---|---|---|---|
| Car | ○ | ○ | ○ |
| Train/bus/tram/metro | ○ | ○ | ○ |
| Bicycle | ○ | ○ | ○ |
| E-bike | ○ | ○ | ○ |
| Speed-pedelec | ○ | ○ | ○ |
| Scooter/ Motorbike | ○ | ○ | ○ |
| On foot | ○ | ○ | ○ |
| Other | ○ | ○ | ○ |
| Not applicable | ○ | ○ | ○ |

On average, how many times do you travel from your home to the following places in a week?

Please give one answer per column.

| | Work/education | Other activities (e.g., grocery/shopping) | Leisure activities (e.g., sports/restaurants) |
|---|---|---|---|
| 0 | ○ | ○ | ○ |
| 1 | ○ | ○ | ○ |
| 2 | ○ | ○ | ○ |
| 3 | ○ | ○ | ○ |

| | | | |
|---|---|---|---|
| 4 | ○ | ○ | ○ |
| 5 or more | ○ | ○ | ○ |
| Not applicable | ○ | ○ | ○ |

On average, how far do you travel from your home to the following places?

Please give one answer per column.

| | Work/education | Other activities (e.g., grocery/shopping) | Leisure activities (e.g., sports/restaurants) |
|---|---|---|---|
| up to 2mph (3km) | ○ | ○ | ○ |
| 2,5 to 3,84mph (4 to 6 km) | ○ | ○ | ○ |
| 4,5 to 6mph (7 to 10 km) | ○ | ○ | ○ |
| 7 to 9mph (11 to 15 km) | ○ | ○ | ○ |
| 10 to 15,5mph (16 to 25 km) | ○ | ○ | ○ |
| 16mph (26km) or longer | ○ | ○ | ○ |
| Not applicable | ○ | ○ | ○ |

→

0% 100%

You have mentioned that you travel more than 6mph (10km) from your place of residence to your work/study place or for other activities . Would you be willing to answer the following questions about a Speed-pedelec, 28mph (45km/h)? It will only take a minute. Thank you!

○ Yes

○ No

A Speed-Pedelec is a fast bike that goes 28mph (45km/h) and is being used by riders who have to cover between 6-15,5mph (10-25km) per way on a daily basis, e.g. commuters. It is not allowed on bike lanes, even not outside city limits and it requires a moped driving license as a minimum.
End Unverified %]

← →

0% 100%

A Speed-Pedelec is not allowed on bike lanes, even not outside city limits and it requires a moped driving license as a minimum.

Would you buy a Speed-pedelec to cover this distance?

○ Yes

○ No

Would you buy a Speed-Pedelec?

Select the answer that applies to you.

☐ - if it was allowed on bike lanes?

☐ - if it was allowed on bike lanes
- and under the condition that within city limits the top speed would be automatically adjusted to 15,5mph (25km/h)?

☐ - if it was allowed on bike lanes
- and under the condition that within city limits the top speed would be automatically adjusted to 15,5mph (25km/h)?
- but only on bike lanes, on car lanes the top speed would remain 28mph (45km/h).

☐ I do not know

What is your guess: how often a week would you use a Speed-pedelec this for this distance?

☐

Would you buy a Speed-pedelec for other reasons?

○ Yes

○ No

Within a price range of 5.000€ to 13.000€: what would you pay for a bicycle like this?
font size="3" color="">Higher Prices will unlock performance upgrades (dynamic feel, range) and a growing number of features (rider assistance and safety features, quality level of gearing and suspension etc.), yet all models would be capable of 28mph (45km/h)

○ 5000€ - 6000€

○ 6000€ - 8000€

○ 8000€ - 10000€

○ 10000€ - 13000€

○ None of the above

←  →

0% 100%

## How do you travel to the following places?

If you use multiple transportation modes to travel (e.g., walking, then the train), please select the one you travel the longest distance in the trip.

Please give one answer per column.

| | Work/education | Other activities (e.g., groceries) | Leisure activities (e.g., sports/restaurants) |
|---|---|---|---|
| Car | ○ | ○ | ○ |
| Train/bus/tram/metro | ○ | ○ | ○ |
| Scooter/ Motorbike | ○ | ○ | ○ |
| On foot | ○ | ○ | ○ |
| Not applicable | ○ | ○ | ○ |

## On average, how many times do you travel from your home to the following places in a week?

Please give one answer per column.

| | Work/education | Other activities (e.g., groceries) | Leisure activities (e.g., sports/restaurants) |
|---|---|---|---|
| 0 | ○ | ○ | ○ |
| 1 | ○ | ○ | ○ |
| 2 | ○ | ○ | ○ |
| 3 | ○ | ○ | ○ |
| 4 | ○ | ○ | ○ |
| 5 or more | ○ | ○ | ○ |
| Not applicable | ○ | ○ | ○ |

On average, how far do you travel from your home to the following places (one way)?

Please give one answer per column.

| | Work/education | Other activities (e.g., groceries) | Leisure activities (e.g., sports/restaurants) |
|---|---|---|---|
| up to 2mi (3km) | ○ | ○ | ○ |
| 2,5 to 3,8mi (4 to 6 km) | ○ | ○ | ○ |
| 4,5 to 6mi (7 to 10 km) | ○ | ○ | ○ |
| 7 to 9mi (11 to 15 km) | ○ | ○ | ○ |
| 10 to 15,5mi (16 to 25 km) | ○ | ○ | ○ |
| 16mi (26km) or longer | ○ | ○ | ○ |
| Not applicable | ○ | ○ | ○ |

← →

0% 100%

*The questionnaire is almost finished. Thank you for your help!*

The questionnaire is almost finished. Thank you for your help!

What is your age? ☐

What is your gender?

○ Male
○ Female
○ gender-neutral
○ Prefer not to answer
○ Other ☐

What is your household structure?

○ Alone
○ With roommates/friends
○ With parent
○ With partner/spouse
○ With partner/spouse and child/children
○ With child/children

What is your current main occupation?

○ Student
○ Employed
○ Self-employed
○ Unemployed
○ Retired
○ Home-maker

○ Other

What is your personal net monthly income (after all deductions)?

○ 1000€-or less
○ 1001€-1500€
○ 1501€-2000€
○ 2001€-2500€
○ 2501€-3000€
○ 3001€-3500€
○ 3501€-4000€
○ 4001€-4500€
○ 4501€-5000€
○ more than 5000€
○ Prefer not to answer

What is the highest education level (on going or completed)?

○ No education
○ Primary school
○ High school
○ Technical degree
○ University degree
○ Postgraduate
○ PhD

← →

0% 100%

Do you carry your child/childern with your bicycle?

☐ Yes, I have a cargo bike
☐ Yes, I use a child bike seat
☐ Yes, I have a bicycle kid\'s trailer
☐ No
☐ Other? __________
☐ Not applicable

→

0% 100%

What is your country of residence?

Please select ▾ ';

What is your postcode (zip code) of your place of residence?

You can write the first part e.g., the first 4 digits

How did you learn about this survey?

- ○ Cycling Union
- ○ Bicycle store
- ○ Bicycle brand webpage
- ○ Bicycle experience centre
- ○ Mailing list
- ○ Friend/Relative, etc.
- ○ Social media (linkedin, facebook, etc.)
- ○ University page/University social media
- ○ Flyer
- ○ Other? Please indicate

← →

0% 100%

☐ If you would like to participate in the prize, click here.

☐ If you are interested in learning the results of this survey, click here.

☐ In the near future we are planning to run field trials in order to test the Smart Bikes. In case you would like to participate in these trials click here.

In the near future we are planning to run field trials in order to test the Smart Bikes. In case you would like to participate in these trials, please leave below your contact details (e.g. phone number, email).

