Technische Universität München
Fakultät für Elektrotechnik und Informationstechnik
Lehrstuhl für Medientechnik

Mobile Device-Complemented Advanced Mobility Assistance Systems

Dipl.-Ing. (Univ.) Stefan Diewald

Vollständiger Abdruck der von der Fakultät für Elektrotechnik und Informationstechnik der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktors der Ingenieurwissenschaften (Dr.-Ing.)

genehmigten Dissertation.

Vorsitzender:	Prof. Dr.-Ing. Norbert Hanik
Prüfer der Disseration:	1. Prof. Dr. rer. nat. Matthias Kranz (Universität Passau) 2. Prof. Dr.-Ing. habil. Gerhard Rigoll

Die Disseration wurde am 29.09.2020 bei der Technischen Universität München eingereicht und durch die Fakultät für Elektrotechnik und Informationstechnik am 24.08.2021 angenommen.

Abstract

Mobility is not only a technological challenge but also a key factor for a self-determined life and social inclusion. Major trends in mobility, such as sharing, e-mobility, and digitization of mobility services, enable a wide variety of new mobility options with enhanced accessibility and improved sustainability. However, these new technological options also increase the complexity of the planning (e.g., finding the most suitable route option depending on the user's abilities and needs) and the execution of trips (e.g., usage of sharing vehicles). Appropriate digital assistance can help people cope with these challenges.

This work explores the potentials of digital mobility assistance on users' personal mobile devices (PMDs). The PMD has been chosen because it is a ubiquitous companion with which users are acquainted, and that has access to information on its users' context. The dissertation covers the three strongly interconnected research areas of mobility assistance: *journey planning*, *support during the journey*, and *assistance for helping people keep their mobility*. In a user-centered system engineering process, these areas have been investigated to identify crucial factors for digital mobility support. The goals of the research presented in this thesis are to reduce barriers, improve mobility, and increase social participation by leveraging the potential of current and future mobility systems.

The dissertation provides novel findings on factors influencing the system development and design of Human–computer interaction (HCI) for digital mobility assistance. The research is based on studies and benchmarks with digital assistance prototypes developed in the scope of this work. It is shown, for example, how user-centered design needs to be adapted when working with digitally inexperienced users (in this case, seniors) or how the context *route* can be used to reduce the mental load for users of an incident warning assistant. Furthermore, the work provides profound insights into approaches for triggering positive mobility behavior and motivating the usage of assistance systems. It is demonstrated how nudging can be used to influence the trust of the presented route information and what odds and risks exist when trying to increase users' motivation by gamification. On the topic of system design, architectural alternatives for integrating mobile devices with their short life cycles in automotive in-vehicle systems, which may have remained unchanged for half a decade, are evaluated.

The central research question of this thesis is how digital mobility assistance can help reduce the overall effort for typical mobility scenarios and maintain self-determined mobility. User studies and an expert evaluation certify the effectiveness and appropriateness of our developed approaches and concepts. User studies with students and seniors allow the discussion of factors critical for the individual groups and the universality of digital assistance systems. The expert evaluation gives insights into aspects that are important for the establishment and acceptance of mobility support. The gathered findings and derived recommendations shall support the future development of advanced digital mobility assistance systems.

Kurzfassung

Mobilität ist die Grundlage für ein selbstbestimmtes Leben und sozialer Inklusion. Aktuelle Mobilitätstrends, wie Sharing (z. B. Car Sharing), E-Mobilität und die Digitalisierung von Mobilitätsdienstleistungen eröffnen neue Teilhabemöglichkeiten und verbessern die Nachhaltigkeit von Mobilität. Jedoch ist damit eine enorme Komplexitätssteigerung bei der Reiseplanung (z. B. Auswahl der passenden Reisemöglichkeit unter Berücksichtigung der Einschränkungen und Anforderungen der Nutzer) und der Reise an sich (z. B. die Nutzung von Sharing-Fahrzeugen) verbunden. Geeignete digitale Assistenzsystemen können bei der Bewältigung dieser Herausforderungen helfen.

In dieser Arbeit werden die Potenziale von digitalen Mobilitätsassistenzsystemen auf persönlichen tragbaren Endgeräten von Nutzern untersucht. Die persönlichen Endgeräte wurden ausgewählt, da sie allgegenwärtige Begleiter sind, die auf viele Kontextinformationen ihres Benutzers zugreifen können, und da die Benutzer im Umgang mit ihnen geübt sind. Es werden dabei drei stark miteinander verbundenen Mobilitätsassistenzbereiche behandelt, die wir im Rahmen einer Prozessanalyse mit Fokus auf Informationsbedarf und Mobilitätsbarrieren identifiziert haben: *Reiseplanung*, *Unterstützung während der Reise* und *Assistenz bei der Erhaltung der individuellen Mobilität*.

Diese Dissertation legt neue Erkenntnisse zu Faktoren dar, die die Systemgestaltung und das Design der Mensch-Maschine-Interaktion von Mobilitätsassistenzsystemen beeinflussen. Anhand der Ergebnisse von Nutzerstudien mit im Rahmen der Arbeit umgesetzten Assistenzsystemprototypen, wird, zum Beispiel, gezeigt, was beim benutzerzentrierten Design mit Nutzern ohne technische Erfahrung zu beachten ist (in diesem Fall mit Seniorinnen und Senioren), oder wie durch die Nutzung des Routenkontexts in Fahrerwarnsystemen die mentale Last der Nutzer reduziert werden kann. Außerdem werden Chancen und Risiken bei der Anwendung von Maßnahmen zur bewussten Beeinflussung (*Nudging*) der Glaubwürdigkeit von Mobilitätsdaten, und beim Einsatz von Spielelementen (*Gamification*) zur Steigerung der Nutzermotivation aufgezeigt. Zum Thema Systemgestaltung werden Architekturansätze für die Integration mobiler Endgeräte mit kurzen Produktzyklen in Fahrzeugsysteme, die bis zu einem Jahrzehnt unverändert bleiben, vorgestellt.

Die zentrale Forschungsfrage dieser Dissertation ist, wie mithilfe digitaler Assistenzsysteme der Gesamtaufwand für Mobilität verringert werden kann und die eigenständige Mobilität erhalten werden kann. Die Eignung und die Effektivität der entwickelten Lösungen werden mittels Nutzerstudien und einer expertenbasierten Evaluation bewertet. Die Nutzerstudien, an denen hauptsächlich die Gruppe der Studierenden sowie Seniorinnen und Senioren teilgenommen haben, erlauben eine Identifikation der zentralen Faktoren für diese Gruppen und die Bewertung der universellen Zugänglichkeit der Assistenzsysteme. Die expertenbasierte Evaluation zeigt die zentralen Aspekte für den Einsatz von digitalen Assistenzsystemen in verschiedenen Mobilitätssituationen auf. Die Erkenntnisse und die daraus abgeleiteten Empfehlungen bilden eine Grundlage für die zukünftige Entwicklung von digitalen Mobilitätsassistenzsystemen.

Preface

The research described in this dissertation was mainly conducted between June 2011 and September 2015 when I was a research assistant at the Chair of Media Technology at Technische Universität München (TUM). During that time, I was part of the Distributed Multimodal Information Processing Group (Forschungsgruppe Verteilte Multimodale Informationsverarbeitung (VMI)) and, since March 2013, also a member of the Embedded Interactive Systems Laboratory (EISLab) at the University of Passau.

The research presented in this thesis was supported by third-party funding. Parts of the research detailed in Chapter 4 and Chapter 5 were carried out within the scope of the project PASSAge (Personalisierte Mobilität, Assistenz und Service Systeme in einer alternden Gesellschaft) , which was funded by the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung (BMBF), funding reference 16SV5748). DENSO Automotive Deutschland GmbH largely funded the research on mobility assistance in the automotive domain (Chapter 6).

Parts of this research have been published previously. These publications are referenced at the beginning of the respective chapters that tie into previously published content. Excerpts of this work may also be found in student theses I supervised. Non-scientific sources, such as web pages, are referenced in footnotes.

As the research for this dissertation was supported by many project partners, co-workers, and supervised students, the 'authorial we' is employed to appreciate these contributions. Despite the use of the 'authorial we', the research presented in this thesis is either the sole work of its author or was conducted with the author being the lead researcher.

All our research is independent of the user's gender. For that reason, we decided to use the singular 'they' when referring to 'any user'[1].

For private and professional reasons, the writing process spanned over several years. However, by a steady state of the art tracking, it is ensured that the research still presents new research results. State of the art in this dissertation reflects the status of November 2019.

---

[1] https://blog.apastyle.org/apastyle/2015/11/the-use-of-singular-they-in-apa-style.html, accessed October 5, 2018.

Acknowledgments

First and foremost, I would like to express my sincerest gratitude to Prof. Dr. rer. nat. Matthias Kranz for having given me the opportunity to conduct my research under his supervision, and for his steady support over the whole time. Even during the busy times when building up his new chair at *Universität Passau*, he always took time to give feedback, answer questions, or provide new impulses when I was stuck at a topic. I also thank Prof. Dr.-Ing. habil. Gerhard Rigoll for co-advising my thesis, and Prof. Dr.-Ing. Norbert Hanik for being the head of the examination committee.

I also thank my former colleagues at Technische Universität München (TUM). A special 'thanks' goes out to my former office and VMI group mates *Andreas Möller* and *Luis Roalter* for all the very productive joint work, their valuable feedback, and the fun we had in the three years. I also want to mention all my colleagues at the Chair of Media Technology (LMT) and the Chair of Communication Networks (LKN) I could exchange my ideas and concerns when I was the last VMI group member. I owe big thanks to Dr.-Ing. *(Doc)* Martin Maier for his administrative support and for always listening to my problems.

The thesis has also been influenced and supported by the excellent work of my students. I want to thank each of them who contributed to this dissertation with their diploma, bachelor's, and master's thesis. I also owe a debt of gratitude to the colleagues of the Institute for Human-Machine Communication (MMK) who let me use their real vehicle-based driving simulator for several user studies.

My time at TUM would not have been possible without third-party funding. I want to thank Tim Leinmüller and Boris Atanassow from Denso Automotive Deutschland GmbH for the joint project on vehicle-to-X (V2X) data visualization. For the BMBF-funded project PASSAge, I appreciate all partners that contributed to the joint research. Special thanks go out to Dr. phil. Monika Siegrist from the center for preventive and sports medicine, who helped to finish the overall project on time, although there were a few setbacks in this way. I further thank her colleague Barbara Geilhof for the joint work on the Rollator Training application.

Finally, I sincerely thank my wife Andrea and my sons Sebastian and Fabian and my daughter Laura for giving me the time to finish the dissertation, although the time together was already scarce due to my job and the work on our house. I know you had to make a lot of compromises during my writing times.

Contents

Notation

Abbreviations, Acronyms and Terms

4G	4th Generation Mobile Telecommunications 66
5G	5th Generation Mobile Telecommunications 139
ACC	Adaptive cruise control 116, 118
ADAS	Advanced driver assistance systems 3, 25, 26, 153, 160
AMAS	Advanced mobility assistance system 4–6, 8, 31, 35, 63, 71, 73, 119, 129, 162, 175, 194, 196, 201
AmI	Ambient intelligence 18
AP	Access point 138, 139
API	Application programming interface 5, 17, 80, 85, 195, 196
APTA	American Public Transportation Association 38
AR	Augmented reality 16, 20–23, 25, 180, 196
ARM	Advanced RISC Machine 139
ASN.1	Abstract Syntax Notation One 140–143
BMBF	Bundesministerium für Bildung und Forschung iv
BTP	Basic transport protocol 139, 140, 143, 144
c2xMessageTester	The c2xMessageTester is a Java application that supports the simulation of vehicle-to-X (V2X) scenarios. The simulation environment uses the protocol buffers (ProtoBuf) format and is compatible with the applications DriveAssist, DriveAssist 2.0, and GLOSA 148, 171–173, 177, 185
CAM	Cooperative awareness message 137, 139–143, 147, 153, 172, 173
CAN	Controller area network 110, 112, 134
CE	Consumer electronics 129
CID	Central information display 110, 111

CPU	Central processing unit 139, 141–143
CTS	A central traffic service (CTS) is an Internet-based service that provides traffic information, e.g., traffic jams 148
DENM	Decentralized environmental notification message 137, 139, 142, 147, 172
DLNA	Digital Living Network Alliance 133
DriveAssist	DriveAssist is an advanced driver assistance systems (ADAS) for the Android platform developed for the research presented in this thesis xiii, 145–152, 155–162, 165, 172, 185
DriveAssist 2.0	DriveAssist 2.0 is a variation of DriveAssist. It was combined with the Android navigation application OsmAnd to provide additional navigation functionality. The application for the Android platform was developed in the scope of this thesis to evaluate route context in a vehicle-to-X (V2X) application xiii, 155–161, 175, 183, 185, 194, 196, 199
EISLab	Embedded Interactive Systems Laboratory iv
ETSI	European Telecommunications Standards Institute 140
EV	Electric vehicle 39–41, 72
FCD	Floating car data 68
GLOSA	Green light optimized speed advisory 41, 129, 162–168, 170–172, 177, 183, 185, 186, 199
GN	GeoNetworking 139, 140
GNSS	Global navigation satellite system 56
GPS	Global Positioning System xiii
GSR	Galvanic skin response 56
GTFS	General transit feed specification 81
GUI	Graphical user interface 16, 19, 172
HCI	Human–computer interaction ii, 4, 6, 8, 16, 18, 30, 32, 129, 130, 165, 174
HD	High-definition 132
HDMI	High-definition multimedia interface 132, 133
HID	Human interface device 134
HMI	Human–machine interface 3–5, 8, 12, 29, 53, 54, 66, 71, 73, 74, 93, 96, 97, 109, 127, 128, 134, 136, 139, 142, 162, 165, 173, 174, 178, 194, 195
HRQ	High-level research question 5, 6, 8, 82, 97, 129, 192

IA	Intelligent agent 17
ICT	Information and communication technology 8, 42, 43, 63, 177, 180, 188
IEEE	Institute of Electrical and Electronics Engineers 132, 133, 139
IoM	Internet of mobility 63
IoT	Internet of things 41, 63
IP	Internet protocol 66, 132, 135
IPA	Intelligent personal agent 17–19
ITS	Intelligent transportation system 141
IVI	In-vehicle infotainment 26, 66, 110, 111, 119, 130, 132, 135, 136
IVIS	In-vehicle information system 3, 12, 53, 66, 130, 131, 172, 173
IVR	Interactive voice response 131
JSON	JavaScript object notation 143
LBS	Location-based service 3, 56
LCT	Lane change task 101, 102, 107, 108, 115, 118
LED	Light-emitting diode 19
MaaS	Mobility-as-a-service 63
MHL	Mobile high-definition link 132, 133
MOST	Media oriented systems transport 134
NASA-TLX	NASA task load index 103, 115
NFC	Near field communication 67, 69, 133
NIST	National Institute of Standards and Technology 9
NUI	Natural user interface 130, 131
OBU	On-board unit 137–144, 182, 184
OS	Operating system 9
OSM	OpenStreetMap 68, 70, 81, 157
OsmAnd	OsmAnd is an open source mobile Global Positioning System (GPS) navigation and map application that runs on many Android-based devices and features optional offline maps and turn-by-turn directions. It was used as basis for DriveAssist 2.0 for adding route context to DriveAssist xii, 155–157

PASSAge	Personalisierte Mobilität, Assistenz und Service Systeme in einer alternden Gesellschaft iv, 45, 48, 75, 84, 177, 180
PC	Personal computer 3, 9, 12, 15, 22, 75, 86, 87, 91, 102, 110, 121, 122, 125, 126, 130, 137, 165, 171, 177, 182, 183, 187, 188
PDA	Personal digital assistant 21
PHEV	Plug-in hybrid electric vehicle 39
PIM	Personal information management 21, 22
PMD	Personal mobile device ii, 3–5, 8, 12, 18, 19, 22, 23, 35, 54, 63, 66–69, 71, 73, 74, 97, 119, 121, 128–131, 135–144, 148, 162, 163, 172, 173, 184, 193–195
PNA	Personal navigation assistant 161, 170
PND	Personal navigation device 134, 185
ProtoBuf	Protocol buffers 143

RAM	Random access memory 139
RF	Radio frequency 22, 56
RPC	Remote procedure call 143
RQ	Research question 5, 82, 100, 159
RS	Recommender system 15, 16, 22, 23
RTP	Real-time protocol 136
RTSP	Real time streaming protocol 135

SAE	Society of Automotive Engineers 40
Seamless Mobile	Seamless Mobile is the context-sensitive intermodal trip planning application developed for the research presented in this thesis. Novel features are its fitness-based routing, and the nudging approach to increase the credibility of the presented trips 74, 79, 83, 179, 180, 194
SEQ	Semiotic efficiency quotient 20
SLAM	Simultaneous localization and mapping 56
SPaT	Signal phase and timing 139

TOPO	Topology 139
TTS	Text-to-speech 19, 112, 145, 147, 151, 153, 154, 174
TUM	Technische Universität München iv, v

U.S.	United States (US) is a short form of United States of America (USA) 9

UI	User interface 19, 22, 28, 42, 78, 130, 135, 153, 159, 188, 189, 195
UN	United Nations 42
USA	United States of America xiv
USB	Universal serial bus 132–136, 138, 188
UX	User experience 6, 31
V2X	Vehicle-to-X v, 8, 25, 41, 56, 66, 129, 134, 136–143, 145, 147, 148, 152, 155, 156, 161, 162, 171, 173–175, 177, 183–185, 194–196
VAPA	Voice-activated personal assistant 17, 22
VMI	Forschungsgruppe Verteilte Multimodale Informationsverarbeitung iv
VNC	Virtual network computing 136
VR	Virtual reality 20, 25
WLAN	Wireless local area network 22, 69, 132–134, 136, 138, 139
WSU	Wireless Safety Unit 138, 139
XML	Extensible markup language 143

Symbols

α	Significance level
χ^2	Chi-squared value
M	Mean
Mdn	Median
σ	Standard deviation
N	Total sample size
n	Sub-sample size
p	Probability
r	Pearson product-moment correlation coefficient
t	Student’s t-test statistic
W	Wilcoxon and Mann-Whitney U test statistic
Z	Standard score

SI base units are used in this thesis. For ages, the mean, median, and standard deviation are given as whole numbers, since the data was only collected as whole rounded down numbers.