Thank you

← →

0% 100%

Thank you very much for taking the time to complete the survey. We appreciate your input. You may now close your browser. End Unverified %]

0% 100%

## Appendix F: Questionnaire 2 (Field trials survey)

# Questionnaire for fieldwork

Link naar de vragenlijst: https://app.maptionnaire.com/q/3pyu2c8laa27

Publicatie id: 888yyj2lny68

Publicatiedatum: 29-4-2024

Print datum: 14-6-2024

Page 1

## Welcome!

Dear participants,  Welcome to our research!  In this questionnaire we would like to focus on your experience with a Warning System. Before and after your bicycle rides, we would like to ask you some questions.  You can find all information about research approach, consent, privacy, and contact details in the information brief.  Best wishes, The Research Team, Annemarie, Deepak, Georgios, Mario

Page 2

## Personal information

**What is your participant number?**

*Waarde mag niet lager zijn dan 1*

*Waarde mag niet hoger zijn dan 150*

**What is your nationality?**

**What is your gender?**

- ☐ Male
- ☐ Female
- ☐ Non-binary/other

**What is your age in years?**

- ☐ <25
- ☐ 25-35
- ☐ 36-45
- ☐ 46-55
- ☐ 56-65
- ☐ 66-75
- ☐ 75<

**What is weight in kilograms?**

- ☐ <60
- ☐ 61-70
- ☐ 71-80
- ☐ 81-90
- ☐ 91-100
- ☐ 101-110
- ☐ 111-120
- ☐ 121<

**What is your length in centimeter?**

- ☐ <150
- ☐ 150-160
- ☐ 161-170
- ☐ 171-180
- ☐ 181-190
- ☐ 191-200
- ☐ 201-210
- ☐ 210<

**How many cups/glasses of caffineated drinks did you drink today, if any?**

**Are you on medication that affects heart performance?**

- ☐ Yes
- ☐ No
- ☐ I don't know

**What is your personal net monthly income in Euro?**

- ☐ 0-1000
- ☐ 1001-1500
- ☐ 1501-2500
- ☐ 2501-3000
- ☐ 3001-3500
- ☐ 3501-4000
- ☐ 4001-4500

- ☐ 4501-5000
- ☐ >5000

**Indicate the highest level of education that you completed.**

- ☐ Primary school
- ☐ Middle/high school
- ☐ Vocational education
- ☐ Academic education
- ☐ Different

Page 3

## Cycling experience

**For how many years have you been cycling at least once per year in The Netherlands?**

- ☐ 0-1
- ☐ 1-2
- ☐ 2-5
- ☐ 5-10
- ☐ 10+

**In how many collisions have you been involved (with other vehicles, bicycles, etc.) in the past 3 years while riding a bicycle?**

- ☐ 0
- ☐ 1
- ☐ 2-3
- ☐ 3-5
- ☐ 5 or more
- ☐ I am not sure

**How many times did you fall down (in a single crash, e.g., due to potholes, grooves, tram tracks) in the past 3 years?**

- ☐ 0
- ☐ 1
- ☐ 2-3
- ☐ 3-5
- ☐ 5 or more
- ☐ I am not sure

**How often do you use the following type of bicycle as means of transport?**

| | Never or less than 1 day per year | 1 to 5 days per year | 6 to 11 days per year | 1 to 3 days per month | 1 to 3 days per week | 4 days or more per week |
|---|---|---|---|---|---|---|
| Bicycle | ○ | ○ | ○ | ○ | ○ | ○ |
| E-bike | ○ | ○ | ○ | ○ | ○ | ○ |

| | | | | | | |
|---|---|---|---|---|---|---|
| Speed pedelec | ○ | ○ | ○ | ○ | ○ | ○ |

**Please indicate to what extent you agree or disagree with the following statements, ranging from strongly disagree to strongly agree.**

| | Strongly disagree | Disagree | Neutral | Agree | Strongly agree |
|---|---|---|---|---|---|
| I feel safe when I cycle in my city. | ○ | ○ | ○ | ○ | ○ |
| I get nervous easily when I cycle. | ○ | ○ | ○ | ○ | ○ |
| I often feel that I'm going at a higher speed than I should be going at. | ○ | ○ | ○ | ○ | ○ |

## Digital Skills

**Do you have a smartphone?**

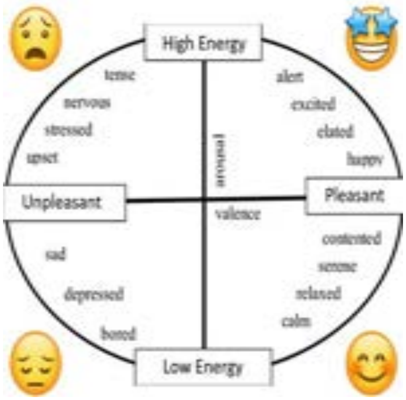
- ☐ Yes
- ☐ Yes, but I use it only for calls/messaging
- ☐ No

**Please indicate to what extent you agree or disagree with the following statements, ranging from strongly disagree to strongly agree.**

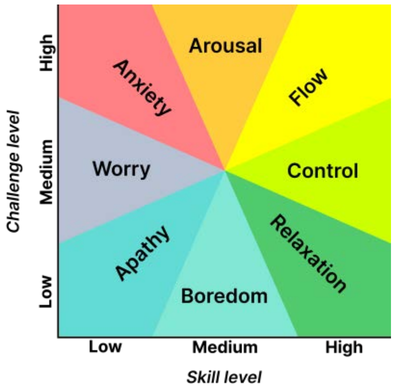
| | Never | Rarely | Sometimes | Often | Very often |
|---|---|---|---|---|---|
| How often have you used a smartphone in the past year to connect to the internet? | ○ | ○ | ○ | ○ | ○ |
| How often have you used a navigation app, on your smartphone, in the past year, to plan a trip by car or bicycle? | ○ | ○ | ○ | ○ | ○ |
| How often have you used a payment app, on your smartphone, in the past year, to pay, for example in a shop or restaurant? | ○ | ○ | ○ | ○ | ○ |
| I am interested in new technologies. | ○ | ○ | ○ | ○ | ○ |
| I think that technological developments will have a positive impact on society. | ○ | ○ | ○ | ○ | ○ |

Page 4

## Emotions & Flow



We are investigating how people feel when they ride bikes, and how our Warning System affects their riding experience. We are using concepts from psychology to help us. The first concept is that emotions can be described by how energized and positive you feel.



The second concept is about "psychological flow," which is when you feel really engaged in, focused on, and capable for, an activity. We want to know if people feel this way when they ride bikes, what makes them feel that way, and how our system influences those feelings. Since everyone is different, we would like to ask you the following questions.

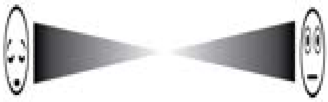
**Please answer the following questions.**

| | Never | Rarely | Sometimes | Often | Very often | Other/I do not know |
|---|---|---|---|---|---|---|
| How often do you evaluate your emotions in terms of how energized (cq. activated or aroused) you feel (Fig. 1)? | ○ | ○ | ○ | ○ | ○ | ○ |
| How often do you evaluate your emotions | ○ | ○ | ○ | ○ | ○ | ○ |

| | | | | | | |
|---|---|---|---|---|---|---|
| in terms of how pleasant (cq. positive/negative) you feel (Fig. 1)? | | | | | | |
| How easily do you get into a state of psychological flow while cycling (Fig. 2)? | ○ | ○ | ○ | ○ | ○ | ○ |

## Emotions right now

**Rate at the slider below this image how energized you feel at the moment.**



*Voer een waarde in tussen 0 (Low energy) en 100 (High energy)*

**Please enter the time in HH:MM (e.g., 14:21) at which you gave this rating.**

**Rate at the slider below this image how pleasant you feel at the moment.**

*Voer een waarde in tussen 0 (Unpleasant) en 100 (Pleasant)*

**Please enter the time in HH:MM (e.g., 14:21) at which you answered this question.**

## Go for ride 1!

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## Questions after ride 1

Now that your ride is completed, we would like to ask you about your current feelings, and about your feelings during the ride.

## Emotions right now

**Rate at the slider below this image how energized you feel at the moment.**

*Voer een waarde in tussen 0 (Low Energy) en 100 (High Energy)*

### Please enter the time in HH:MM (e.g., 14:21) at which you answered this question.

### Rate at the slider below this image how pleasant you feel at the moment.

*Voer een waarde in tussen 0 (Unpleasant) en 100 (Pleasant)*

### Please enter the time in HH:MM (e.g., 14:21) at which you answered this question.

### Rate to what extent you were in a flow during the ride.

*Voer een waarde in tussen 0 (No flow) en 100 (Full flow)*

### Rate to what extent you felt safe during the ride.

*Voer een waarde in tussen 0 (Unsafe) en 100 (Safe)*

### Please indicate to what extent you agree or disagree with the following statements, ranging from strongly disagree to strongly agree.

| | Strongly disagree | Disagree | Neutral | Agree | Strongly agree |
|---|---|---|---|---|---|
| The bicycle I just used is trustworthy. | ○ | ○ | ○ | ○ | ○ |

## Influence of context on your experience

### Please rate how the following factors influenced your cycling experience during the route.

| | Strongly negative | Negative | Neutral | Positive | Strongly positive |
|---|---|---|---|---|---|
| The activity of cycling (intensity, length, fatigue, etc.) | ○ | ○ | ○ | ○ | ○ |
| Environment (noise, buildings, landscape, etc.) | ○ | ○ | ○ | ○ | ○ |
| Road infrastructure (cycling lanes, intersections, pavement quality, etc.) | ○ | ○ | ○ | ○ | ○ |
| Other road users (cars, pedestrians, volume, speeds, proximity, etc.) | ○ | ○ | ○ | ○ | ○ |
| Weather (wind, temperature, sunshine, etc.) | ○ | ○ | ○ | ○ | ○ |
| Mood (average weekly feelings, memories, etc.) | ○ | ○ | ○ | ○ | ○ |
| Fitness (personal strength, health condition, etc.) | ○ | ○ | ○ | ○ | ○ |

**If there were any other influences, please describe them.**

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## Location ratings

Please rate to what extent you think each of the following pictures/locations is safe, ranging from 1 = "unsafe" to 5 = "safe."

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Please rate to what extent you think the location pictured above is safe. | ○ | ○ | ○ | ○ | ○ |

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Please rate to what extent you think the location pictured above is safe. | ○ | ○ | ○ | ○ | ○ |

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Please rate to what extent you think the location pictured above is safe. | ○ | ○ | ○ | ○ | ○ |

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Please rate to what extent you think the location pictured above is safe. | ○ | ○ | ○ | ○ | ○ |

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Please rate to what extent you think the location pictured above is safe. | ○ | ○ | ○ | ○ | ○ |

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Please rate to what extent you think the location pictured above is safe. | ○ | ○ | ○ | ○ | ○ |

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Please rate to what extent you think the location pictured above is safe. | ○ | ○ | ○ | ○ | ○ |

Page 7

## Warning System

In our research, we want to evaluate the design and effects of a warning system. The system warns you to avoid collisions with other road users. The warnings are given at hazardous locations, through visual, audio and/or vibration signals. We would like to ask you some questions about your expectations of this system.

**Please indicate to what extent you agree or disagree with the following statements, ranging from strongly disagree to strongly agree.**

| | Strongly disagree | Disagree | Neutral | Agree | Strongly agree |
|---|---|---|---|---|---|
| I believe the Warning System will have a positive impact on society. | ○ | ○ | ○ | ○ | ○ |
| I would feel safe with a Warning System. | ○ | ○ | ○ | ○ | ○ |
| I expect that the Warning System provides me with more safety compared to a normal e-bike. | ○ | ○ | ○ | ○ | ○ |
| I would trust the Warning System. | ○ | ○ | ○ | ○ | ○ |
| I think with the Warning System I can increase my safety. | ○ | ○ | ○ | ○ | ○ |
| I will ride with more stress using a Warning System. | ○ | ○ | ○ | ○ | ○ |
| I would like to use the Warning System. | ○ | ○ | ○ | ○ | ○ |
| I think that riding with a Warning System can reduce the risk of me getting involved in a crash compared to a conventional bike. | ○ | ○ | ○ | ○ | ○ |
| I think that there will be fewer crashes for users with the Warning System. | ○ | ○ | ○ | ○ | ○ |
| I think the Warning System would be easy to use. | ○ | ○ | ○ | ○ | ○ |

| | | | | | |
|---|---|---|---|---|---|
| I expect that the capabilities of the Warning System will meet my requirements. | ○ | ○ | ○ | ○ | ○ |

## Go for ride 2!

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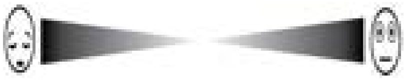
## Questions after ride 2

Now that your ride is completed, we would like to ask you about your current feelings, and about your feelings during the ride.

## Emotions right now

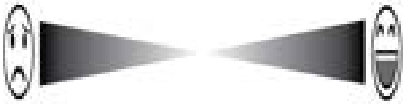
**Rate at the slider below this image how energized you feel at the moment.**



*Voer een waarde in tussen 0 (Low Energy) en 100 (High Energy)*

**Please enter the time in HH:MM (e.g., 14:21) at which you answered this question.**

**Rate at the slider below this image how pleasant you feel at the moment.**



*Voer een waarde in tussen 0 (Unpleasant) en 100 (Pleasant)*

**Please enter the time in HH:MM (e.g., 14:21) at which you answered this question.**

**Rate to what extent  you were in a flow during the ride.**

*Voer een waarde in tussen 0 (No flow) en 100 (Full flow)*

**Rate to what extent you felt safe during the ride.**

*Voer een waarde in tussen 0 (Unsafe) en 100 (Safe)*

## Experiences with the Warning System

**Please indicate to what extent you agree or disagree with the following statements, ranging from strongly disagree to strongly agree.**

| | Strongly disagree | Disagree | Neutral | Agree | Strongly agree |
|---|---|---|---|---|---|
| I felt safe with the Warning System. | ○ | ○ | ○ | ○ | ○ |
| The Warning System provided | ○ | ○ | ○ | ○ | ○ |

| | | | | | |
|---|---|---|---|---|---|
| me with more safety compared to a normal e-bike. | | | | | |
| I trusted the Warning System. | ○ | ○ | ○ | ○ | ○ |
| I think with the Warning System I can increase my safety. | ○ | ○ | ○ | ○ | ○ |
| I rode with more stress using a Warning System. | ○ | ○ | ○ | ○ | ○ |
| I would like to use the Warning System. | ○ | ○ | ○ | ○ | ○ |
| I think that riding with a Warning System can reduce the risk of me getting involved in a crash compared to a conventional bike. | ○ | ○ | ○ | ○ | ○ |
| I think that there will be fewer crashes for users with the Warning System. | ○ | ○ | ○ | ○ | ○ |
| The Warning System was easy to use. | ○ | ○ | ○ | ○ | ○ |
| The capabilities of the Warning System met my requirements. | ○ | ○ | ○ | ○ | ○ |

**What aspects (communication, meaning, intensity, etc.) of the warnings did you like?**

**What aspects (communication, meaning, intensity, etc.) of the warnings bothered you?**

Please evaluate the warnings that you received during the ride on the following points:

☐ Very badly noticeable
☐ Badly noticeable
☐ Neutral
☐ Noticeable
☐ Very noticeable

☐ Very demotivating

☐ Demotivating
☐ Neutral
☐ Motivating
☐ Very motivating

☐ Very badly understandable
☐ Badly understandable
☐ Neutral
☐ Well understandable
☐ Very well understandable

☐ Very useless
☐ Useless
☐ Neutral
☐ Useful
☐ Very useful

☐ Strongly worthless
☐ Worthless
☐ Neutral
☐ Assisting
☐ Strongly assisting

☐ Very undesirable
☐ Undesirable
☐ Neutral
☐ Desirable
☐ Very desirable

☐ Strongly reducing alertness
☐ Reducing alertness
☐ Neutral
☐ Raising alertness
☐ Strongly raising alertness

## Influence of context on your experience

**Please rate how the following factors influenced your experience with the warnings during the route.**

| | Strongly negative | Negative | Neutral | Positive | Strongly positive |
|---|---|---|---|---|---|
| The visual, auditory, and/or vibration warnings | ○ | ○ | ○ | ○ | ○ |
| The activity of cycling (intensity, length, fatigue, etc.) | ○ | ○ | ○ | ○ | ○ |
| Environment (noise, buildings, landscape, etc.) | ○ | ○ | ○ | ○ | ○ |
| Road infrastructure (cycling lanes, intersections, pavement quality, etc.) | ○ | ○ | ○ | ○ | ○ |
| Other road users (cars, pedestrians, volume, speeds, proximity, etc.) | ○ | ○ | ○ | ○ | ○ |
| Weather (wind, temperature, sunshine, etc.) | ○ | ○ | ○ | ○ | ○ |
| Mood (average weekly feelings, memories, etc.) | ○ | ○ | ○ | ○ | ○ |
| Fitness (personal strength, health condition, etc.) | ○ | ○ | ○ | ○ | ○ |

## Go for ride 3!

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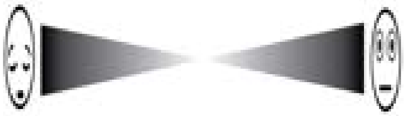
## Questions after ride 3

Now that your ride is completed, we would like to ask you about your current feelings, and about your feelings during the ride.

## Emotions right now

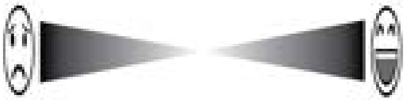
**Rate at the slider below this image how energized you feel at the moment.**



*Voer een waarde in tussen 0 (Low Energy) en 100 (High Energy)*

**Please enter the time in HH:MM (e.g., 14:21) at which you answered this question.**

**Rate at the slider below this image how pleasant you feel at the moment.**



*Voer een waarde in tussen 0 (Unpleasant) en 100 (Pleasant)*

**Please enter the time in HH:MM (e.g., 14:21) at which you answered this question.**

**Rate to what extent you were in a flow during the ride.**

*Voer een waarde in tussen 0 (No flow) en 100 (Full flow)*

**Rate to what extent you felt safe during the ride.**

*Voer eenwaarde in tussen 0 (Unsafe) en 100 (Safe)*

## Experiences with the Warning System

**Please indicate to what extent you agree or disagree with the following statements, ranging from strongly disagree to strongly agree.**

| | Strongly disagree | Disagree | Neutral | Agree | Strongly agree |
|---|---|---|---|---|---|
| I felt safe with the Warning System. | ○ | ○ | ○ | ○ | ○ |
| The Warning System provided me with more safety compared to a normal e-bike. | ○ | ○ | ○ | ○ | ○ |
| I trusted the Warning System. | ○ | ○ | ○ | ○ | ○ |
| I think with the Warning System I can increase my safety. | ○ | ○ | ○ | ○ | ○ |
| I rode with more stress using a Warning System. | ○ | ○ | ○ | ○ | ○ |
| I would like to use the Warning System. | ○ | ○ | ○ | ○ | ○ |
| I think that riding with a Warning System can reduce the risk of me getting involved in a crash compared to | ○ | ○ | ○ | ○ | ○ |

| | | | | | |
|---|---|---|---|---|---|
| a conventional bike. | | | | | |
| I think that there will be fewer crashes for users with the Warning System. | ○ | ○ | ○ | ○ | ○ |
| The Warning System was easy to use. | ○ | ○ | ○ | ○ | ○ |
| The capabilities of the Warning System met my requirements. | ○ | ○ | ○ | ○ | ○ |

**What aspects (communication, meaning, intensity, etc.) of the warnings did you like?**

**What aspects (communication, meaning, intensity, etc.) of the warnings bothered you?**

Please evaluate the warnings that you received during the ride on the following points:

☐ Very badly noticeable
☐ Badly noticeable
☐ Neutral
☐ Noticeable
☐ Very noticeable

☐ Very demotivating
☐ Demotivating
☐ Neutral
☐ Motivating
☐ Very motivating

☐ Very badly understandable
☐ Badly understandable
☐ Neutral
☐ Well understandable
☐ Very well understandable

☐ Very useless
☐ Useless
☐ Neutral
☐ Useful

☐ Very useful

☐ Strongly worthless
☐ Worthless
☐ Neutral
☐ Assisting
☐ Strongly assisting

☐ Very undesirable
☐ Undesirable
☐ Neutral
☐ Desirable
☐ Very desirable

☐ Strongly reducing alertness
☐ Reducing alertness
☐ Neutral
☐ Raising alertness
☐ Strongly raising altertness

## Influence of context on your experience

**Please rate how the following factors influenced your experience with the warnings during the route.**

| | Strongly negative | Negative | Neutral | Positive | Strongly positive |
|---|---|---|---|---|---|
| The visual, auditory, and/or vibration warnings | ○ | ○ | ○ | ○ | ○ |
| The activity of cycling (intensity, length, fatigue, etc.) | ○ | ○ | ○ | ○ | ○ |
| Environment (noise, buildings, landscape, etc.) | ○ | ○ | ○ | ○ | ○ |
| Road infrastructure (cycling lanes, intersections, pavement quality, etc.) | ○ | ○ | ○ | ○ | ○ |
| Other road users (cars, pedestrians, volume, speeds, proximity, etc.) | ○ | ○ | ○ | ○ | ○ |
| Weather (wind, temperature, sunshine, etc.) | ○ | ○ | ○ | ○ | ○ |

| | | | | | |
|---|---|---|---|---|---|
| Mood (average weekly feelings, memories, etc.) | ○ | ○ | ○ | ○ | ○ |
| Fitness (personal strength, health condition, etc.) | ○ | ○ | ○ | ○ | ○ |

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## Many thanks!

**Do you have any further comments or questions?**

**Can we contact you for future participation?**

- ☐ Yes
- ☐ No
- ☐ Maybe

**Would you like to stay up to date about our research?**

- ☐ Yes
- ☐ No

**Email address (for future participation and/or research updates)**

Congratulations, you finished the survey!  We are very thankful for your participation. The results will be meaningful for the Smart Connected Bike project and beyond.  You can contact us any time in case of questions or ideas.  Best regards, The Research Team

Click the button below to submit your answers. Many thanks again for your participation!