All statistical analyses have been performed with R[2]. It was also used to create the boxplots and some diagrams in this thesis. In order to check the statistical significance, the Student’s t-test [338], the Mann-Whitney U test [250], the Wilcoxon signed-rank test [414], and the Friedman test [129]

---

[2] https://www.r-project.org/, accessed February 27, 2019

have been used. For evaluating the difference of two unpaired samples, the unpaired Student's t-test has been used. As a precondition for the t-test, the normality was checked with the Shapiro–Wilk test [334]. In case the samples were not normally distributed, or their variances were heterogeneous, the Mann-Whitney U test has been performed. For paired samples, the Wilcoxon signed-rank test [414] has been used as an alternative to the paired t-test. For comparing multiple paired samples, the Friedman test was employed.

For several visualizations, the JavaScript library *D3.js*[3] has been used.

Icons used in this thesis are from *Noun Project*[4]. The author has a *NounPro* account to use the icons royalty-free.

---

[3] https://d3js.org/, accessed February 28, 2019.

[4] https://thenounproject.com/, accessed March 9, 2019.

Part I

Introduction and Background

Chapter 1

Introduction

> “In contrast to the past, where the customer paid for traditional vehicle ownership even if the car was unused much of the time, future consumers will tend to pay for using mobility on demand, depending on the individual real-time situation and application.”
>
> *KPMG’s Global Automotive Executive Survey 2016 [202]*

1.1 Motivation

Mobility is a crucial aspect of independent and self-determined living. Because mobility affects all areas of life, it is subject to constant changes caused by technological trends and social transformation. Today’s society is increasingly shaped by globalization and digitalization[1], as is mobility [395]. Besides these central factors, current and future mobility concepts are influenced by, for example, ecological and environmental factors, such as by the demand for increasing sustainability [314], and by societal factors, such as demographic change [74, 333].

In developed countries, a paradigm shift in transport is occurring from owning the means of mobility toward having access to the means of mobility and mobility services [235, 270]. Especially in big cities, novel mobility services, such as car-sharing or ride-sharing, have an increasing presence and are finding a ready market. Surveys show that informed users are “continuously striving for . . . optimization of . . . cost, time and quality of life in real-time” [202, p. 24], which corresponds to the market orientation of these services.

An essential factor for realizing these sharing-economy concepts [24] is the ubiquitous availability of access to digital services on the one hand and the digitization of each aspect of mobility on the other side. By using portable devices with mobile communication capabilities, the digital platforms that coordinate shared products and services can be accessed anywhere and anytime.

---

[1] In this thesis, we use the term *digitalization* to describe the effects of *digitization* on social and business life. See https://www.forbes.com/sites/jasonbloomberg/2018/04/29/digitization-digitalization-and-digital-transformation-confuse-them-at-your-peril/ (accessed October 29, 2019) for more details.

Thanks to the built-in localization technology [205] of portable devices, location-based services (LBSs) [416] can further simplify mobility.

In the automotive domain, development is currently driven by the demand for more sustainability, safety, and comfort [202]. This has led to electric and hybrid-electric mobility concepts and connected advanced driver assistance systems (ADAS) that help improve safety and comfort. The digitalization has also found its way into automobiles. In-vehicle information systems (IVISs) provide applications for various tasks that are not necessarily mobility-related. Via modern human–machine interfaces (HMIs), such as touch screens or interactive voice interfaces, the driver can steer the vehicle and use the digital systems simultaneously.

Although mobility trends create additional mobility possibilities and match people's demand for ubiquitous travel without the need to possess expensive, environment-unfriendly vehicles, new challenges arise at the same time. For example, the multitude of available transportation possibilities makes trip planning increasingly complex. There are not just different modes of transportation (multimodality) but also various possible combinations of them (intermodality). In particular, the planning of efficient intermodal trips requires digital assistance when the selected legs and the means of transportation during the trip shall account for personal restrictions (e.g., length or steadiness of a walking segment) or preferences (e.g., eco-friendly means of transport).

A central social challenge is to ensure the inclusion of the total population. This especially concerns the aging population [8, 11, 405] and travelers that need (temporarily) barrier-free access (e.g., when something needs to be transported) [31]. Digital services are gradually replacing traditional transportation services that have been provided by people (e.g., ticket sales) or offered on paper (e.g., timetable and maps). Thus, universal access in terms of "increas[ing] the possibility for everybody to access, interact with, and complete his or her goals" [301, p. 524] with these mobility services is essential.

The motivation of this work is to invent, research, complement, extend, and unify mobility-related digital services and interfaces that consider people's context, personal abilities, and preferences. We argue that digital assistance can not only create new mobility services but also contribute to solving current challenges in mobility.

In this work, we shape the term "advanced mobility assistance system" (AMAS) by going beyond the traditional digital mobility services (e.g., by integrating the fitness level and health state into route planning, as we will show in Chapter 5) and providing support for the entire mobility process (e.g., from planning to wrap-up, as we will show in Chapter 3). As key devices for accessing digital assistance and services from, PMDs, such as smartphones, tablet personal computers (PCs), or wearable computers, have been chosen because they are ubiquitous companions in daily life for many people (the detailed motivation is presented in Section 2.1).

1.2 Research Questions and Contributions

1.2.1 High-Level Research Questions

We developed the following high-level research questions (HRQs) as guidance for our research on advanced mobility assistance system (AMAS):

> **HRQ1**: What are the typical steps of intermodal mobility scenarios?

A process analysis of exemplary intermodal mobility scenarios shall provide the main steps users may face when planning or undertaking a trip.

> **HRQ2**: What are the main requirements for information and digital services of mobility users?

This research question concerns the required information and (digital) services needed by users to plan and complete trips.

> **HRQ3**: What steps in intermodal mobility scenarios can benefit from digital assistance through users' PMDs?

Identified gaps are investigated for potential improvements that can be provided through digital assistance systems.

> **HRQ4**: How can the complexity of operating mobility services and assistance systems be reduced for users?

It is explored how the complexity of mobility assistance systems on PMDs can be reduced by measures related to HCI, context usage, and range of functions.

> **HRQ5**: How can users be supported in accessing and using mobility services and means of mobility?

While **HRQ4** is aimed at the operation of digital mobility assistance systems in general, this research question targets the support for accessing and operating already existing mobility services and systems. It investigates approaches to providing context-aware instructions or creating integrated services to reduce the effort of operating different HMIs.

> **HRQ6**: How can users be motivated to actively deal with their mobility and assistance systems that can improve their mobility situation?

Offering a digital assistance system does not automatically lead to improvement; the potential users need to be motivated to use the assistance system. This research question aims at motivating the user and keeping the motivation.

The high-level research questions (HRQs) are broken down into several further research questions (RQs) in the respective research chapters. In the conclusion (Chapter 8), a summary of the central results for every HRQ is given. By providing answers to the research questions, we describe *where* and *how* digital systems can assist with everyday mobility — from planning and conducting the journey to maintaining the abilities necessary for self-determined mobility.

1.2.2 Target Groups and Application Areas

Potential users are people of legal age (in our context, older than 18 years), including older people with limited technical experience and people with special mobility needs as a result of physical impairments. We do not explicitly consider people with mental impairments or blind and deaf users. This would have been beyond the limitations of a thesis.

The work covers the typical phases of mobility processes — from planning the actual trip to wrap-up. Moreover, we present selected research results on maintaining self-determined mobility by fostering physical exercising and training of mobility-related HMIs.

1.2.3 Overview of Contributions

The main research contributions of the dissertation in the field of digital AMASs are:

- We present a breakdown of an intermodal mobility process with a detailed analysis of information and requirements for the different mobility-related tasks (description of the design space). (Chapter 3)
- For selected representative process steps, we highlight the benefits of using a user's PMD for interacting with mobility services. (Sections 4.4, 5.2, 5.4, and 6.4)
- We conceive and evaluate new approaches for training the operation of existing HMIs in mobility. (Sections 4.3 and 5.3)
- We propose and evaluated assistance functions that can enhance individual mobility by physical exercise. (Sections 4.3 and 5.4)
- We provide recommendations for motivating users to use the digital assistance functions in different mobility-related situations. (Sections 5.2, 5.3, and 5.4)
- We propose and implement a concept for creating future-proof physical interfaces and application programming interfaces (APIs) between products with short life cycles (e.g., PMDs) and long life cycles (e.g., means of mobility, buildings). (Section 6.2)
- We present novel insights into data visualization and interaction with PMDs in mobility scenarios. (Sections 6.2, 6.4, and 6.5)

Following the HRQs, the contributions address the overall mobility process. An essential factor of mobility investigated in this thesis is the support for preserving the necessary physical and mental abilities.

For the selected mobility process steps, we created digital assistance prototypes that have been evaluated. The evaluation was done by performing user studies where we have created prototypes for end users or by measuring technical system characteristics when such a system had been designed. The contributions in this thesis are based on obtained insights during the conception and implementation of prototypes and the results of the evaluations.

We share our insights on the following aspects:

Engineering The engineering aspect targets the challenges of the technical concepts and the implementation of a digital mobility assistance system. We focus on the topics of data acquisition and data processing for creating seamlessly connected AMASs.

Human–Computer Interaction For HCI, we focus on optimizing the usability and overall user experience (UX) of mobility assistance systems. We present the results of conducted user studies and discuss how shortcomings in the design process and of the actual prototypes could be eliminated.

Motivational Aspects The motivational aspects summarize our efforts and findings on the topics of maximizing the engagement with our created AMASs and influencing the mobility behavior of our subjects.

1.3 Thesis Outline

Figure 1.1 depicts the outline of the thesis. It shows how the different chapters are related to each other and which exemplary use cases have been chosen to fill the identified research gaps on AMASs. The thesis is structured as follows.

In Chapter 1 (this chapter), we justify our research on AMASs. We further present our high-level research question that are answered in this thesis and the main contributions of this work.

In Chapter 2, we define the key terms of the thesis and provide the necessary background for the covered topics. We elaborate on the current state of the art as well as related work to align available research with our work. We justify the choice of personal mobile devices (PMDs) as the main interaction device for our digital AMASs. The chapter covers types, characteristics, and modalities of available digital assistance systems in general and digital mobility assistance systems in particular. We further present a summary of theories on creating incentives to motivate the usage of digital systems and methods to influence the behavior of their users. The chapter concludes with an overview of evaluation methods for digital systems concerning usability and technical system characteristics.

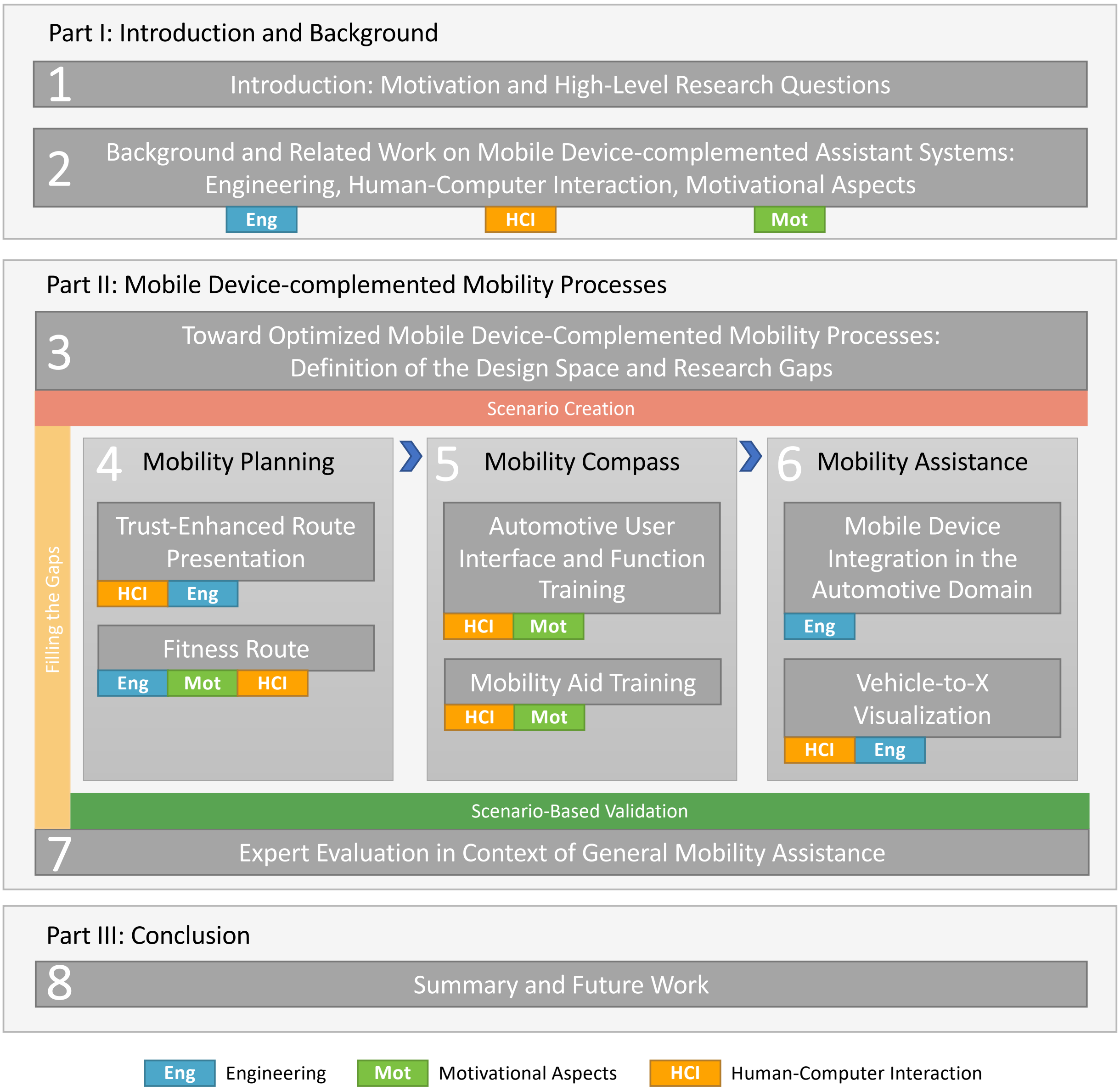


Figure 1.1: The outline of the dissertation. The diagram visualizes the contents of the individual parts and indicates which aspects are covered in the use cases presented in the chapters. The main aspects are engineering (Eng, colored in blue), human–computer interaction (HCI, colored in orange), and motivational aspects (Mot, colored in green). In Part II, we first create scenarios based on personas to identify research gaps in realistic mobility scenarios. These gaps are afterwards filled by exemplary research covering the whole mobility process from planning to assistance during the journey as well as support for maintaining self-determined mobility. The scenarios are also used as the basis for an expert evaluation to show how the presented research meshes.