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# Summary

The number of people using bicycles is increasing every year, and the COVID-19 pandemic has led to an even bigger increase. This is good news since cycling can in general increase sustainability and reduce transport emissions and congestion in cities. Cycling also has health benefits, especially for conventional bicycle users. During the last decades, there has been a burst in e-bike use. E-bikes have an ever bigger contribution to transport emissions and congestion since they can replace motor vehicles for short trips. Due to their motor assistance, people can cycle further with less effort. This has resulted in an increase in e-bike sales and use in many countries, including the Netherlands. Their popularity is growing rapidly, particularly among commuters and the elderly, however, this increased use of e-bikes comes with an increase in vulnerability. More specifically, in the last years, there has been an evident increase in cycling crashes, often including e-bikes. Smart connected bicycles could be the next revolution in the urban road transport field, since they could offer users an alternative transportation mode that brings all the positive characteristics of a(n) (e-)bike, such as easy accessibility to the city while increasing users' safety.

This thesis evaluates the impacts of smart connected bicycles on users' acceptance, preferences, and willingness to pay. In addition, users' experience with a smart connected bike prototype is evaluated through a field experiment. A smart connected bicycle is an e-bike integrated with sensors and various systems, such as telecommunication technologies, which is connected to the urban infrastructure through wireless technologies to increase cyclist's safety and comfort. Therefore, fulfilling its overarching aim, this thesis examines bicycle technologies affecting cyclist safety and investigates factors that influence users' preferences for accepting smart bicycle technologies across different European countries. It also investigates users' preferences for individual technologies and estimates willingness to pay values for these technologies in Europe and in the Netherlands. Individuals' perceived safety, perceptions and riding behaviour changes are also measured in practice with the use of a specific set of smart bicycle technologies through field trials in the Netherlands.

At the first step of this thesis (Chapter 2), we examine the smart bicycle technologies that can be embedded on the bicycle frame to enhance cyclist safety and propose a topology for different bicycle smartness levels. In the literature, there are different types of smart bicycle technologies with no concise terminology and different maturity levels (varying from simulation experiments to near-to-market products). Thus, we start with a literature review following a systematic approach to searching the existing literature, looking for all the possible smart bicycle technologies. We use different academic databases as well as grey literature in order to be more inclusive and as comprehensive as possible. We found more than 1000 documents, and after

screening, we ended up with 36 documents that met the inclusion criteria we had defined a-priori for this research question. Classifying the existing literature, we define six bicycle smartness levels with various functionalities, while also considering their technology readiness level. Namely: “Level 0” contains all the conventional bicycles or e-bikes without any assistance. “Level 1” includes passive support, such as post-crash notifications. “Level 2” comprises warning assistance such as collision avoidance systems. “Level 3” contains active assistance with speed adaptation of e-bikes as well as bicycle to infrastructure communication. “Level 4” consists of a fully connected environment where the bicycle can communicate with other bicycles and motor vehicles in addition to infrastructure. “Level 5”, the highest level, makes it possible for governments and/or road authorities to intervene, for instance, adjusting the speed based on real-time data of the bicycle. Level 5 is still theoretical, and such systems are under investigation. The current state of technology falls at Level 2: bicycles that can detect obstacles and warn cyclists in order to avoid possible collisions. From the available applications that affect cycling safety, the state of the art are based on network technology, GPS, sensors and LIDAR. Overall, the proposed bicycle smartness levels topology serves as a common terminology among different actors, such as researchers and bicycle manufacturers, and defines the broad term “smart” bikes. In addition, it sheds light on future directions that could assist in deploying smart bicycle technologies on bicycles, especially e-bikes, making them safer and more comfortable.

The second step of this thesis (Chapter 3) investigates user’s acceptance of the “smart e-bike”. The smart e-bike is based on the bicycle smartness level 3, “Active assistance” as defined earlier in Chapter 2 and consists of different systems/functionalities, such as warning or automatic speed reduction when a cyclist approaches a location with high crash risk and Bicycle to Infrastructure (B2I) communication. The latter allows the bicycle to get a “green wave” at the traffic lights; hence, the cyclist will stop fewer times. In addition, the smart e-bike can not only recommend safe routes but also send the location to an ambulance in case of a crash so the cyclist will get first aid faster. Through an online survey, we collected data from five European countries (Austria, Belgium, Germany, Greece and the Netherlands), and we included two different options for the smart e-bike: one for smart pedelecs and one for smart speed-pedelecs. Thus, we distinguish between respondents who prefer a pedelec and those who prefer a speed-pedelec. The main scope of analysing this data is to examine factors influencing user acceptance of the smart e-bike. For this, we apply the Unified Theory of Acceptance and Use of Technology 2 by estimating a structural equation model. We adjust the initial model to fit the scope of this research better. Specifically, we add the factors of “perceived safety” and “social status” and drop the “habit”, “facilitating condition” and “price” since these factors predict the actual use while we use a hypothetical scenario, and respondents cannot test the smart e-bike. In addition, we control our model with different sociodemographic characteristics, technology friendliness and safety-related characteristics, such as perceived safety, and availability of cycling infrastructure. Also, we estimate a multi-group (country) analysis to examine differences between respondents from different countries and investigate the measurement invariance to confirm the validity of the results. We test the measurement invariance for the multigroup analyses for the five countries and between smart-pedelec and smart Speed-pedelec groups. This allows us to examine whether a factor is equivalently perceived across the groups (countries and smart e-bikes). Our analyses show no differences among the groups, allowing us to investigate if there are differences among the groups by testing the multigroup analysis.

Overall, we test six psychological factors, and of those only: “performance expectancy”, “hedonic motivation”, and “perceived safety” have a significant influence towards the behavioural intention to use smart e-bikes in the pooled sample. Age and previous involvement in bicycle crashes have a positive and significant effect on behavioural intention for the smart e-bike. The multigroup analyses show that there is heterogeneity across the five countries since different factors play key roles in different countries. Lastly, regarding the smart Pedelec and smart speed-pedelec, performance expectancy and hedonic motivation are the dominant factors in both smart e-bikes.

Chapter 4 examines individuals’ preferences and willingness to pay for specific smart bicycle technologies. While all the technologies investigated in Chapter 2 affect cycling safety, individuals might have different preferences for these technologies. Hence, we examine how these preferences are derived and linked with sociodemographic, geographical and attitudinal variables. We analyse individuals' preferences using stated preference data collected from five European countries. We apply a latent class choice model to this data to: 1) investigate respondents' preferences, 2) examine heterogeneity in preferences, and 3) estimate the willingness to pay. The latent class choice model consists of two distinct classes: Class 1 - Technology cautious (52% of the respondents), which includes respondents who do not show a higher preference for advanced technologies and are cost-sensitive, and Class 2 - Technology prone (48% of the respondents) which includes respondents who have a higher preference for advanced smart bicycle technologies and are less cost-sensitive, which in turn also influences their willingness to pay. We found that respondents falling in Class 2 have a higher willingness to pay for all of the systems that were tested. In addition, it is worth mentioning that even though respondents falling in Class 1 have a higher utility for the “assistance smart routes”, they have a lower willingness to pay for this system since they are more cost- sensitive. Regarding respondents' probability of falling into each of the classes, we see that respondents coming from Greece are more likely to fall into Class 2 (~70%), while for the respondents from the rest 4 countries, the likelihood of falling into Class 2 is ~44%, meaning there is a higher probability for the later to be in Class 1 - Technology prone. Overall, we found that those living in areas lacking cycling infrastructure, who are technologically savvy and have an above-average monthly income, have a higher preference for smart bicycle technologies and are more likely to use advanced bicycle technologies. We observed heterogeneity in respondents' preferences for smart bicycle technologies, which can partially be explained by sociodemographic characteristics, geographical information, safety-related questions as well as attitudinal questions.