Chapter 3 describes our process of identifying the research gaps that are covered in chapters 4–6. We start with a high-level analysis of intermodal processes, current mobility usage patterns, and trends in order to delimit the design space. For the identification of shortcomings, we present a list of possible mobility barriers and hurdles, depending on the individual needs and abilities of users. By combining the identified usage patterns, trends, and mobility barriers, we create three personas with corresponding scenarios to make the research gaps tangible. From these scenarios, we derive user requirements for digital mobility assistance and finally present a vision of a connected mobility solution. Finally, we present the identified research gaps in the fields of *trip planning*, *exercising for maintaining self-determined mobility*, and *assistance during journeys*.

In the following three chapters, we describe selected results from our experiments in the identified fields (*trip planning* 4, *exercising for maintaining self-determined mobility* 5, and *assistance during journeys* 6). The chosen prototypes are representative examples that show central engineering principles, HCI approaches, and motivational aspects for creating user-centered mobile device-complemented AMASs.

For mobility planning (Chapter 4), we interlink trip planning with fitness aspects and share our insights into using behavioral intervention techniques to influence the trust in presented route information. The examples in our *mobility compass* (Chapter 5) demonstrate means of providing orientation when users need to handle different automotive HMIs and how the physical abilities for self-determined mobility can be fostered. We apply gamification mechanisms as motivational aspects and show central findings for the creation of mobility-related exercising and training applications on PMDs. The mobility assistance in Chapter 6 focuses on the automotive domain and V2X in particular. We present a concept for a future-proof interface between automotive products with long product life cycles and non-durable consumer electronics in the form of PMDs. On that basis, we demonstrate how such a combination can be used for rapid prototyping of intuitive visualization on known HMIs with internalized user interaction mechanisms.

The expert evaluation in Chapter 7 takes up the exemplary mobility scenarios carved out in Chapter 3 with a focus on elderly users. The scenarios were the basis of the structured evaluation performed by 11 experts from different mobility- and information and communication technology (ICT)-related fields. Their feedback covers the meaningfulness and suitability of our designed functionalities and contains general remarks on creating mobility-related digital assistance systems.

Chapter 8 concludes the dissertation by providing answers to our HRQs. We close the dissertation with a few remarks on possible future work.

Chapter 2

Background and Related Work

In this chapter, the background and the related work are summarized. This helps both to delineate the existing body of knowledge and to underline the novel research conducted within the context of this thesis.

2.1 Definition of Terms

In order to ensure a common understanding of key concepts and terminology, we give definitions for the most important terms that will be used in the remainder of this dissertation thesis.

2.1.1 Personal Mobile Device

An important term in this work is *mobile device*, which shall describe the ubiquitous travel companion for accessing and using the digital services described in this work. Although the term is widely used and part of everyday speech, there is no clear definition. In a 2013 publication by the United States (U.S.) National Institute of Standards and Technology (NIST) on mobile device security, it is stated that "it is difficult to define the term *mobile device*" [285], as the features of mobile devices are continually changing. For that reason, hardware and software characteristics were used to describe a common baseline. The characteristics are summarized in the following itemization [285]:

- Small form factor to fit well into shirt pockets or trouser pockets, or in maximum shape (around 10 inches) to fit in mid-size handbags.
- At least one wireless network interface for internet access.
- Local built-in persistent data storage.
- The operating system (OS) is not a fully-fledged desktop PC operating system (OS).
- Applications available through multiple methods, an application store being the most common one.

Although this seems to be a good starting point, especially the description of the physical dimensions with “small form factor” is a matter of interpretation. For that reason, we want to narrow this specification by using the size analogy from Weiser [410]. Weiser concluded that computing devices could be described as “tabs, pads, and boards: inch-scale machines that approximate active Post-It notes, foot-scale ones that behave something like a sheet of paper ... and yard-scale displays that are the equivalent of a blackboard or bulletin board” [410]. Since device portability is a crucial aspect for our understanding of mobile devices, we are in the range of inch-/centimeter-sized wearable devices (tabs), and foot-/decimeter-sized devices (pads).

> “ Portable computers go everywhere with their owners. ”
>
> *Mark Weiser, 1991 [410]*

Poslad further highlights that, also, the definition of *mobile* is vague [311, p. 122ff]. Strictly speaking, most mobile devices are not mobile themselves but are bound to a mobile host, e.g., a human that carries the device. That fact is also expressed by the above quote from Weiser with the subtext that the devices do not *go* themselves but are carried by their owners. Examples of *real* mobile devices would be robots or autonomous vehicles. Poslad concludes that device mobility can be viewed from several dimensions. The suggested dimensions are [311, p. 122ff]:

- Physical dimensions of the mobile device.
- Source of mobility (is the device or its host mobile?).
- Type of host, the mobile device can be bound to (e.g., living things, or physical world objects such as vehicles).
- Ways of attachment, the mobile device can be attached to a host.
- Periods, the mobility occurs in.

The visualization in Figure 2.1 shows the dimensions with examples. For the physical dimension, Poslad also followed the classification of Weiser [410]. The size includes the range from *dust* to *pads* (decimeter-sized devices).

Besides the physical dimension, the dimension *attachment* shall be considered in more detail. Poslad [311, p. 29] distinguishes between the following types:

- *Hand-held*: devices that allow for one-handed or hands-free operation.
- *Portable*: devices that are usually operated two-handed while seated.
- *Accompanied*: hand-held or portable devices that are carried in clothes or bags.
- *Wearable*: devices integrated with accessories, clothes, or jewelry that can be operated while being worn.
- *Implanted or embedded*: devices inserted or fixed in a person’s body.

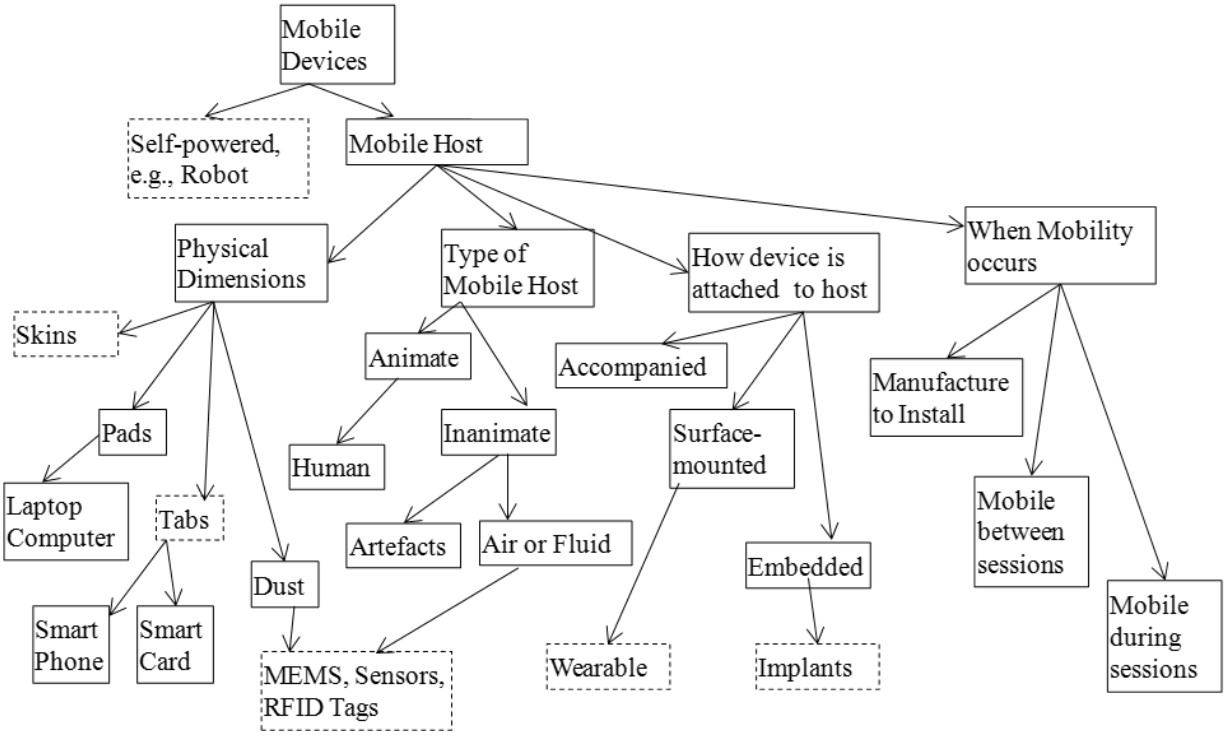


Figure 2.1: According to Poslad [311, p. 122ff], device mobility can be viewed from several dimensions. Besides physical dimensions and time aspects, the dimensions include the fact that mobile devices are usually bound to a mobile host, e.g., a human, that makes the device mobile. Dust-sized elements can be bound to air or fluids, e.g., sensors that flow around in physical environments just by physical forces.
Image source: http://www.eecs.qmul.ac.uk/~stefan/ubicom/concept-graphs.html, the *Mobile Devices* sub-tree has been extracted.

All the above types describe devices that can be taken along by humans, as the types indirectly incorporate the physical dimension.

The last point that shall be considered for our definition is the specification when the device can be used to access digital services (compare dimension *when mobility occurs* in Figure 2.1) and the consequences this has for the device's properties. Devices for our purpose shall allow accessing digital service from everywhere without needing to connect it to wired infrastructure (power or communication networks). For that reason, a mobile device – as we want to define it – needs a wireless communication unit that enables access to the Internet. Additionally, it needs to have an independent power supply (internal battery or external portable power supply). The service access may be intermittent, e.g., due to the limited battery power that needs recharge time or missing wireless network coverage.

Based on the above considerations, we use the following definition in this work:

Definition 1. *A* mobile device *is an accompanied, wearable, or embedded computing device with at least one wireless communication unit and independent power supply.*

Today, there is still mainly a one-to-one relation between mobile devices and their users. Devices are often only shared for specific time-limited tasks [189], such as making or receiving a call, or for showing photos or videos.

Due to this one-to-one relationship and the fact that the mobile device stores a lot of private data and is linked to many private resources (e.g., calendar, messaging, social networking), a mobile device usually "knows" its user, i.e., it is *context-aware* in matters of its user [348] (e.g., identity/profile, location, or social situation).

Definition 2. *A* personal mobile device (PMD) *is a mobile device that is aware of its user in terms of identity, preferences, social situation, locations, and schedule.*

That means that a PMD persistently stores personal information or can access linked private data sources (e.g., social network accounts, or online calendars) and can make use of this data without having the user repeatedly input necessary data.

The motivation for using a PMDs as central interaction device in this work is summarized in the following itemization:

- PMDs are usually taken along en route when leaving home.
- Users are usually more acquainted to the HMI of their PMDs than to the interfaces of, e.g., ticket vending machines or IVISs.
- Today's PMDs have various sensors, e.g., for determining the current location. They contain individual contextual information that can be used to adapt to different contexts and to provide the necessary assistance.
- PMDs offer multiple (usually multiple) (wireless) communication systems that allow coupling with other digital systems. Mobile data connection provides access to Internet services. Other systems can share its Internet connection.
- PMDs are regularly upgraded. With an upgrade cycle of approximately 21 months[1], PMDs typically fulfill or exceed hardware requirements of default applications and digital services.

However, people do not just use mobile devices on the move. In a study on mobile device use at home, Kawsar and Brush concluded that the "Desktop PC is now a special-purpose device, which [is used] only for specific activities such as working from home or online gaming" [191]. Especially for lightweight activities, such as social networking, online shopping, or news browsing, people prefer mobile devices over desktop PCs. A key reason for using the mobile device at home is its portability [291], which allows using the device everywhere at home.

---

[1] https://techpinions.com/the-smartphone-lifetime-challenge/42647, accessed January 4, 2019

2.1.2 Mobility

The goal of the digital mobility assistance suggested in this dissertation is to support door-to-door mobility (and partially also indoors). For that reason, several mobility-related terms need to be defined.

The first term is *intermodal transport* (sometimes also called *intermodalism*, especially in the context of good transportation [396]). The origin of the term lies in the area of logistics, more specifically in freight transport [38]. In a 1997 communication of the European Commission to the European Parliament and the Council, intermodal transport was defined as "[t]he movement of goods in one and the same loading unit or vehicle which uses successively several modes of transport without handling of the goods themselves in changing modes" [117, p. 1]. An example of a *loading unit* is the intermodal container compliant to ISO 6346 [175].

> Strictly speaking, intermodal transportation has been in existence throughout human history, such as when the first sailing ships were loaded with cargo taken from horse-drawn carts.
>
> *Goetz and Vowles [139, p. 12]*

As the quote says, intermodal transportation (freight and passengers) has been performed for many centuries. However, the research on holistic intermodal approaches began only in the 20th century [139]. Since then, *intermodal transportation* was defined as using a combination of several modes of transportation on a journey. In this work, we define it as follows (derived from Crainic and Kim [69]):

Definition 3. *Intermodal transportation is the transportation of a person or a load from its origin to its destination by a coordinated sequence of at least two modes of transportation.*

Intermodal passenger transport is sometimes also called *mixed-mode commuting* [272]. An intermodal route can be a combination of private (e.g., car) and public (e.g., subway) transportation. The coordinated manner is a central feature realized by interconnection locations that are called *intermodal terminals*, *transfer points* [266], or *intermodal facilities* [328]. An in-depth view of intermodal transportation is given in Section 3.1.

The term multimodality is often used synonymously to intermodality. In this work, however, we define *multimodality* as follows [266]:

Definition 4. *Multimodality describes the availability of multiple different modes of transportation or intermodal routes alternatives for a journey or a part of a journey.*

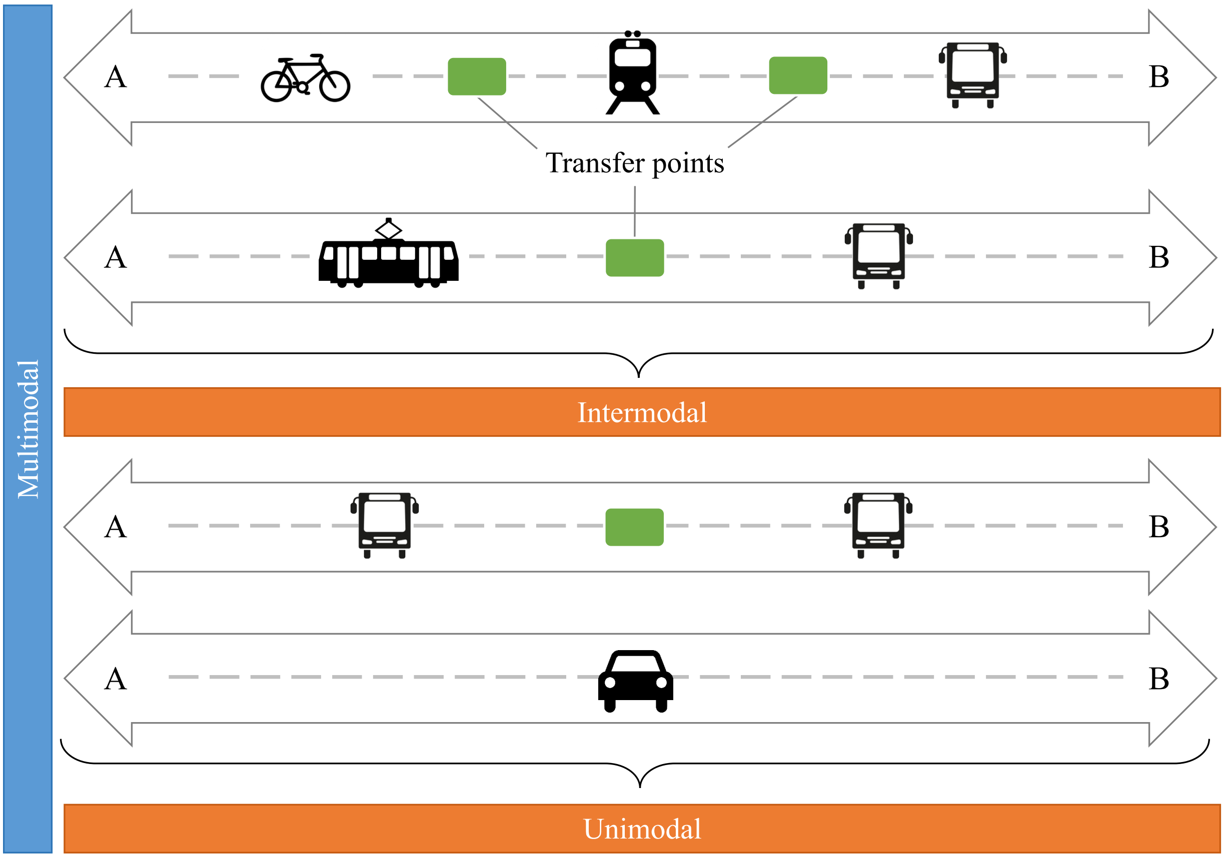


Figure 2.2: Visualization of the definitions for intermodality (c.f. Definition 3) and multimodality (c.f. Definition 4). While intermodality stands for using a sequence of different modes of transport, multimodality means the availability of multiple alternatives to get from A to B.
Image freely adapted from http://multi-mobility.tumblr.com/post/60830879635

The illustration in Figure 2.2 visualizes the difference of intermodality and multimodality, as defined in this thesis. Intermodal routes are a part of multimodal transportation. The choice available in a multimodal transportation network can be influenced by several factors, such as comfort, travel time, or cost. More detailed analysis of the influence factors is given in Section 3.1.

A comprehensive collection of mobility-related terms is available in a glossary[2] of the European project *LINK – The European Forum on Intermodal Passenger Travel* [328]

2.2 Assistance Systems in Information Technology

In this section, the background of currently available digital assistance systems is presented. Although the focus is on mobile digital assistance systems, important developments for traditional

---

[2] http://www.fgm.at/linkforum/index.phtml?ID1=1222, accessed February 19, 2019

desktop PCs and web pages are included.

2.2.1 Basic Properties and Evolution of Digital Assistance Systems

The history of digital user assistance systems began with the broad availability of interactive computing systems [183]. So-called *online help systems* were introduced to support users during interaction with the digital system [29, 312]. The systems were created to replace specialized training in artificial situations with on-demand knowledge enhancement during real tasks. That way, task-oriented help could be provided, which users preferred to printed technical documentation [324]. Already in 1984, Houghton [169] concluded that "[u]sers of computer systems are [...] accustomed to the convenience of online help systems and generally demand these amenities in the computers they buy".

> “One method to promote user acceptance of a system and relieve user anxiety is to design the system so that it can always assist the user upon demand. In order for the assistance to be effective and for the user to perceive a system as a valuable tool, this assistance must be constantly available, accurate, responsive to the current context of use, up-to-date with all portions of the system, and presented in a consistent manner.”
>
> *Fenchel [120]*

While online help supports users of digital systems with performing single tasks, recommender systems (RSs) can help users to identify functions and items that may be of use to a user to reach a specific goal [326]. These systems can provide help to select an option in areas where an overwhelming number of alternatives are available, and the user does not have sufficient personal experience to evaluate the options [323]. An RS can also support the use of digital services by interpreting the context and goal of user actions [277].

An example of a computer application assistant was Microsoft's *Clippy*[3], which was included in previous Microsoft Office versions. *Clippy* could, for example, detect when a user typed an address and would offer to open an assistant for creating proper letter formatting. Today, almost all Internet services with a for humans unmanageable amount of choices are equipped with RSs, helping to find a suitable choice based on collected information about users' preferences [33]. Examples are e-commerce platforms, social networks, or streaming services. With having more and more route options available, trip planning services also act as RSs by summarizing and limiting available options based on personal preferences or abilities.

Since RSs make suggestions to humans without being always able to communicate the reason for choosing specific options comprehensively, two central properties determine whether presented recommendations are considered [277]:

---

[3] The official name of Microsoft's assistant was *Clippit*.

- the ease with which the recommendations are understood, and
- the level of trust a user assigns to a recommendation.

These factors are also vital when another human makes a recommendation [401].

> One of the major issues for user assistance systems consists of "providing help at an appropriate level."
>
> *Kohlhase and Kohlhase [198]*

The comprehensibility of recommendations is strongly dependent on the receiver's context and the type of recommendation [154, 379]. Besides the language (in terms of complexity and wording [146]) used for the presentation of the information, the modality of recommendation delivery is also a relevant factor [39, 59]. For example, augmented reality (AR) has been proven to be a suitable user interaction modality for RSs in the area of tourism and traveling [135]. More information on modalities for HCI is presented in Section 2.2.2.

In order to gain trust in digital services, Bart et al. [19] name the following eight factors as main drivers: *privacy* (protection of individually identifiable information), *security* (safety of the end device and financial information), *navigation and presentation* (graphical user interface (GUI) and HCI), *brand strength* (symbol of quality and assurance), *advice* (information and guidance towards appropriate solution), *order fulfillment* (delivery of a product or service), *community features* (interact with other users), and *absence of errors* (lack of mistakes in information and input processing). Depending on the type of recommendation, the weight of the factors very. For example, for choices with significant financial implications, the factor *advice* matters most [19].

According to Whitworth [412], *politeness* is another critical characteristic of RSs — especially when systems actively offer their recommendations. *Politeness* in the information context can be defined as "any unrequired support for situating the locus of choice control of a social interaction with another party to it, given that control is desired, rightful and optional" [412]. In order to create a system that is perceived as polite, Whitworth proposes the following *HCI politeness rules* [412]:

- *Respect* user choice: No preemptive acts that deny user choices.
- *Disclose* itself: Declare itself and its purpose.
- *Offer* useful choices: Present understandable choices.
- *Remember* past choices: Make use of interaction memory.

The suggested politeness is strongly tied to desired user choices that a system offers or supports. Conversely, impolite software is taking valid choices away. Whitworth gave the aforementioned Microsoft Office assistant *Clippy* as an example of impolite software. The analysis of user feedback identified it as being intrusive and oblivious to user choices.

In order to provide appropriate support for tasks and services across different domains, information from multiple sources needs to be combined. The starting point is the user's goal that is given to the system either explicitly as input or is derived implicitly from the user's context [230]. In order to react appropriately to the input and to find the necessary information or to use an applicable service, semantic understanding and knowledge are necessary [133]. So-called intelligent agents (IAs) can further extend their initial knowledge by machine learning in order to achieve their goals [417].

IAs that can actively assist users by collaborating with them are called intelligent personal agents (IPAs) [278]. The prevalent IPAs are voice-activated personal assistants (VAPAs) running on mobile devices. Examples are Apple's *Siri* [9], Microsoft's *Cortana*[4], or Google's *Google Now*[5]. The systems combine speech recognition with natural language understanding techniques in order to "understand" the user. Contextual data is available through stored personal data, linked calendars, and social accounts, as well as the mobile device's various sensors. That allows, e.g., to derive information about the current location and doing. Tasks are performed by accessing APIs to other applications or online services that either return information (e.g., weather reports, news, transportation schedules) or support the realization of a goal (e.g., create an appointment in the calendar, send a message to a contact, or reserve a table at a specific restaurant).

Websites make also use of automated online assistants [58] to provide basic customer service on websites day and night. The virtual assistants (often with a humanoid avatar) use a dialog system [37] with natural language understanding to communicate with the website visitors. The answers to inquiries are searched in expert systems [229] that may be filled manually or by automated information processing, e.g., from the respective website [121].

With the enormous popularity of instant messaging applications on mobile devices, these platforms also became interesting for offering services. Under the proclamation "bots are new apps"[6], companies started to provide automated services via messaging interfaces. There are task-specific chatbots that can suggest apparel by asking a few questions to the user[7] or allow ordering flowers with only a handful of messages[8]. And there are general bots that act like IPAs by learning from previous conversations. *Facebook M*[9] is an example for such a digital chatbot assistant that can purchase items and services and make arrangements on the user's behalf in different domains.

A specialty of IPAs is that they are not only active when a user starts interaction with them, but they can also notify users when certain conditions are fulfilled, a task has been completed, or an action is required. Sahami Shirazi et al. [342] have analyzed the role of notifications on mobile devices. The results show that especially notifications from messaging and communication apps,

---

[4] https://www.microsoft.com/en-us/windows/cortana, accessed August 10, 2019

[5] http://google.com/landing/now/, accessed August 10, 2019

[6] http://techcrunch.com/2015/09/29/forget-apps-now-the-bots-take-over/, accessed April 22, 2019

[7] http://www.forbes.com/sites/rachelarthur/2016/04/12/shopping-start-up-spring-launches-one-of-first-bots-on-facebook-messenger/#2682eeec4ee7, accessed August 11, 2019

[8] http://digiday.com/brands/two-months-1-800-flowers-facebook-bot-working/, accessed August 11, 2019

[9] https://www.theguardian.com/technology/2015/aug/27/facebook-m-virtual-assistant-siri-google-now, accessed August 11, 2019

as well as from calendars, are valued positively. The study by Pielot et al. [308] confirms that notifications are favorable for the users when they match their expectations. That means IPAs need to adjust their proactiveness to the users' preferences.

Users may further have different situational requirements and preferences in the manner of support. Sometimes *passive assistance* in the form of continuous information and presentation may be preferred (e.g., showing a map with the navigation route). However, for example, in situations with high cognitive load or distraction, active assistance by triggering automated actions or explicitly showing information (e.g., warnings in dangerous settings) may be more applicable [123].

Proactiveness is also an essential factor of ambient intelligence (AmI), which describes smart environments that are equipped with technology to support people in their everyday life [66]. It builds upon paradigms of pervasive and ubiquitous computing [341], but with an extended approach of artificial intelligence that allows for proactive and sensible support [12]. According to Aarts [1, p. 14], AmI is shaped by these five fundamental qualities:

- *Embedded:* Many networked devices are integrated into the environment.
- *Context-aware:* These devices can recognize the user and its situational context.
- *Personalized:* The environment and the incorporated devices can be tailored to the user's needs.
- *Adaptive:* The system can change in response to the user.
- *Anticipatory:* The environment can anticipate the user's desires without conscious mediation.

In the remainder of this dissertation, the realization of digital assistance systems is focused on PMDs. However, the support could also be offered by embedded devices in smart environments that are also a vital part of the mobility assistance vision in Chapter 3.

2.2.2 Modalities for User Interaction

In this section, we provide a short overview of interaction modalities that are commonly used on PMDs for communication with the user [15]. When speaking of *interaction modalities* in this thesis, the "type of communication channel used to convey or acquire information" [284] for HCI is meant. Almost all available input and output modalities rely on the five classical human senses: sight, hearing, touch, smell, and taste. While sight and hearing are distant senses, touch, smell, and taste require vicinity or contact [371].

Input Interaction Modalities

Today's primary input interaction method of PMDs is touch. Touch includes pointing on a touchscreen, typing on a soft keyboard [221] as well as performing multi-touch gestures on a touchscreen to trigger particular actions, such as pinching for zooming shown content. Many platforms can also recognize handwriting with (special) input pens. In addition to determining multiple touch positions, modern touch interfaces can also distinguish between pressure levels [365]. There are also approaches for the *back of device* interaction based on small touch devices [20]. Besides the touch-sensitive input areas, there are often a few mechanical keys for triggering certain actions (e.g., a power button, volume adjustment, or a home button to change to the main menu). Dependent on the device, fixed or attachable physical keyboards can be available.

A more and more important input modality is audio, and especially speech. Text can be dictated, and voice commands can be used to interact with IPAs. Due to specialized audio processing chips and detection algorithms, devices can even listen in low-power mode continuously for so-called hot words [425] (such as Google's "Okay Google") in order to wake up and activate the voice command mode.

Gestures with the devices themselves can be used to perform or trigger specific actions. Built-in accelerometers, magnetometers, and gyroscopes can capture motion gestures in the three-dimensional space [336].

Integrated cameras can be used to capture the environment and the user. With computer vision [269] or distance sensors [207], around-device gestures can be recognized and used for input. That allows for natural interaction as no mechanical devices with certain constraints need to be operated. Besides hand or full-body gestures, these systems can also detect facial gestures [424] that could, for example, be used for emotion recognition.

Output Interaction Modalities

The most common output modality of PMDs is based on the sense of sight. Screens are used to present the user interface (UI), which is mainly a GUI. Single (multicolor) light-emitting diodes (LEDs) can be used for notifying the user [380] about newly available information (e.g., incoming messages, or missed calls), or for reminding (e.g., of an upcoming appointment). Built-in projectors enable larger interaction areas [102], or can be used for augmenting the reality with digital content (e.g., for navigation [190]).

Integrated speakers or bone conduction audio transducers [245] can generate audio output. The output can either be pre-recorded or computer-generated, for example, by a text-to-speech (TTS) system [6]. Auditory displays use sonification [159], audification [75], and earcons [134] to convey information via the auditory channel or for directing the user's attention to a particular element in monitoring environments [408].

Active haptic feedback, often generated by a vibration motor, is used for generating feedback when pressing soft keys [166], or for notification of users via the so-called vibrating alert. With adaptive surface technology [177], customizable tactile feedback and dynamic textures can be generated, which can, for example, be used to make soft keys easier to hit.

Multimodal Interaction

Multimodal interaction means that more than one interaction modality is used for input, output, or both [389]. The different modalities can either be applied sequentially or in parallel; they can be fused or employed independently [284].

AR scenarios [157] are an example of rich multimodal interaction. Cameras are used to capture the environment and, depending on the application, also the users. Inertial sensors deliver the user's orientation and view direction. The screen shows the captured environment with additional digital information. A similar orchestration is used for virtual reality (VR) scenarios [187] with the screen showing the virtual scenery.

Depending on the environment and application, different combinations of interaction modalities are practical. For example, Pfleging et al. [305] used a combination of speech and gestures to enable access to car functionality, drivers would need to traverse nested menus or find a physical button that is not commonly used. Correa et al. [68] used pen-based sketching and voice commands of low complexity to control the route and tasks of an autonomous forklift. For the performance of navigating on a virtual map, Rohs et al. [330] found in a study that physical device movement for moving the map is better than the navigation with a joystick.

However, to create rich multimodal interaction, input from several sensors and context data need to be fused and evaluated. In order to allow for fast integration of multimodal interaction on mobile devices, frameworks with input and output device abstraction, context awareness, and rule-based switching of interaction modality are available [274].

Choosing the appropriate modality or modalities is a very complex task [167]. For example, although spoken voice has a higher semiotic efficiency quotient (SEQ)[10] than writing the same message, it may not be appropriate for privacy-concerning tasks in public or loud working environments. Users with sensory impairments may also have difficulties to use specific modalities [407]. For that reason, it can be beneficial to offer different modalities with homologous functionality [320]. When new interaction techniques are applied, it is essential to provide an introduction or guide without overloading the user.

---

[10] http://www.visaeuropecollab.com/news/2016/5/18/vuis-versus-guis-how-voice-became-the-interface-to-your-digital-assistant, accessed August 7, 2019

For our prototypes, we also combined different user interaction modalities. For example, our mobile training assistant for exercising with mobility aids presented in Section 5.4 uses text, video, and audio to describe the exercises' steps and give hints on the exercise execution.

2.2.3 Application Areas of Mobile Digital Assistance Systems

The breakthrough of mobile assistance devices began in the 1980s with the availability of personal digital assistants (PDAs) [313, 413]. In the 2000s, mobile phone and PDA features were "mated" [15], which can be seen as the advent of today's modern *smartphones*. That added further drive to the development of mobile digital assistance systems. A summary of the significant application areas beyond mobility is given in the following.

Medical/Health Assistance Systems

Medical digital assistance systems can support medical personnel as well as patients. Medical personnel mainly use digital assistants for guidance in diagnoses and surgeries, or for choosing methods during a therapy [399]. For diagnosing, assistance systems are not only gateways to drug [241] and patient information databases [331], but can actively support the diagnosis [199]. For example, image analysis combined with machine learning approaches can be used for skin cancer detection [112]. For surgeries, the use of AR technologies has tremendous potential [42].