For Chapter 5, the focus turns on Dutch respondents. Here, we focus on the sub-set of the data gathered earlier coming from the Netherlands since the Netherlands is the leading country in e-bike adoption in Europe and second worldwide, after China. Hence, analysing e-bike users’ preferences for smart bicycle technologies and willingness to pay is of interest. To study Dutch respondents' preferences, we estimate a mixed logit model with random parameters to account for random heterogeneity in respondents' choices. In addition, we explore deterministic heterogeneity by interacting specific attribute levels with sociodemographic characteristics. We find that respondents older than 60 years old are less likely to choose the “assistance emergency call” or “collision avoidance rear side” since we found lower utility compared to the other age groups. Also, respondents between 25–44 are more likely to choose the “automatic speed risk areas” system, and finally, males are less likely to select the “automatic speed limit” system.

Additionally, heterogeneity exists in respondents' preferences since all the random parameters were significant. We further examine respondents' heterogeneity by estimating market segmentation for different population groups based on these findings. The segmentation approach shows that among different population groups, such as male vs female, low vs high income, e-bike vs non-e-bike users, and high vs low education respondents have huge differences in willingness to pay for smart bicycle technologies. In conclusion, all of the smart bicycle technologies tested have positive utilities, except the cost, meaning that respondents are cost-sensitive. “Smart routes” functionality is the more significant attribute level, followed by the “automatic speed limit”, “Collision avoidance rear side” and “blind spot”.

Finally, Chapter 6 examines individuals’ perceived safety, trust, perception, and riding behaviour changes by collecting GPS and survey data in a field experiment testing a context-aware safety warning prototype. We use bicycle crash data from the Police (BRON) report in the Netherlands and develop a safety model by estimating high crash bicycle locations for the city of Enschede, in the Netherlands, using a kernel density estimation. Then, we design and develop a safety warning system that uses the information from the safety model to warn cyclists when approaching a high crash location. The safety warning system could warn cyclists with two different types of communication, audio or tactile, while additional visual information is always available. We used a predefined route, in which each participant had to cycle three times. The first ride was used as a control ride, and the other two rides took place with visual warnings in combination with either audio or tactile warnings. After each ride, participants completed a survey stating their experiences with the context-aware warning system. Additionally, GPS data was collected during each ride to examine participants’ trajectories and speed. The analysis encompasses survey and GPS data before and after the three rides. The results indicate that the context-aware safety support system increases the perceived safety of the participants while the overall trust in the system remains low. In addition, participants were found to reduce their speed after receiving a warning when approaching at a high crash risk location with high speed, which means that the system has effective results for participants' safety. Male participants had a higher speed reduction when they received warnings than females; however, females rode at lower speeds overall. Participants who use e-bikes or conventional bicycles were also found to be more likely to reduce their speed following a warning. We found no significant difference in participants' speed changes between the different warning types (audio vs tactile).

In summary, this thesis provides new insights into smart bicycle technologies and user acceptance by employing different behavioural and discrete choice models. We collected European-based and field experiment data to examine expected and experienced aspects regarding the influence of smart bicycle technologies on users’ perception and riding behaviour changes. We investigate how individuals from different countries with different cycling cultures perceive smart bicycle technologies, and we examine the impact of these factors on users’ preferences. We distinguish individuals based on their preferences for smart bicycle technologies and account for their heterogeneity on big and small geographical scales. The findings of this research serve multiple insights and provide several recommendations for practical (policymakers, governments, bicycle manufacturers) as well as theoretical (further research) implications.

# Samenvatting

Het aantal mensen dat gebruik maakt van de fiets stijgt ieder jaar en de COVID-19-pandemie heeft tot een verdere toename geleid. Dat is goed nieuws: fietsen is duurzaam en draagt bij aan het verminderen van transportemissies en congestie in steden. Fietsen biedt ook gezondheidsvoordelen, vooral voor gebruikers van gewone, conventionele fietsen. In de afgelopen decennia is het gebruik van de elektrische fiets (e-bike of e-fiets) explosief gegroeid. De e-bike draagt in toenemende mate bij aan het verminderen van emissies en congestie aangezien deze voor korte ritten een alternatief biedt voor motorvoertuigen. Dankzij de motorondersteuning kan met minder inspanning een langere afstand worden afgelegd dan op de conventionele fiets. Dit heeft in veel landen, waaronder Nederland, geleid tot een toename in de verkoop en het gebruik van e-bikes. De e-bike is met name populair onder forenzen en ouderen, maar de toegenomen populariteit gaat gepaard met een toename in kwetsbaarheid. Het aantal fietsongevallen is de laatste jaren duidelijk gestegen, en vaak zijn e-bikes hierbij betrokken. De slimme verbonden fiets (smart connected bicycle) zou de volgende revolutie in stedelijk verkeer en vervoer kunnen zijn. Deze fiets biedt gebruikers namelijk een alternatief vervoermiddel en combineert de positieve eigenschappen van de e-bike en de gewone fiets.

Dit proefschrift evalueert de impact van smart connected bikes op de acceptatie, voorkeuren en betalingsbereidheid van gebruikers. Daarnaast wordt de gebruikerservaring met een prototype van een slimme verbonden fiets geëvalueerd door middel van een veldexperiment. Een slimme verbonden fiets is een e-bike met geïntegreerde sensoren en systemen zoals telecommunicatietechnologieën, en is draadloos verbonden met stedelijke infrastructuur om de veiligheid en het comfort van de fietser te verhogen. Dit proefschrift onderzoekt fietstechnologieën die de veiligheid van fietsers beïnvloeden en onderzoekt factoren die van invloed zijn op de gebruikersvoorkeuren voor de acceptatie van slimme fietstechnologieën in verschillende Europese landen. Tevens worden de voorkeuren van gebruikers voor individuele technologieën onderzocht en wordt een schatting gemaakt van de betalingsbereid voor deze technologieën in Europa en Nederland. De waargenomen veiligheidspercepties en veranderingen in rijgedrag van individuen zijn ook gemeten in veldproeven in Nederland met behulp van een specifieke set slimme fietstechnologieën.

In het eerste deel van het proefschrift (Hoofdstuk 2) onderzoeken we slimme fietstechnologieën die de fietsveiligheid verbeteren en aan het fietsframe kunnen worden bevestigd. Daarnaast presenteren we in dit hoofdstuk een topologie voor verschillende niveaus van ‘fietsslimheid’. In de literatuur is een reeks aan slimme fietstechnologieën geïntroduceerd, maar zonder eenduidige terminologie en met verschillende volwassenheidsniveaus (variërend van simulatie-experimenten tot producten die bijna marktklaar zijn). We beginnen met een literatuuronderzoek waarbij we een systematische aanpak volgen om alle mogelijke slimme fietstechnologieën te identificeren. Om een zo volledig mogelijk beeld te krijgen, maken we gebruik van zowel academische databases als grijze literatuur. Meer dan 1000 documenten zijn geïdentificeerd waarvan er na screening 36 overbleven die voldeden aan de vooraf vastgestelde inclusiecriteria. Op basis van deze literatuur zijn er zes niveaus van fietsslimheid gedefinieerd waarbij rekening is gehouden met de bijbehorende technologische volwassenheidsniveaus. ‘Niveau 0’ bevat alle conventionele fietsen of e-bikes zonder enige ondersteuning. ‘Niveau 1’ omvat fietsen met een passieve ondersteuning, zoals meldingen na een ongeval. ‘Niveau 2’ omvat waarschuwingssystemen, zoals botsingsvermijdingssystemen. ‘Niveau 3’ omvat actieve ondersteuning met snelheidsaanpassing van e-bikes en communicatie tussen fiets en infrastructuur. ‘Niveau 4’ bestaat uit fietsen die volledig zijn verbonden met de omgeving, waarbij de fiets kan communiceren met zowel de infrastructuur als met andere fietsen en motorvoertuigen. ‘Niveau 5’, het hoogste niveau, maakt het mogelijk voor overheden of wegautoriteiten om in te grijpen, bijvoorbeeld door de snelheid van de fiets aan te passen op basis van real-time informatie. Niveau 5 is op dit moment theoretisch van aard aangezien dergelijke systemen nog worden onderzocht. De huidige technologie bevindt zich op Niveau 2: obstakels kunnen worden gedetecteerd en fietsers kunnen worden gewaarschuwd om botsingen te voorkomen. State-of-the-art toepassingen om de fietsveiligheid te bevorderen maken gebruik van netwerktechnologie, GPS-sensoren en LiDAR. De beschreven topologie van fietsslimheidsniveaus biedt een gedeelde terminologie voor stakeholders als onderzoekers en fietsfabrikanten, en definieert de brede term ‘slimme’ fietsen. Bovendien werpt deze topologie licht op toekomstige richtingen om slimme fietstechnologieën in te zetten ter verbetering van de veiligheid en het comfort van met name e-bikes.