Current medical assistance systems mainly focus on data acquisition [377] or rehabilitation training [82]. However, the mobile health (also referred to as *mHealth*) sector is rapidly growing [43]. Especially for the treatment of chronic diseases [56, 149] and for health support in regions with less-developed medical infrastructure (such as developing countries) [144], digital assistance systems offer a practical approach that can be integrated into daily life.

Personal Information Management

> “Personal information management (PIM) refers to both the practice and the study of the activities a person performs in order to acquire or create, store, organize, maintain, retrieve, use, and distribute the information needed to complete tasks (work-related or not) and fulfill various roles and responsibilities (for example, as a parent, employee, friend, or community member).
>
> ...
>
> One ideal of PIM is that we always have the right information in the right place, in the right form, and of sufficient completeness and quality to meet our current needs.”
>
> *Jones [180]*

Personal information managements (PIMs) systems do not store the information in an isolated manner, but connect it to other pieces of information and enrich it with meta-data that allows retrieving it in a particular context. The meta-data is usually comprised of tags describing contextual factors and manually added or automatically generated classification info [404]. In contrast to PIM on desktop PCs, the use of PIM on mobile devices can benefit from additional context information, such as the user's location, or nearby other devices or users, that may help to retrieve data when it is needed [254].

Most PIM systems are passive and text-intensive, store the information in browse-able organizational structures, and provide a search interface that allows searching for contents and its meta-data [411]. However, there are also approaches for PMDs that offer limited text input capabilities [225]. Zhou et al. [428] created a mobile PIM agent that supports natural language input through voice recognition. The conducted user study showed that users working with the VAPA were more efficient compared to text input. Schmeil and Broll [349] presented an anthropomorphic assistant in a mobile AR environment that could handle PIM functions, such as taking notes, or manage appointments, and present a route.

There are also group information management approaches that allow sharing information and, thus, simplify the collaboration on tasks [111].

Shopping Assistance

In 1994, Asthana et al. introduced a personal shopping assistance system that could help to locate items, remind the user of buying certain items, and inform about current discounts that could be interesting to the user [10]. The system used radio frequency (RF) triangulation for approximating the current location and was connected to a central shopping server via wireless local area network (WLAN). The UI was very basic in this approach and required the user to search for a product explicitly. That can be solved by AR-assisted systems that allow users to identify relevant products quickly. For example, Ahn et al. [4] use AR overlays to highlight healthy food in grocery stores. Individual recommendations are given to users by matching health concerns, such as allergies or caloric/diet requirements, with the products' properties.

In a study by Broll et al. [46], different output modalities for a shopping assistant have been compared. The results show that users prefer a combination of visual and haptic feedback, as this allowed a fast recognition of certain products, but also offered privacy compared to audio output.

Shopping assistants are not limited to physically finding certain products, but can also support the user in choosing a suitable and desired product. RS can help to filter vast choices based on product properties, previous choices, or other customers' ratings [212].

Tourist Information and Sightseeing

Tourist assistance applications cover one or several phases of a trip that have different objectives (adapted overview of Smirnov et al. [363]):

1. Pre-travel phase: provide services to facilitate travel-related information search, e.g., descriptions of attractions, booking of hotels and mobility services.
2. Travel phase: provide the traveler with real-time information about the destination, e.g., information about transportation delays, events, places of interest, advice, and other recommendations.
3. Post-travel phase: gather feedback from the tourist and share the travel experience with others (input for pre-travel information).

Conventional pre-travel assistance systems are RSs that help to select destinations, accommodation, and transportation [325, 386]. Travel details can then be summarized and aggregated in trip planning applications [105] so that users can get complementary real-time information during traveling. The information can be directly related to the trip, such as delays or route changes, or it can be about the surrounding (e.g., advice due to the change of environmental conditions, such as the weather) [240]. AR applications can enhance the exploration of the surroundings and finding nearby points of interest [420].

Post-travel assistance targets mainly on preserving and sharing memories, and gathering feedback and rating on certain parts of a trip (e.g., accommodation, visits of attractions, or transportation) [83].

2.3 Mobility Assistance Systems in Information Technology

In this section, a short overview of available digital mobility assistance systems is given. Compared to the overview in the previous section, it is not limited to applications and systems on PMDs.

2.3.1 Trip and Route Planning

Trip and route planning are used synonymously in this thesis (in a few other publications, trips are defined as parts of routes or the other way round [80]). A route or trip describes the ensemble of means of traveling between two or more given locations [48]. It can consist of multiple segments that are covered by different means of mobility. A route planning system usually makes use of map data and (public) transport schedules and itineraries in order to allow traveling between the defined locations.

When user- and environment-dependent constraints are taken into account, route planning can be described as a multi-factor optimization problem [81]. Default optimization criteria for route planning are the *shortest travel time* and the *shortest travel path*. Travel time optimization is often coupled to historical or real-time traffic flow data to enhance the prediction [76]. When public transportation is involved, additional constraints, e.g., availability of accessibility features [280], and optimization criteria for reducing the "disutility cost" [227], e.g., waiting times or the number of necessary transfers, may be included. For traveling with electric vehicles, the minimization of the overall energy consumption on a route could be desirable [406].

Overall, context-aware routing [364] can enhance the travel experience. That is not limited to factors that are directly related to the act of traveling (e.g., the before-mentioned factors of duration or distance), but can include personal preferences. For example, Lu et al. [242] created a trip planner where users could choose their route by selecting photos of nearby places they want to go past on their way. *TRIP* by Letchner et al. [226] "produces routes that are more suited to the driver's individual driving preferences." For instance, it takes into account which types of roads a user likes to take by analyzing driving habits. With *AffectRoute*, Huang et al. [170] demonstrated a route planning concept that uses crowd-sourced perceived safety and attractiveness rating of places in order to calculate routes travelers are more comfortable with.

A detailed overview of contextual data that can be relevant for route creation is given in Section 3.5.

2.3.2 Booking, Reservation, and Sharing

Most trip planning applications offer booking tickets for transportation online [195]. In intermodal trip planners, this option is often combined with the possibility to reserve a car- or bike-sharing vehicle, to book a ride-hailing service, or to find a place in a carpool [107]. Although booking is directly available from the trip planners, so far, customers must book or reserve the service for each segment individually. That can be very complex and time-consuming, and, in case of delays or cancellations, the user may need to re-book, prolong reservations, or search for other alternatives.

2.3.3 Navigation and Guidance

The output of the route planning process is the input for the navigation process. Navigation refers to the basic physical movements in order to follow a given route. That is usually composed of trajectory determination (e.g., current location, direction, velocity) and guidance, which describes the next necessary changes to the movement trajectory (e.g., turning) [165, p. 2].

Most navigation applications are based on turn-by-turn guidance, where the systems "only present information which is relevant to the oncoming maneuver" [53]. Besides distances and turning instructions, these systems can also incorporate landmarks [52] to better support human navigation strategies [262]. The most common output of turn-by-turn instructions is audio played at defined distances before turning points are reached coupled with visual presentation. For pedestrian navigation, tactile output can be used to notify the traveler that a direction change is necessary [329].

For areas with many junction points that may also look very similar (e.g., indoor navigation in large buildings), AR can support the navigation process [236]. However, as the study of Möller et al. [275] has shown, the use of AR needs high positioning and orientation accuracy. In case of low accuracy, switching to VR views or a 2-dimensional map [54] can avoid disorientation.

2.3.4 Advanced Driver Assistance Systems

Today's automobiles have integrated a high number of ADASs. Besides improving safety, the systems shall also increase the driving convenience. Many features are based on external sensory that monitors the surrounding. Examples of safety systems are emergency brake [211], lateral collision avoidance [184], or lane-keeping assistance [98]. Autonomous driving features, such as stop and go traffic pilots or distance controlled cruise control [258], are marketed as comfort features that enhance the safety in monotonous driving situations.

By sharing traffic and sensory information with other vehicles and receiving data from roadside appliances (e.g., red lights), ADAS can be further enhanced. For example, V2X communication allows warning forthcoming and following vehicles about traffic incidents (e.g., collisions, broken-down vehicles, or slippery road conditions) in real time over a distance of several kilometers [103]. Large-scale back-end systems that collect and process movement and sensory data from vehicles, allow traffic jam prediction and avoidance [231] or finding a free parking space [251].

However, having a high number of active ADASs combined with the increasing number of other infotainment features that steadily inform the driver, can lead to overloading situations. For counteracting this potential distraction, concepts have been developed that monitor the environment, the vehicle, and the driver to detect situations where supportive information is required [316].

2.3.5 Mobile Devices as Mobility Assistance Systems

The most common mobility and driving assistance applications are route planning and navigation systems. About 81 % of connected travelers used a mobile application to find their way around in 2015[11]. The most popular ones are the *maps* applications that come directly with the mobile

---

[11] https://globenewswire.com/news-release/2015/06/30/748490/10140122/en/TripAdvisor-Study-Reveals-42-of-Travelers-Worldwide-Use-Smartphones-to-Plan-or-Book-Their-Trips.html,accessed November 9, 2019

platforms, i.e., *Google Maps* on the Android platform and *Apple Maps* on the iOS platform[12]. Besides the general-purpose navigation applications, several mobility assistance applications are aimed at certain user groups. An example is route planning for users requiring barrier-free access [280].

There are also mobile applications that provide features comparable to vehicle-integrated ADASs. Bergasa et al. [28] created an application that can detect and warn inattentive drivers. Ling and Seng [234] presented a mobile application for traffic sign recognition via the mobile device's integrated back camera. Detected traffic signs are subsequently shown to the user for creating endured awareness about temporary bans (e.g., ban on passing) and possible dangers in road sections.

In 2007, Rehrl et al. concluded that "multimodal trip planning systems and in-car navigation systems are at present non-interoperating domains" [321]. In the last few years, this situation started to change. For example, in-vehicle infotainments (IVIs) are now connected to mobile applications [107]. That way, a mobile guiding application can take over the route guidance to the destination via different means of mobility when the vehicle is parked.

2.4 Incentives for Using Digital Assistance Systems

The sheer availability of an assistance system does not guarantee that users having a possible advantage begin using the system and stick to it until a positive effect is perceivable [228]. In this section, we explore motivational aspects that can be exploited in applications to make the experience of using an assistance system more engaging.

2.4.1 Introduction to Motivation Theory

A prevailing theory for motivation is the incentive theory [340] that distinguishes between intrinsic and extrinsic motivation [339].

Intrinsic motivation is often described as a strong force that arises from a task itself. That is, for example, the case when enjoyment and personal interest are involved in an activity. Since interests are strongly individual, all tasks cannot be intrinsically motivating for everyone.

In contrast, extrinsic motivation is based on external forces such as separable striving outcomes (e.g., material rewards) or control from the outside (e.g., pressure). Figure 2.3 depicts the different types of extrinsic motivation as defined by Ryan and Deci [339]:

1. *External regulation* describes the motivation triggered by expected rewards (e.g., money or points), or imminent punishment (e.g., extra work or loss of material things).

---

[12] http://www.comscore.com/Insights/Presentations-and-Whitepapers/2017/The-2017-US-Mobile-App-Report, accessed November 9, 2019

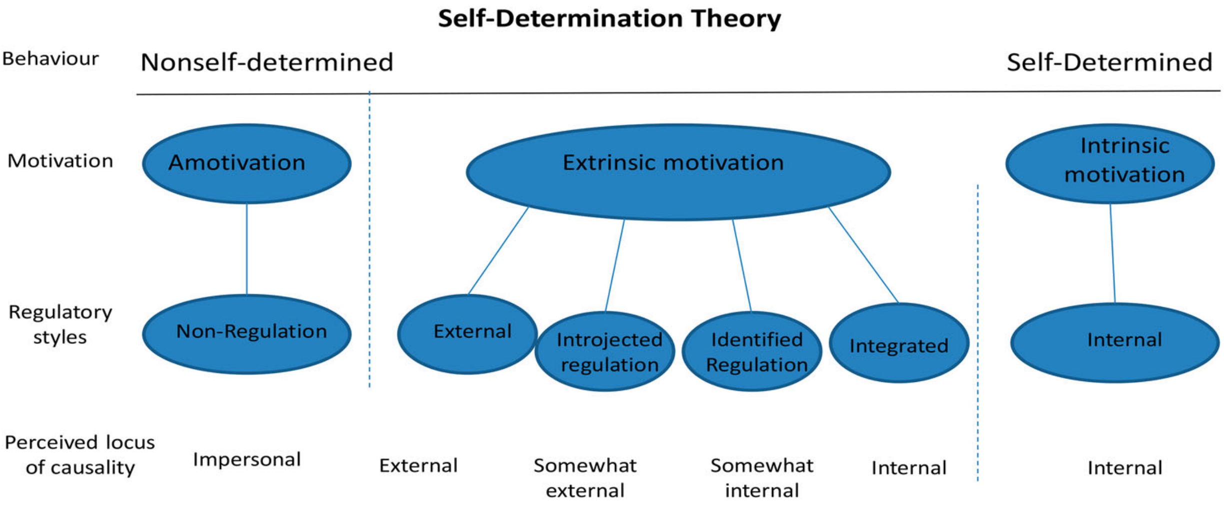


Figure 2.3: The taxonomy of human motivation by Ryan and Deci [339] differentiates between amotivation, extrinsic motivation, and intrinsic motivation. From left to right, the "extent to which the motivation for one's behavior emanates from one's self" [340] increases.
Graphic source: Mariager-Anderson et al. [256]

2. *Introjection* is motivation that occurs, e.g., due to the will of avoiding the feeling of anxiety or guilty when not performing a task. One feels that a task must be done because of others.
3. *Identification* is caused when one identifies with the importance of an activity or behavior (e.g., learning vocabulary to be able to speak a foreign language).
4. *Integration* means that one believes a particular task may contribute to another, often larger, goal, need, or personal value.

From 1. to 4., or, in Figure 2.3 from left to right, the self-determination is increasing.

Since intrinsic motivation cannot be directly affected, we focus on evoking extrinsic motivation [339], e.g., through gamification Section 2.4.2, or influencing the behavior and decisions of people with methods known from behavioral economics Section 2.4.3.

2.4.2 Gamification – Using Game Design Elements to Evoke Motivation

Games are working with multiple extrinsic motivation types to create and maintain motivation. Examples are the awarding of points (gratification as a form of external regulation), forming of teams (fulfilling the need of belongingness in the integration type), or presenting a clear winning goal (triggering the identification and integration type).

The effect of creating motivation through games has been exploited in so-called *serious games* in many different areas such as the military, academics, medicine, or professional training [435]. The entertaining gaming effect is used to educate, train, and inform the "player" [267]. In recent years, it has been shown that gameful design can likewise be a benefit for applications outside the gaming context. The location-based application *Swarm* (former *Foursquare*) and the science puzzle application *FoldIt* [193] are prominent examples of gamified applications that award users with points and badges for completing certain actions. Deterding et al. [78] researched the current use of gamification and proposed the following definition: "Gamification is the use of game design elements in non-game contexts" [78].

In order to create high motivation with game design elements, according to McGonigal, four things need to be considered: satisfying work (consisting of a clear goal and next actionable tasks), the hope/experience of being successful (feedback system), social connection, and meaning (e.g., contribute to a superior goal) [263, p. 53]. According to Zichermann and Cunningham [429], the basic game mechanics are points, levels, leaderboards, badges, onboarding, challenges/quests, and engagement loops.

Since gameful design can arouse sustainable motivation and strong commitment, it has found its way into the automotive domain [90, 93]. So far, it is mainly used for marketing, eco-driving, and driving safety. In our research, we extended the scope to automotive UI training (cf. Sections 5.2.1 and 5.3).

2.4.3 Nudging – Exploiting Behavioral Biases and Decision Heuristics

Another approach to steer the behavior and decision of people into a particular direction is called *nudging* [378]. Nudges are "behavioral interventions that do not restrict choice, but attempt to account for bounded rationality in decision making" [7]. In the following, a few examples of proven mechanisms for nudging people are summarized [378].

Default rules exploit the so-called status-quo bias of decision heuristics. The status-quo bias is the tendency not to change an established behavior unless there is an incentive to do so [419]. For example, Thaler and Benartzi [383] used the default rule of automatically joining a saving plan to nudge people to save more money. Only 22 % of the participants made use of the provided opt-out, although all participants initially decided that they did not want to invest.

Anchoring is the tendency to orient a decision very strongly on an implicitly given reference point [391]. For example, Marchiori et al. [255] used a reference portion to set an *anchor* for the following estimation of whether the participants will eat more or less than the presented portion. By presenting a smaller portion size anchor, for example, the desired pasta portion size was just three-quarters of the desired portion size without an anchor. In the context of commerce, this bias is, for example, exploited in 'pay what you want' pricing schemes [186].

Priming describes the effect of affecting the behavior by "incidentally-presented stimuli" [409]. The stimuli can, for example, be words, audio, images, or activities. In a study by Bargh et al. [17], students had to find words in word search puzzles. The students that had words from the area of competition (e.g., *compete*) and performance (e.g., *master*) in their puzzles found significantly more words on subsequent word search puzzles than those that had neutral words (e.g., *carpet* or *window*) in their first puzzles. Alone finding and reading words related to performance were incentives enough to push oneself.

In the context of HMI, these methods are often employed in so-called *persuasive* systems [125]. In order to change the behavior or attitude of users, the mechanisms mentioned above are exploited in those systems. In our work, we use these mechanisms to motivate users and to optimize the credibility of provided journey data. Our understanding of credibility is based on the definition of Fogg and Tseng [126]:

Definition 5. *Credibility is a perceived quality of information.*

It mainly depends on the source's perceived trustworthiness and expertise [126]. These factors are heavily influenced by the presentation and the context of the information. An example is the so-called *white-coat effect* [44] causing a higher authority and trust for medical practitioners that wear a white coat as compared to wearing casual clothes.

In this thesis, we made use of *nudging* to influence the credibility of shown route data (cf. Section 4.4).

2.5 Evaluation Methods for Digital Assistance Systems

> “There are two polar views about how to structure human-machine interaction. One is the computer as tool. Under this view, one wishes to make the computer a better tool more responsive, easier to wield, more reliable in application, capable of doing a bigger job at a stroke. Control remains with the user. The other view is the computer as intelligent assistant. In this view one wishes to make the computer more intelligent and communication with it more natural. One does not wield an intelligent assistant, one tells it what one wants. Intelligent agents figure out what is necessary and do it themselves, without bothering you about it. They tell you the results and explain to you what you need to know.”
>
> *Sondheimer and Relles [369, p. 106]*

In the following two sections, we summarize how measurements of technical system characteristics on the one hand and human factor experiments, on the other hand, can be used to evaluate the requirements of digital mobility assistance systems we mentioned above.

2.5.1 Analysis of Technical System Characteristics

For this thesis, the technical system behavior analysis focuses on the following functional and non-functional requirements:

Capacity As capacity, we understand the number of maximum supported concurrent operations or users. That means we combine it with the requirements concurrency and throughput. As mobility is strongly related to location, the capacity may often be given per area. In a technical system, the capacity can be limited by the available resources as well as by physical limits.

Performance In this thesis, the performance describes how long the technical system needs to respond to a specific action. The response time also includes immanent system delays. Performance is often related to capacity, as it may vary dependent on the system's load.

Scalability In order to evaluate the suitability of the proposed technical systems, the scalability is examined. It describes the required effort to apply the system on a larger scale.

We performed an analysis of technical system characteristics in Section 6.3 to evaluate the different work split architectures for mobile device integration in the automotive domain.

2.5.2 Methodologies for Interactive Systems

Human factor experiments in the context of digital systems started with the broad availability of interactive computing systems in the 1980s [369]. Their goal is to improve the usability [287], the user experience [286], and the learnability [367] of digital systems.

> “However, is ease of use the only need? The answer is a resounding NO! The challenge [...] for HCI is how to support individuals and groups of individuals in developing expertise in their professions, in developing richer and deeper understandings of content and practices. Making people smarter is really the long term goal of computing.”
>
> *Soloway et al. [367]*

In the following, we present a summary of the HCI evaluation methods we applied in this dissertation.

User Study Settings for the Evaluating of a Concept or Prototype

The following three types of settings have been used for studies on concepts and prototypes in this thesis [100, p. 327ff].

Laboratory study A laboratory study is conducted in a controllable space, the so-called lab, without having the (overall) characteristic context. This kind of study style was, for example, used when driving performance under specific secondary/tertiary tasks has been assessed. The use of a driving simulator was safer for the participants and made results more comparable, as the driving task and environment were identical for all subjects. That was the primary study type employed in our research. For example, we conducted driving simulator studies for the evaluation of the effect on automotive user interface training in Section 5.3.

Field study In contrast to the laboratory study, the field study is conducted in the typical context (e.g., while traveling). This kind of study was, for instance, used to evaluate the actual use of route planning and mobility training applications. The challenges of field studies are the collection of relevant context data and direct user feedback. We used this type of study for the evaluation of our trip planning prototype (Section 4.4.6).

Online study Online studies are useful when large-scale feedback shall be gathered on general concepts. Typical online user studies gather information in the form of a survey. When a concept shall be evaluated, descriptions, images, and videos can help subjects to immerse themselves in the desired context. We performed an online study in Section 6.6, where we gathered large-scale feedback on the design of red light indications.

Data Collection

Dependent on the setting of a study, and the questions to be answered, different methods for data collection have been used in the thesis.

Expert Review In expert reviews or expert evaluations, the knowledge of professionals is utilized to evaluate a solution [387]. The focus is often on UX. In perspective-based inspections, experts evaluate products from a different perspective (e.g., design or UX). That can be reinforced by performing the review with experts from different domains. When experts from the area the system is targeted to perform the evaluation, the experts can use their experience and inquired context. The advantages of expert reviews are the fast implementation and that experts often have no problem to evaluate early prototypes with incomplete or unstable functionality [130]. We used this method in Chapter 7 for the combined evaluation of our developed AMASs as a whole.

Survey Interviews or questionnaires are the most common forms of surveys. A survey can be part of a laboratory, field, or online study, but also be performed standalone, e.g., to gather data on the general mobility situation of people. Common question types are [118]:

- Dichotomous questions (e.g., yes/no),
- Open-ended questions,
- Multiple-choice questions,
- Rank order (e.g., first choice, second choice),
- Likert questions, or
- Semantic differential questions.

p	$P(x \geq 1) = 0.5$	0.75	0.9	0.95	0.99
0.01	69	138	230	299	459
0.05	14	28	45	59	90
0.10	7	14	22	29	44
0.25	3	5	9	11	17
0.50	1	2	4	5	7
0.90	1	1	1	2	2

Table 2.1: Required sample size to detect a usability problem at least once. p denotes the problem occurrence probability, $P(x \geq 1)$ is the likelihood of detecting a problem at least once. Derived from Sauro and Lewis [347, p. 146]

We made use of surveys to gather the feedback of the participants in all conducted user studies (e.g., in Sections 4.2, 4.4.6, 5.2, 5.3, or 6.4.2)

Observation Observation describes the gathering of data by monitoring or measuring certain aspects or factors during the user study [400]. That can be used to gather quantitative data (e.g., through measurements of task execution or interaction times) as well as qualitative data (e.g., a subject's behavior). We made us of *observations*, for example, in Section 4.2 where we measured the task execution time and tried to identify the most challenging tasks of route planning.

Sample Sizes

> “ Sample sizes in HCI studies are typically between 10 and 20 participants. ”
>
> *Baxter and Courage [21, p. 203]*

In the area of usability testing, a specific sample size is required to reach a minimal problem discovery rate [350]. In general, the sample size depends on the following factors [347, p. 6]:

- Required precision for estimation (margin of error)
- Number of groups that shall be compared
- Problem discovery (find a certain percentage of problems with a specified probability of occurrence)

In order to relate these factors to the required sample size, a statistical model is necessary. The most commonly used model is derived from the binomial probability formula [347]. Equation 2.1 shows the resulting formula for calculating the required sample size n, for a discovery probability of $P(x \geq 1)$ and a target problem occurrence probability of p.

$$n = \frac{\ln(1 - P(x \geq 1))}{\ln(1 - p)} \tag{2.1}$$

Table 2.1 shows a set of calculated sample sizes with selected values of p and $P\left(x \geq 1\right)$. When aiming at major usability issues (e.g., $p \geq 0.25$), a decent detection probability ($P\left(x \geq 1\right) \geq 0.9$) can already be reached with 9 study participants. That is consistent with the rule of thumb by Macefield [246] which states that a sample size of 5 to 10 participants is enough when targeting the major usability issues.

For all our studies, we used this statistical model to determine the minimum number of participants. Studies conducted in this work are meant to provide the first proof of concept [335]. The results shall demonstrate the feasibility of the concept and do not raise a claim to be complete.

Part II

Mobile Device-complemented Mobility Processes

Chapter 3

Toward Optimized Mobile Device-Complemented Mobility

In this chapter, we identify and describe areas of potentials for optimizing mobility with mobile device-complemented services. Figure 3.1 depicts the structure of the chapter and the relation of chosen research methods. We start with a mobility process description to describe the different steps and phases of mobility (**HRQ1**), which provides the structure for the following analysis of barriers, factors influencing the choice of a trip, and requirements of users for mobility assistance systems (**HRQ2**).

We employ the technique of engaging personas and create three exemplary mobility scenarios that are used to identify research gaps in the topic of PMD-complemented AMASs (**HRQ3**). Another outcome is a vision of future mobility that makes use of these services.

3.1 Analysis of Intermodal Mobility

The focus of the analysis is on intermodal mobility, which is, especially in urban areas, the fastest-growing type of mobility [136].

3.1.1 Description and Model of Intermodal Mobility Processes

In general, the mobility process is composed of several locations with different meanings:

- *Starting point*: location where a trip starts.
- *Transfer point* or *station*: 1–n locations where the line or means of mobility is changed.
- *Stopover*: 1–n stopping points that may be en route or detour.
- *Destination*: location where the trip shall end.

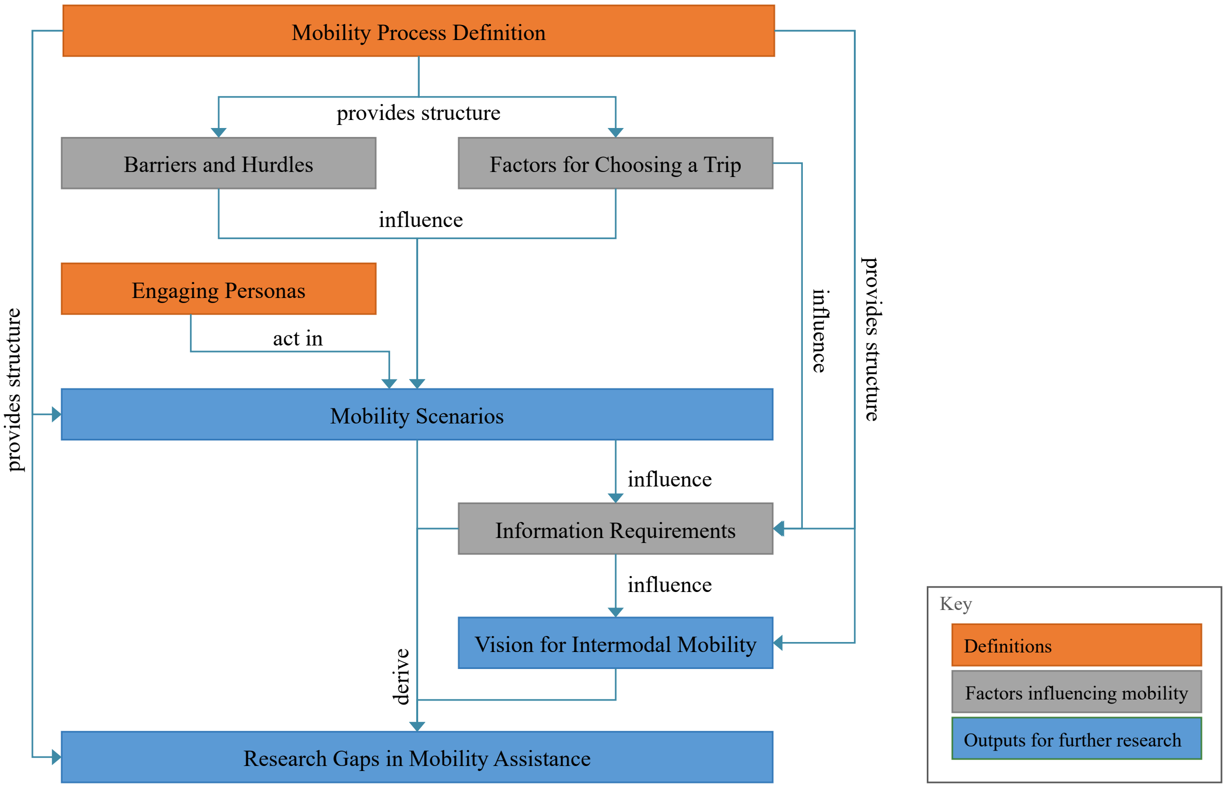


Figure 3.1: The structure of the chapter corresponds to our chosen research method. The basis is a generic process model of mobility that allows structured research of barriers, mobility-influencing factors, and information requirements. The derived factors are, in turn, input for mobility scenarios and a vision presented in this chapter.

For round-trips, *start* and *destination* are the same locations. *Transfer points* and *stopovers* may overlap. When the locations are not identical, it takes a certain time t to travel from one location to another. At *transfer points*, a user might have to wait a certain time t_{wait} until the trip can be continued. At *stopovers*, the user might want to stay a certain time t_{dwell} before proceeding with the trip. The travel time t between locations is dependent on the average velocity and can be prolonged by a time t_{delay} that can, for example, be caused by traffic jams, red lights, etc.

For traveling from one location to another, a *path* between the two locations has to be taken. This path is called a *segment*. There can be multiple paths between the two locations. The paths can differ in numerous aspects, such as length, duration, or difficulty.

Digmayer et al. performed an extensive literature review to identify the typical steps and phases of an intermodal trip [97]. The identified phases and steps were the basis of the following, adapted model that shall be used as a basis for further analysis and description of the mobility process in the remainder of the thesis. Our adaptations of the model by Digmayer et al. [97] are marked with *.

Before the trip In this phase, the *starting point* of a trip is in the focus where usually the preparation for a trip happens, e.g., trip planning, or booking.

During the trip The phase is comprised of multiple steps that allow the description of getting from the *starting point* to the *destination*:

1. *Way to station A (the first mile)*: The way from the starting point to the first station or transfer point is often different from other *segments*. It often covers a short walk or drive to a nearby public transport station, a rental spot, or a shared vehicle parking [355].
2. *At station A*: Station A is considered as the point where the intermodal trip starts.
3. *On the move**: This step describes the movement on the first segment from station A to a station B.
4. *At station B**: The station B stands for all transfer points and stopovers of a trip. For an intermodal trip, there must be at least one station B where the mode of transport is changed.
5. *On the move**: Between two stations, there is always a phase related to an actual movement.
6. *At station C*: Station C denotes the final station of a trip where the last mile to the destination starts.
7. *Way to the Destination (the last mile)*: Like the first mile, the last mile is often a short walk to the actual destination.

After the trip In that phase, trip-related activities at the *destination* occur, e.g., a recapitulation of the journey, or checking the costs.

Between trips* In the time between trips, (often unconscious) activities for maintaining the self-determined mobility take place. Those activities can be, e.g., gathering information on mobility services or exercising to preserve the necessary physical health.

For covering the first and last mile (e.g., to the nearby public transport station, or the parked private vehicle), walking is the predominant mode of mobility. Walking is also considered as “natural bridge” [136] at transfer points. In this thesis, walking is considered as an own mode of transportation for an intermodal trip, when it lasts more than 10 minutes for the user as Olvera et al. [292] proposed it.

3.1.2 Usage of Intermodal Mobility

In the context of the project *UrMo* (Urban Mobility)[1], a survey with 1,098 responses on the intermodal behavior of households in Berlin was conducted in 2016 [293]. Their results show that in Berlin, about 58 % use a combination of different modes of transport to get to work or

---

[1] https://www.dlr.de/vf/en/desktopdefault.aspx/tabid-2974/1445_read-42208/, accessed February 20, 2019.