Hoofdstuk 3 van dit proefschrift bespreekt de gebruikersacceptatie van de ‘slimme e-bike’. De slimme e-bike is gebaseerd op het eerder in Hoofdstuk 2 gedefinieerde fietsslimheidsniveau 3 ‘Actieve ondersteuning’. Dergelijke fietsen bevatten verschillende systemen of functionaliteiten, zoals een waarschuwing of een automatische snelheidsreductie wanneer een fietser een locatie met hoog crashrisico nadert, en bicycle-to-infrastructure (B2I) communicatie. Dit laatste maakt het mogelijk een ‘groene golf’ voor de fiets te realiseren bij verkeersregelinstallaties: de fietser hoeft dan minder vaak te stoppen. Bovendien kan de slimme e-bike niet alleen veilige routes aanbevelen, maar ook de locatie naar de ambulancedienst sturen zodat de fietser na een ongeval sneller hulp kan krijgen. Data is verzameld aan de hand van een online, Europese vragenlijst (verspreid in Oostenrijk, België, Duitsland, Griekenland en Nederland) waarbij respondenten werden gevraagd naar hun mening over twee soorten slimme e-bikes: de slimme pedelec en de slimme speed-pedelec. We maken hier onderscheid tussen respondenten die de voorkeur geven aan een pedelec en degenen die de voorkeur geven aan een speed-pedelec. Het belangrijkste doel van de analyse van deze gegevens is het onderzoek naar factoren die van invloed zijn op de acceptatie van de slimme e-bike. Hiervoor gebruiken we de Unified Theory of Acceptance and Use of Technology 2, en schatten een structureel vergelijkingsmodel. Het oorspronkelijke model is aangepast zodat het beter aansluit bij het doel van dit onderzoek. De factoren ‘waargenomen veiligheid’ en ‘sociale status’ zijn toegevoegd aan het model en de factoren ‘gewoonte’, ‘faciliterende omstandigheden’ en ‘prijs’ zijn uit het model verwijderd aangezien deze factoren het daadwerkelijke gebruik voorspellen, terwijl hier een hypothetisch scenario wordt onderzocht waarin respondenten de slimme e-bike niet daadwerkelijk testen. Daarnaast controleren we het model aan de hand van verschillende sociaaldemografische kenmerken, technologievaardigheid en veiligheidsgerelateerde kenmerken zoals waargenomen veiligheid en beschikbaarheid van fietsinfrastructuur. We maken een multigroepsanalyse (per land) om de verschillen tussen respondenten uit de verschillende landen te bekijken, en onderzoeken de meetinvarantie om de validiteit van de resultaten te toetsen. We testen de meetinvariantie voor de multigroepsanalyses voor de vijf landen en tussen de groepen slimme pedelec en slimme speed-pedelec. Hiermee onderzoeken we of een factor gelijk wordt ervaren voor de verschillende groepen (landen en slimme e-bikes). Onze analyses laten geen verschillen zien tussen de groepen, waardoor we kunnen onderzoeken of er verschillen zijn tussen de groepen door middel van een multigroepsanalyse. We testen zes psychologische factoren en van deze factoren hebben alleen ‘prestatieverwachting’, ‘hedonische motivatie’ en ‘waargenomen veiligheid’ een significante invloed op de intentie om een slimme e-bike te gebruiken. Leeftijd en eerdere betrokkenheid bij fietsongevallen hebben een positieve en significante invloed op deze intentie. De multigroepsanalyses laten zien dat er heterogeniteit is tussen de vijf landen, aangezien verschillende factoren een sleutelrol spelen in verschillende landen. Ten slotte zijn prestatieverwachting en hedonische motivatie de dominante factoren voor zowel de slimme pedelec als de slimme speed-pedelec.

Hoofdstuk 4 gaat in op de voorkeuren van individuen en hun betalingsbereidheid voor specifieke slimme fietstechnologieën. Hoewel alle technologieën die in Hoofdstuk 2 worden onderzocht van invloed zijn op fietsveiligheid, kunnen individuen verschillende voorkeuren hebben voor deze technologieën. Daarom onderzoeken we hoe deze voorkeuren zijn afgeleid en gekoppeld aan sociaaldemografische, geografische en attitudinale variabelen. We analyseren de voorkeuren van individuen met behulp van stated preference-data, verzameld aan de hand van een vragenlijst voorgelegd aan respondenten uit vijf Europese landen. We maken een latenteklassemodel om (1) de voorkeuren van respondenten te onderzoeken, (2) de heterogeniteit in voorkeuren te onderzoeken en (3) de betalingsbereidheid te bepalen. Het model bestaat uit twee afzonderlijke klassen. Klasse 1 - Technologievoorzichtig (52% van de respondenten) omvat respondenten die geen hogere voorkeur hebben voor geavanceerde technologieën en kostenbewust zijn. Klasse 2 - Technologiegeneigd (48% van de respondenten) beschrijft respondenten die een hogere voorkeur hebben voor geavanceerde slimme fietstechnologieën en minder kostenbewust zijn, wat ook hun betalingsbereidheid beïnvloedt. Respondenten in Klasse 2 hebben een hogere betalingsbereidheid voor alle geteste systemen. Opmerkelijk is dat respondenten in Klasse 1 een hogere voorkeur hebben voor de ‘hulp bij slimme routes’ maar een lagere betalingsbereidheid hebben voor dit systeem aangezien ze meer kostenbewust zijn. Wat betreft de waarschijnlijkheid dat respondenten in een van de klassen vallen, zien we dat respondenten uit Griekenland meer kans hebben om in Klasse 2 te vallen (~70%). De waarschijnlijkheid dat respondenten uit de overige vier landen in Klasse 2 vallen is ~44%, wat betekent dat er een grotere kans is dat de zij in Klasse 1 (Technologievoorzichtig) terechtkomen. De analyse laat zien dat over het algemeen diegenen die in gebieden wonen waar fietsinfrastructuur ontbreekt, technologisch onderlegd zijn en een bovengemiddeld maandelijks inkomen hebben een hogere voorkeur hebben voor slimme fietstechnologieën en meer geneigd zijn om geavanceerde fietstechnologieën te gebruiken. De heterogeniteit in de voorkeuren van respondenten voor slimme fietstechnologieën kan gedeeltelijk worden verklaard door sociaaldemografische kenmerken, geografische informatie, veiligheidsgerelateerde vragen en attitudinale vragen.