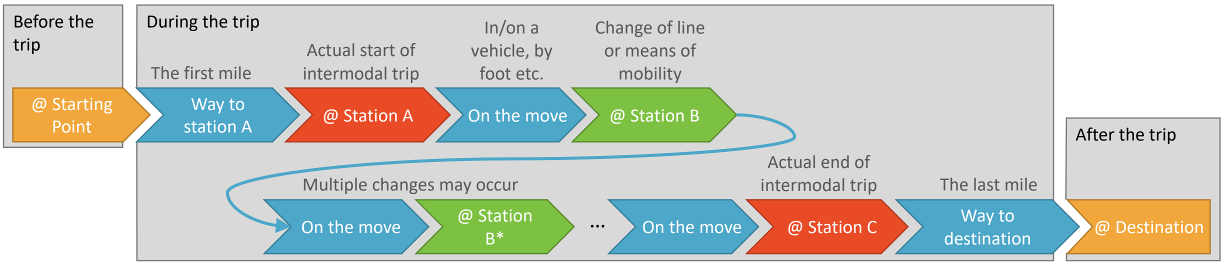


Figure 3.2: A generic intermodal mobility process is composed of at least one *station B* at which the means of mobility is changed. When only a line change occurs, it is strictly speaking a unimodal mobility process. The orange fields indicate the starting point and the destination. Blue fields stand for movements. The red fields indicate the first and the last location of the actual mobility process. In order to get to the station A, the first mile needs to be covered. To get from station C to the destination, the so-called last mile needs to be travelled. All green fields indicate transfer stations in the intermodal mobility. The visualization is adapted from Digmayer et al. [97]; colors and the station B handling have been added in this work.

education from time to time, compared to 70 % that cover this way with a single mode. Daily, 31 % are traveling intermodal and 40 % unimodal. The most common intermodal journeys (48 %) are a combination of different means of public transportation (e.g., bus, tram, or subway). A combination of bike and public transport is used by 22 % of the respondents, followed by car and public transport with 7 %.

A study[2] by the American Public Transportation Association (APTA) in 2013 examined the mobility behaviors and mindset of the millennial generation (people born between 1982 and 2003). Although driving a car was the most preferred mode of transportation, walking was by far the most frequently chosen transportation option. Directly after the second most used mode of transportation *driving a private car*, the public transport options *bus*, *subway*, and *commuter rail* were chosen. For 25 % of the trips, private bikes are used. Car and bike sharing are employed for 10 % to 15 % of the ways. The choice of transport mode is heavily dependent on the situation. While traveling with kids or needing to transport objects, privately-owned cars are mainly used. When the weather is nice, or one is into exercising, walking is the preferred mode. For getting to work or school, people prefer public transport. In that case, the advantage of working during the commute was mentioned. On average, three different transfer options are used when an intermodal trip is made, which is the case a few times per week for 69 % of the millennials.

> “ [Car access] enables older people with physical limitations to still live independently and participate in normal daily activities, and as such the car can act as a compensation tool for functional limitations. ”
>
> *Haustein [155, p. 18]*

---

[2] https://www.apta.com/resources/reportsandpublications/Documents/APTA-Millennials-and-Mobility.pdf, accessed February 25, 2019.

Haustein [155] performed a study with 1,500 people aged 60 years and above. The results showed that the usage of transportation modes is heavily dependent on people's situations. The people can be clustered in four mobility types: *captive car users*, *affluent mobiles*, *self-determined mobiles*, and *captive public transport users*. *Captive car users* have good access to a car, which is used to get around since there are very few facilities nearby that can be reached on foot. These users perform 78 % of the trips by car and have a negative attitude towards public mobility, as well as walking and cycling. People in the group of *affluent mobiles* have a very high availability of cars, the highest income of the four groups, and a vast social network. They perform 66 % of their trips by car and 14 % by bicycle. 41 % of the trips by *self-determined mobiles* are by car. With 22 %, they have the highest usage of bicycles in their mobility. The *captive public transport users* are the only group with significant use of public transport (19 %). Besides the 41 % of trips that are done by car, their second frequently used mode of transportation is walking.

3.1.3 Trends in Infrastructure and Mobility

A well-developed infrastructure and a certain choice of mobility service operators and means of mobility are essential to intermodal mobility. In this section, we want to focus on the trends in the mobility sector [264].

Analyzing the trends allows us to estimate the future of mobility, and to focus our research on directions that get more and more relevant. The trends are important input factors for our mobility scenarios that we derive in Section 3.3.

Vehicle Electrification

In the last few years, the supply of and demand for electrified cars got momentum. In 2018, the mark of 4 million in overall electric vehicle (EV) sales (including plug-in hybrid electric vehicles (PHEVs) and electric busses) was surpassed — with the expectation to reach 5 million only six months later[3]. A similar trend in supply and demand can be seen for light EVs, such as e-bikes or e-scooters.

So far, vehicles with internal combustion engines typically refuel at gas stations along their regular route. However, the charging stations for EVs have their highest value at places where the vehicles are parked for a long time innately, e.g., at home, at work, in public, or along highways for longer trips [50]. Sufficient chargers in those areas can be easily implemented for new settlements. However, retrofitting chargers is quite a challenge since new electrical power supply lines need to be installed, or existing ones must be replaced in order that the additional power can be

---

[3] https://cleantechnica.com/2018/09/03/4-million-electrified-vehicles-sold-globally-5-million-expected-in-6-months-bnef/, accessed February 21, 2019.

delivered [119]. Besides the power supply for the charging station, the connection of the EVs to the charger can also be challenging, especially for the fast chargers[4].

Shared Mobility

Shared mobility is mainly shaped by car sharing, bike sharing, on-demand ride-hailing, and ride-sharing. The services can either be operated by professional operators or be organized in a peer-to-peer manner.

Car and bike sharing enable access to vehicles as needed. The sharing can be either *station-based* or organized in a *free-float* manner. While the vehicles have to be picked up and returned to particular places (stations) in the station-based case, the free float approach allows parking the vehicles in defined areas (e.g., on-street parking in a specific urban area). The reservation of the vehicles is usually only possible for a short time (e.g., only several minutes). Billing is done on a usage basis, e.g., per driven distance, used time, or a combination of both.

On-demand ride-hailing is comparable to a taxi service. However, the rides are usually executed by private people in their private vehicles that received the ride request via an online platform. Examples of ride hailing-services are *Uber*[5], *Lyft*[6], or *DiDi*[7]. In several countries, passenger transportation laws prohibit commercial ride-hailing [152].

In contrast to ride-hailing, where the requesting user defines the ride, ride-sharing or carpooling means bringing together drivers and passengers that have similar starting points and destinations, or at least share a certain common path. The matching of drivers and passengers is usually done via ride-sharing platforms, e.g., *BlaBlaCar*[8].

Autonomous Driving

Autonomous driving in the form of self-driving vehicles without a driver (Society of Automotive Engineers (SAE) J3016 levels 4 and 5) is currently under development and expected to be available for specific use cases in the early 2020s. For intermodal mobility, autonomous driving can have multiple effects:

- Driverless ride-hailing will be established. Since no driver needs to be paid, this form of individual traveling can get cheaper.

---

[4] http://quantumworks.com/which-dc-fast-charger-standard-will-win-or-will-regions-have-to-have-multiple-standards-or-will-the-world-be-divided-into-regions-using-different-standards/, accessed February 21, 2019.

[5] https://www.uber.com, accessed February 21, 2019.

[6] https://www.lyft.com/, accessed February 21, 2019.

[7] https://www.didiglobal.com/, accessed February 21, 2019.

[8] https://www.blablacar.com/, accessed February 21, 2019.

- The time during driving with a vehicle can be used for other activities. For example, commuters could switch back to individual driving since productive activities would then also be possible [248].

In the remainder of the work, it is assumed that drivers need — at least partially — to steer the vehicles themselves.

Connectivity

The Internet of things (IoT) is also a driver for smart mobility [423]. Sharing operators are already relying on connectivity to track their vehicles and show customers where suitable vehicles can be found. In ride-hailing use cases, the platforms use the real-time location and occupation data of the different the fleet in order to distribute the ride requests.

IoT applications also have the potential to reduce the traffic in inner city areas, which is caused by the search for a parking spot. Parking lots equipped with sensors can determine whether there are free spaces, and on-street parking information can be derived in real-time from the sensors embedded in passing vehicles [259].

V2X communication allows road safety applications with increased reliability (e.g., forward collision warnings via the positions and sensor data communicated between the vehicles) as well as efficiency optimization of traffic, for example, by communication with red lights and presenting green light optimized speed advisory (GLOSA) information to the driver. It is also a key enabler for fully autonomous vehicles [164]. For example, when two autonomous vehicles are in a deadlock situation, direct communication can be used to solve the situation.

Sustainability

Growing concerns over air quality in large cities cause discussions on the sustainability of everyday traffic [72]. As counter-measures, the development of public transportation, the promotion of EVs, or the extension of bike lanes[9] are under consideration.

3.2 User Perspectives on Mobility and Mobility Behavior

In order to create a vision of the future (intermodal) mobility, we examine the users' perspectives on the current mobility situation. We start with an analysis of main mobility barriers and an overview of factors for choosing a trip. The results provide a basis for the identification of the

---

[9] https://www.theguardian.com/environment/bike-blog/2017/dec/01/bike-lanes-dont-clog-up-our-roads-they-keep-london-moving, accessed February 21, 2019.

fields where users require assistance, or where mobility behavior can be influenced to be more comfortable, effective, and sustainable than today.

3.2.1 Barriers and Hurdles

According to the 2018 United Nations (UN) report on the world's social situation [394], mobility barriers can be divided into two main fields: physical and communication barriers.

Physical barriers can be described as "structural obstacles in natural or manmade environments that prevent or block mobility (moving around in the environment) or access"[10]. Besides curbs, steps, or narrow entrances, also appliances that need special movements to be used (e.g., climbing into a vehicle) can be summarized as physical barriers.

Communication barriers can be summarized as the lack of human contact persons, as well as the inability to use certain information and communication technology. Especially since digital services more and more replace contact persons, the problem is more and more shifted towards the ICT aspect. Problems using ICT can be the lack of access, missing knowledge on its usage, or impairments that prevent using it (e.g., visual or auditory impairments).

Both types of barriers are mainly affecting people with limited physical or mental abilities. For that reason, most studies are focused on older people [215, 317, 360] and people with disabilities [332, 382].

A survey of 104 people over 65 years identified the following central barriers [360, p. 13ff]:

- Stairs: 12.5 % responded that they could not climb a single step. For 18.3 %, no more than ten steps can be taken. Although alternative ways without steps may be available, those are often not labeled.
- Missing public restrooms: many respondents mentioned the lack of public restrooms. As with the steps, in many cases, available restrooms are often not labeled.
- Transport of objects: missing physical support, lacking or defect elevators, as well as too little space in means of public transportation were mentioned as factors that make the transport of objects difficult. 12.5 % of respondents need support to load their purchases into their vehicles. 16.3 % require support for transporting objects to their place and 20.2 % to get these objects finally into their apartment.
- Ticket vending machines: typical problems were related to touch display-based ticket vending machines. Respondents mentioned that the reflecting screens were often hard to read during daylight. UIs with long responding delays and without immediate feedback made the operation also difficult. Nested screens and complex views with many options also cause confusion.

---

[10] https://www.cdc.gov/ncbddd/disabilityandhealth/disability-barriers.html, accessed February 18, 2019.

- Trip planning: trip planning is mainly done manually with printed timetables and maps. Access to Internet-based trip planning platforms is not used due to missing Internet access, missing knowledge, or the difficulty of using these.
- Vehicle operation: besides physical difficulties with getting into and out of vehicles as well as loading and unloading of vehicles, the difficult operation of in-vehicle infotainment systems was mentioned.

Strohmeier [375] also conducted a study with 68 people aged 65 years and above. In the study, 1,915 trips have been tracked and analyzed. The results were clustered into six categories with subcategories. These categories have been used as the basis for the overview presented in Table 3.1. The list is not only valid for elderly users. The severity of the barriers is strongly dependent on the individual situation, capabilities, and attitude.

Table 3.1: Barriers for mobility divided into categories as defined by Strohmeier [375]. We extended the list with our own findings and information from related work.

Category	**Subcategory**	**Barrier Characterization**	**Barrier Examples**
Transportation	Public transport	Inadequacy of waiting areas	Waiting areas are dirty. Seats are missing or broken. Schedules are missing, outdated, or not legible.
		Unexpected long waiting times	Schedules are not harmonized. Delays are not communicated.
		Difficulties at entering the vehicle	Gaps between platform and vehicle. Missing low floor vehicles.
		Many and difficult transfers	Trips require too many transfers. Transfers are difficult to perform. There is too little time for the transfer.
		Too many transfers	Vehicle drives off immediately before a seat can be taken. The vehicle has too few seats.
	Pedestrian (incl. walking aids)	Difficulties at crossings	Green phases of red lights are too short. Vehicles are driving too fast so that the street cannot be crossed. Missing traffic refuges.
	Car	Congestion	Too much traffic in the streets make driving difficult.
		Insufficient parking possibilities	There are not enough parking spaces or parking spaces are too narrow.
	Bicycle	Missing bike racks	Suitable spaces for parking the bicycle are missing. Bike racks are always full of old and unused bikes.
	Car Sharing	Unknown vehicle types	The operation of unknown vehicle types is difficult (e.g., the HMI, or automatic/manual transmission). Adjustments and settings need to be done individually again and again.
		Distant or unclear operating area	The operating area of the free-float vehicles is not clear or too distant to the starting point or destination.
	Bike Sharing	Difficult adjustment	The bike is not adjusted to the user's needs, and the adjustment is challenging.
		Distant or unclear operating area	It is not clear where the vehicles can be parked. The parking stations are too distant to the starting point or the destination.
Interaction	Conflicts	Pedestrian vs. vehicles	Vehicles are parked on the sideways blocking the way for the pedestrian. Vehicles are driving too fast to cross the street safely.
		Pedestrian vs. bicycles	Bikes on a shared pedestrian/bike paths are driving very fast and cause fear.
		Bicycles vs. cars	Bicycle riders ignore the traffic rules (e.g., riding the wrong direction in one-way streets or ignore red lights). Vehicles are parked on bike lanes.
		Pedestrian vs. pedestrian	In crowded areas, people are blocking the ways or collide due to inattention or distraction (e.g., due to smartphone usage).
		Near accidents	Aggressive mobility behavior in the streets are causing near accidents.
Information	Before the trip	Difficulties at planning a trip	Printed information is not available or too complex. No access to ICT for accessing the digital trip planning platform.
	During the trip	Unmarked station	Due to missing signature, one does not know where the station is or whether it is the station for the desired direction.
		Missing or poor announcement of stations	Missing and mumbled announcement could lead to missing the desired station.
		Missing or wrong schedules	Schedules at stations or in vehicles can be outdated, illegible, or missing.
		Inadequate signposting	Finding the correct station, line, or way is difficult due to missing, misleading, or illegible signs.

Table 3.1: Continuation from previous page.

Category	Subcategory	Barrier Characterization	Barrier Examples
		Missing or untrained personnel	There is nobody to ask in case of problems or uncertainty. The available personnel cannot provide the necessary information.
	After the trip	Unknown height of expenses	A journey can be composed of several payments; keeping track of these is difficult and can lead to the fear of being ripped off.
Environment	Weather	Rain	Rain makes the pavement slippery. One gets wet. The view is obstructed by heavy rain.
		Snow	Snow and icy road conditions make the pavement slippery. The view is obstructed by heavy snowfall.
		Fog	Fog can obstruct the view and lead to disorientation.
		Smog	Smog can cause illness.
Personal	Safety/Security	Fear	In certain areas, one feels unsafe due to possible assault or theft.
		Insecurity	One can feel unsafe because other traffic participants are not paying enough attention to traffic.
		Darkness	One can feel unsafe in darkness, as one cannot see every other traffic participant and vice versa.
	Wealth	Expensiveness	Maintaining a vehicle is too expensive. Fares and ticket prices are too high
	Capacities	Physical impairments	Climbing stairs or just one high curb is not possible. It is difficult to get into a vehicle. One cannot move fast enough.
		Auditory and visual impairments	Seeing or hearing is limited. Approaching vehicles cannot be noticed early enough. Navigating is very difficult. Steps or other obstacles cannot be seen.
		Cognitive limits	Too much information needs to be processed in traffic (e.g., road signs in dense urban areas). The schedules and tariff options are too complex to comprehend.
Built Environment/ Infrastructure	Insides	Unmarked obstacles	Beginning and end of stairs are not highlighted. Glass doors cannot be noticed.
		Complex architecture	Buildings are difficult to navigate or the ways are very long.
		Missing handrails or handles	Handrails to provide hold are not available or not suitable. Handles, e.g., to get into or out of a vehicle, are not available or are not suitable.
		Missing elevators	The building does not have an elevator in case one cannot climb stairs or needs to transport something.
	In the street	High curbs	Curbs are too high to climb with walking aid.
	Crossings	Too wide distance	Refuge islands are missing.
		Too short time	The green phase of red lights is too short.
	Stations	Difficult access	Stations can only be reached via stairs. The signposting is missing or misleading.
	Construction site	Blocked ways	Due to the construction site, the street side has to be changed.
	Road network	Missing sidewalks	Sidewalks are completely missing or end half-way.
		Insufficient bike lanes	Bike lanes are not available at all or are too narrow.