Hoofdstuk 5 richt zich op de Nederlandse respondenten van de vragenlijst, aangezien Nederland in Europa vooroploopt in het aantal e-bikes, en wereldwijd op de tweede plaats staat, na China. Het is daarom van belang de voorkeuren en de betalingsbereidheid van Nederlandse e-bike-gebruikers voor slimme fietstechnologieën te analyseren. Om de voorkeuren van Nederlandse respondenten te bestuderen ontwerpen we een mixed logit model met random parameters, waarbij rekening wordt gehouden met de stochastische heterogeniteit in de keuzes van respondenten. Daarnaast wordt een model onderzocht waarbij deterministische heterogeniteit wordt aangenomen door specifieke attributieniveaus te koppelen aan sociaaldemografische kenmerken. We zien dat respondenten ouder dan 60 jaar minder geneigd zijn om te kiezen voor ‘hulp bij noodoproep’ of ‘botsingsvermijding achterzijde’, uitgedrukt in het lagere ervaren nut in vergelijking met andere leeftijdsgroepen. Ook zijn respondenten tussen de 25-44 jaar meer geneigd om te kiezen voor het systeem ‘automatische snelheidsbeperking bij risicogebieden’ en zijn mannen minder geneigd om functionaliteit ‘automatische snelheidslimiet’ te selecteren. Tevens bestaat er heterogeniteit in de voorkeuren van respondenten, aangezien alle random parameters significant zijn. We onderzoeken verder de heterogeniteit van respondenten door op basis van de bevindingen de marktsegmentatie te schatten voor verschillende bevolkingsgroepen. De segmentatiebenadering toont aan dat er tussen verschillende bevolkingssegmenten, zoals man versus vrouw, laag versus hoog inkomen, e-bike gebruikers versus niet-gebruikers en hoog- versus laagopgeleide respondenten, grote verschillen bestaan in de betalingsbereidheid voor slimme fietstechnologieën. Kortom, alle geteste slimme fietstechnologieën worden positief beoordeeld, behalve de kosten, wat betekent dat de respondenten kostenbewust zijn. De ‘slimme routes’-functionaliteit is het belangrijkste attribuut, gevolgd door de functionaliteiten ‘automatische snelheidslimiet’, ‘botsingsvermijding achterzijde’ en ‘dode hoek’.

Ten slotte onderzoeken we in Hoofdstuk 6 de ervaren veiligheid, vertrouwensperceptie en veranderingen in rijgedrag van individuen door GPS- en enquêtegegevens te verzamelen gedurende een veldexperiment waarbij een prototype van een contextbewuste veiligheidswaarschuwing wordt getest. Op basis van politiedata (BRON) over Nederlandse fietsongevallen ontwikkelen we een veiligheidsmodel door met behulp van kernel density estimation locaties in Enschede met een hoog aantal fietsongevallen te kiezen. Vervolgens ontwerpen en ontwikkelen we een veiligheidswaarschuwingssysteem dat de informatie van het veiligheidsmodel als input gebruikt om fietsers te waarschuwen wanneer ze een locatie met een hoog risico op ongevallen naderen. Het veiligheidswaarschuwingssysteem kan fietsers waarschuwen door middel van audiosignalen of tactiele communicatie, waarbij ook aanvullende visuele informatie wordt gegeven. Elke deelnemer werd gevraagd een vooraf vastgestelde route drie keer te fietsen. De eerste rit werd gebruikt als nulmeting en de andere twee ritten vonden plaats met visuele waarschuwingen in combinatie met audiosignalen of tactiele waarschuwingen. Na elke rit vulden de deelnemers een vragenlijst in waarbij ze hun ervaringen met het contextbewuste waarschuwingssysteem beschreven. Bovendien werden tijdens elke rit GPS-gegevens verzameld om trajecten en snelheden te bepalen. De analyse is gebaseerd op enquête- en GPS-gegevens, verzameld voor, tijdens en na de drie ritten. De resultaten geven aan dat het contextbewuste veiligheidsondersteuningssysteem de ervaren veiligheid van de deelnemers verbetert, hoewel het algehele vertrouwen in het systeem laag blijft. Daarnaast blijkt dat deelnemers hun snelheid verlaagden na een waarschuwing bij het naderen van een locatie met een hoog risico, wat betekent dat het systeem effect had op de veiligheid van de deelnemers. Na een waarschuwing vertraagden mannelijke deelnemers hun snelheid meer dan vrouwen. Echter, vrouwen reden over het algemeen met lagere snelheid. Deelnemers die gebruik maakten van e-bikes of conventionele fietsen bleken ook meer geneigd te zijn hun snelheid te verlagen na een waarschuwing. We vonden geen significant verschil in snelheidsveranderingen van deelnemers tussen de verschillende waarschuwingsmodi (audio versus tactiel).

Samenvattend biedt dit proefschrift nieuwe inzichten in slimme fietstechnologieën en gebruikersacceptatie door gebruik te maken van verschillende gedrags- en discrete-keuzemodellen. De data verzameld tijdens een veldexperiment en aan de hand van een (Europese) vragenlijst is gebruikt om de invloed van verwachte en ervaren aspecten van slimme fietstechnologieën op de perceptie en het fietsgedrag van gebruikers te onderzoeken. Dit proefschrift onderzoekt hoe individuen uit verschillende landen met verschillende fietsculturen slimme fietstechnologieën ervaren en hoe deze factoren gebruikersvoorkeuren beïnvloeden. We onderscheiden individuen op basis van hun voorkeuren voor slimme fietstechnologieën en houden rekening met hun heterogeniteit op kleine en grote geografische schaal. Dit onderzoek biedt verschillende nieuwe inzichten alsmede een aantal praktische (voor beleidsmakers, overheden, fietsfabrikanten) en theoretische aanbevelingen.

# About the author

Georgios Kapousizis was born in Giannitsa, Greece, on December 21, 1987. He received his BSc degree in 2013 in Surveying Engineering and Geoinformatics from the Technological Educational Institute in Serres, Greece. Since 2012, Georgios worked as a Surveyor Engineer and Urban Planner at Geochoros S.A., for five years in Thessaloniki, Greece. In 2018, in parallel to his work, he received his MSc degree in Techniques and Methods for Spatial Analysis, Planning and Management from the Faculty of Engineering of the Aristotle University of Thessaloniki.

In October 2017, Georgios joined the Department of Infrastructure, Unit of Intelligent Transport Systems and Planning, of the University of Innsbruck, Austria, as a Researcher. Between January 2019 and July 2020, Georgios worked as a Research Associate at the School of Architecture and Cities in the Active Travel Academy group at the University of Westminster in London on the research project “Reducing Cycling Injuries While Cycling Grows”.

In September 2020, Georgios moved from London to Enschede, the Netherlands, to pursue his PhD at the Department of Transport Planning, University of Twente, in the innovative project “Smart Connected Bikes”, supported by Accell Group. His research focused on modelling and assessing user acceptance, preferences, and willingness to pay for smart bicycle technologies to enhance cyclists' safety, especially for e-bikes. He assisted in teaching activities of the Master courses “Traffic Safety” and “Smart Mobility” at the Department of Civil Engineering. Between April and May 2024, Georgios was a visiting researcher at the Institute for Transport Planning and Systems, ETH Zürich, Switzerland. During his PhD, Georgios published his research in high-quality academic journals and presented at various international conferences. Georgios received the TRAIL diploma and served as a reviewer in various scientific journals.

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1. **Kapousizis, G.,** Jutte, A., Ulak, M. B., Geurs, K. "How do cyclists evaluate a context-aware prototype warning system? A safety assessment through a field experiment study." (under review).

2. **Kapousizis, G.,** Ulak, M. B., Geurs K., Havinga, P.J.M, "Assessing Potential Uptake and Willingness to Pay for Smart Bicycle Technologies Affecting Cycling Safety. A Stated Preference Survey Among e-bike Users in The Netherlands". (under review).

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1. **Kapousizis, G.,** (2024). "Smart Connected Bicycles". Integration of non-motorized traffic into the digitalized transport system, EBP, www.ebp.ch [Interview]

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# Smart Connected Bicycles

## User Acceptance and Experience, Willingness to Pay and Road Safety Implications

**Georgios Kapousizis**