The list of possible barriers is also influencing the factors for choosing a trip or modes of transportation. For that reason, several points are also part of the analysis of factors for choosing a trip in Section 3.2.2.

3.2.2 Factors for Choosing a Trip and Modes of Transportation

The factors for choosing a particular trip and corresponding modes of transportation can be various. Akhavan and Vecchio [5] and Bamberg et al. [16] differentiate between people-based and place-based factors. People-based factors are endogenous variables such as age and gender. For example, females try to avoid public transport during nighttime when traveling alone, and older adults “prefer the modes with more independent mobility [e.g., taxis]” [5, p. 12]. Physical and cognitive abilities combined with the perception of mobility and means of mobility, as well as the willingness to move, are other determinant people-based features. Income and wealth are influencing the possibility and the choice of transportation mode, especially when people are rather poor [145]. Place-based features focus on the spatial settings, such as the physical features of spaces, the transport infrastructure, or the available mobility services.

Tyrinopoulos and Antoniou [392] propose a structural equation model which takes, again, the factors age and gender besides latent variables into account. The latent variables were the degree of parking, transportation link quality, congestion, travel distance/time, and travel costs. In their research, they tried to identify the main reasons why people are discouraged from using public transport. The main reason was that people considered public transportation as very unreliable, although this was, objectively seen, not the case. They conclude that this is caused by the missing perception of control with public transport. The research from Gardner and Abraham [131] supports this theory. For mitigating this problem, the provision of real-time schedules and more service information is proposed. Another dominant reason was the crowding in means of public transport and transfer points. Especially females named this as a reason for avoiding public transport.

In a study by Haustein [155], age, physical health, and the size of the social network have been identified as determining factors for mobility. The choice of transport mode depends on the availability of vehicles, the weather resistance, and the attitudes towards using specific modes. The attitude includes factors such as control, autonomy, excitement, and privacy.

In Figure 3.3, we give a summary of the most critical factors that may influence mobility behavior and the choice of transport modes. The summary is based on findings in the literature [5, 16, 131, 155, 293, 392] and discoveries in the mobility project Personalisierte Mobilität, Assistenz und Service Systeme in einer alternden Gesellschaft (PASSAge).

Some of the presented factors are in most use-cases related to each other. For example, the personal weather resistance and the current or forecast weather play a role in choosing *walking* or *biking* as part of a trip. Costs and personal income also heavily influence most trip choices [145]. Having to transport a massive object will most likely lead to using a car.

> “[T]here are no static pro- or contra argumentations [sic] for or against a specific means of transportation. Mobility behaviors are not a question of faith or affinity to specific means of transportation. Rather, acceptance follows a highly context-related and situational dependent view. Persons are to a much lesser extent committed to a specific vehicle type or form or modality; they rather do respond to individual preferences and situational needs, be it ecological or economical or efficiency or comfort-related.”
>
> *Ziefle and Wilkowska [431, p. 142]*

For many factors, it is difficult to define how they will influence the choice of a trip and modes of transportation. That is due to the individual personal context. Ziefle and Wilkowska [431] conducted a study on pro and con arguments for choosing public transportation. For example, a pro argument is *restfulness*. The corresponding con argument is *stress*. The perception of a *restful* and a *stress* situation is, however, very dependent on the context and the situation.

For that reason, our research focuses on solutions that are user-centered and take individual preferences into account. Besides, all our proposed assistance systems shall be designed in a way that its user may have a positive effect, but people that choose not to use the assistance system do not have a detriment. For example, our proposed automotive user interface training in Section 5.3 could be linked to engine start permission of car-sharing vehicles, so that users have proven their knowledge about operating the vehicle before they can drive. That would heavily penalize users that choose not to use the assistance function since they could not use the vehicles then.

Figure 3.3: Factors influencing the choice of a trip and modes of transportation are various. Besides personal context, the availability and quality of public transportation, the trip context, and the infrastructure play a central role.

3.3 Deriving Challenges and Potentials from Intermodal Scenarios

Based on the data from the last sections, we derive challenges and potentials for intermodal mobility in this section. For this, we created engaging personas [261] that traverse typical intermodal scenarios. The basis for the analysis is the process model described in Section 3.1.1.

> “Personas are a critical method for orienting design and development teams to user experience. [...] Personas can engage teams in thinking about users during the design process, making efficient design decisions without inappropriate generalization, and communicating about users to various stakeholders.”
>
> *Matthews et al. [261]*

Personas can be seen as a kind of archetypes that represent ‘typical’ user groups [390]. They are created based on real data from multiple individuals, which is clustered to create a fictional character with properties many individuals of a particular user group share. An advantage of working with concrete personas instead of user groups is the better tangibility. Asking “how would Anna react when the trip planning app shows incorrect data” is less abstract than asking “how would people in above 65 years with walking impairments react when the trip planning app shows incorrect data”.

A specialty of *engaging personas* — that we use in this thesis — is that one also describes emotions and backgrounds that are not directly related to the goal of the product or workflow to analyze. That way, the persona can become more ‘real’ and engaging.

We created the personas based on data we gathered during surveys in the project PASSAge as well as from literature research on typical user groups [23, 34, 156, 257].

3.3.1 Personas for the Mobility Scenarios

Anna, 74 years, Retiree

Anna is a 74 years old retiree. She lives alone in her small two-room apartment in the city of Munich. She has problems to walk longer distances. For that reason, she uses a walking aid. She cannot climb more than ten steps. In her house, she can use the elevator. She receives a decent retirement pay. For her daily mobility in the city, she has an annual ticket for the inner city. She possesses a smartphone but sometimes has problems reading the small texts and with understanding the technical messages. Her two children support her with technology-related problems and help her once a week to buy convenience goods.

Marcus, 45 years, Manager

Marcus is a 45 years old manager in a medium-sized engineering company. He lives in a house in the suburbs of Munich. He is married and has two children that go to school. He has to travel a lot, usually by rental or company cars. Although he usually is under time pressure, he attaches great importance to comfort during traveling. Since training comes short very often, he tries to be active during his workday.

Vera, 23 years, Student

Vera is a 23 years old media communication student, who lives in a one-room apartment at the city boundary. Her university is in the inner city. She does not own a car but has an old bike she uses to get to the next suburban train station. She buys monthly tickets during the lecture period. She is a heavy smartphone user and likes connecting via social media applications. She is registered at several bike- and car-sharing operators. She is into exercising and pays attention to a sustainable lifestyle.

3.3.2 Example Scenarios of Intermodal Trips

With the personas at hand, we next defined typical mobility scenarios in which the personas are acting as active characters. Although personas and scenarios are often seen as two distinct user-centered design thinking methods [283, p. 95], connecting both methods can be beneficial, when one wants to make user behavior in a specific scenario more comprehensible. Especially with engaging personas, the developers can empathize with a persona and understand why one would react in the way as it is described in the story of the scenario.

The example scenarios assume a well-developed infrastructure and an established public transportation system.

The situation depends on people's individual abilities, the mobility context (purpose of the trip, time constraints, start, and destination), the available and usable means of mobility, and external factors such as the time, weather, or delays.

Scenario 1: Anna Travels to the Mountains

Figure 3.4 depicts Scenario 1. The start is at Anna's home in the inner city of Munich. The destination is a mountain in the Bavarian Prealps[11]. Since the persona Anna requires a mobility aid to cover longer distances, she uses her rollator. To get to the mountain, Anna has to use the

---

[11] For better conceivability, the mountain *Brauneck* in *Lenggries* was used here.

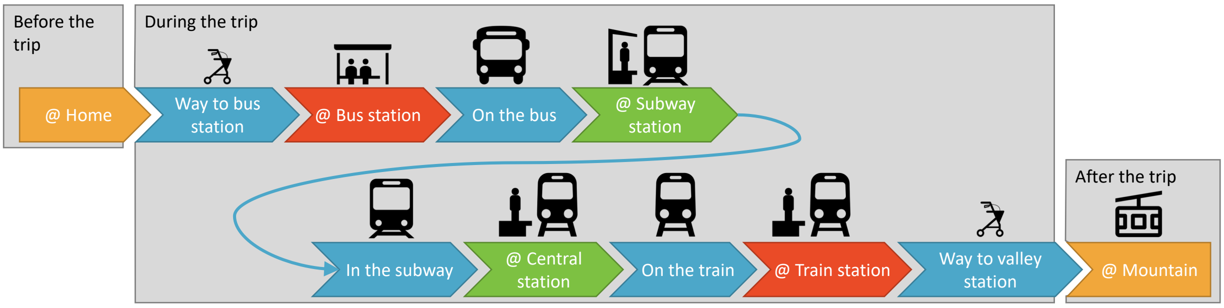


Figure 3.4: Scenario 1: *Anna Travels to the Mountains*. The first mile is traveled with the mobility aid rollator. After a short journey by bus to the subway station, she takes the subway to the central station. A train is used to travel to the mountains. The mobility aid needs to be carried all the way.

train from the central station. In order to reach the central station, a combination of bus and subway is chosen here.

Anna must take her mobility aid with her over the whole journey. That means she has to get on and off the bus, the subway, and the train with her rollator. In this scenario, the first and the last mile is covered by walking with the rollator. Thus, she needs a quasi-barrier-free environment to get from the start to the destination. Anna has a public transport subscription that covers the journey to the central station.

Scenario 2: Marcus Travels with Luggage

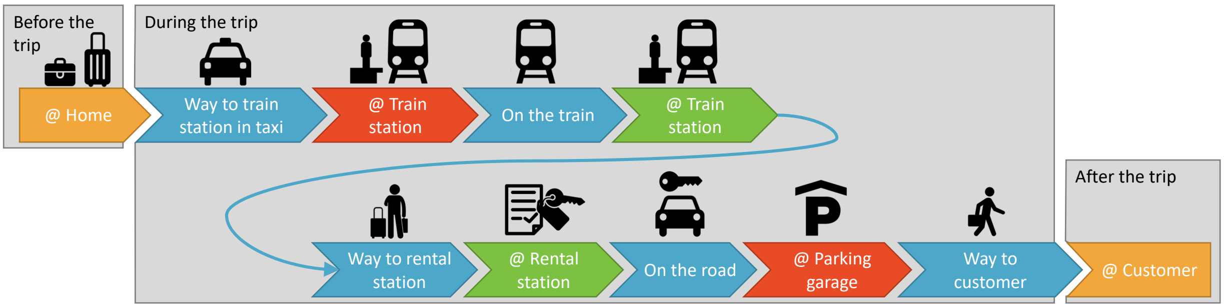


Figure 3.5: Scenario 2: *Marcus Travels with Luggage*. For the business trip, a suitcase needs to be carried. After a short ride to the train station, he takes a long-distance train to another city. There, a rental car is picked up, to get to the destination.

In Figure 3.5, Scenario 2 is presented. Marcus goes on a business trip of several days' duration to a different city. Since he has to carry the luggage, he does not walk to the train station but calls a taxi. He can take a train that travels directly to the desired city. Since the customer, he visits on his business trip, is located in an industrial park outside of the city, he booked a rental vehicle in advance. The rental station is close to the train station so that he could walk there. After signing the contract, he gets the keys and can fetch the vehicle. After driving to the address of the customer, he parks the rental car in a parking garage and arrives at the customer.

Marcus has a discount card for traveling with the railway company and for the car rental company. The taxi needs to be called in advance (e.g., already in the previous day's evening when starting a journey in the morning).

Scenario 3: Vera Uses Sharing Concepts

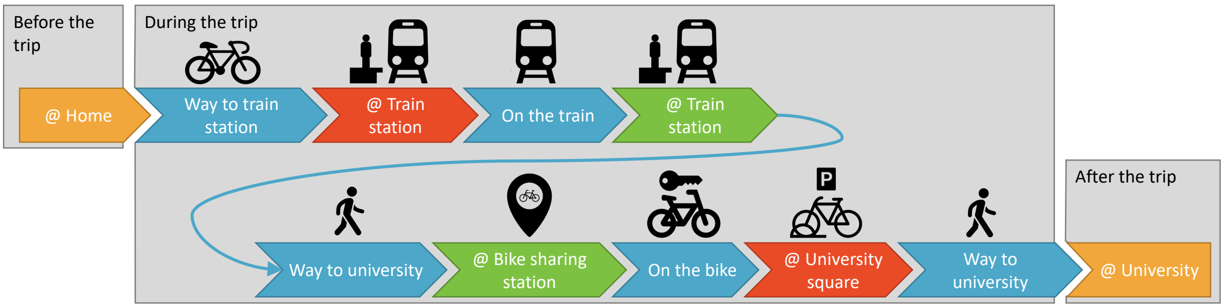


Figure 3.6: Scenario 3: *Vera Uses Sharing Concepts*. A privately-owned bicycle is used to get to the suburban train station. After taking the train to the city, a walk to the university follows. However, when passing a bike-sharing station, a sharing bicycle is spontaneously used to drive the rest of the journey. The sharing bike can be parked outside of the university.

Scenario 3 is shown in Figure 3.6. Vera is on her way to university. She covers the first mile with her private bicycle. After parking and locking the bike at the provided bike racks, Vera takes the suburban train to get in the city. From the train station in the city, she usually walks to university. However, on this journey, she came by a parked bike-sharing bicycle. Since she is a registered customer of the bike-sharing operator, she can spontaneously take the bicycle and cover the remaining way with it. Arrived at the university square, she can park the vehicle somewhere on the sidewalk and end her booking. Afterward, Anna can walk the last mile into the university.

She uses a trip planning application only to get information on current delays of the suburban train so that she does not have to wait at the train station. The booking process for the bike-sharing vehicle is done via smartphone.

3.3.3 Challenges and Potentials of Intermodal Mobility

In the following, the scenarios will be taken as the basis for identifying concrete research gaps. The final determination of topics that are examined in this thesis is given in Section 3.8.

According to numbers presented by Gebhardt et al. [136], intermodal mobility usually only happens in larger cities and nearby areas with some kind of public transportation or where private transportation operators offer their services. The trends sharing, e-hailing, and electric-driven micro-mobility [47] have the potential that intermodal trips can be made possible for more and more people in a larger area as these concepts can fill gaps in public transportation. Working intermodal mobility concepts promise sustainable and socially fair mobility [182].

> “An optimal transport system provides diverse mobility options and incentives to use the most efficient option for each trip, taking into account all benefits and costs.”
>
> *Litman [235, p. 23]*

However, good and reliable intermodal mobility requires also support processes, such as trip planning, payment, or sharing. For the user, the mobility process does not begin with the departure from the start location, but in most cases with the trip planning process. A big challenge is the weighting of different factors for choosing a suitable intermodal route. Especially in areas with well-developed public transportation, there are often several route alternatives that would generally fit the users' needs. When individual means of mobility (including the mentioned micro-mobility, e.g., in terms of mobility aids) are further taken into account, the number of alternatives may explode [433]. For that reason, a single connected mobility service incorporating all possible mobility alternatives would be the best for the users. However, when a concrete trip needs to be planned, the trip and user context shall be used to present only those alternatives that fit the requirements in the individual situation.

As seen in mobility scenario 3 (*Vera Uses Sharing Concepts*), users need information also during the journey. In that scenario, the persona *Vera* did not plan an actual trip, but only uses the real-time delay information for a single means of mobility. Finding the correct public transportation line and the aimed vehicle is here a major challenge. Gardner and Abraham [131] concluded in their analysis on reasons of commuters to take the car that “[g]reater access to service information and more interactive services (e.g., real-time timetable information) may enhance perceptions of control over journey management.”

Looking at the mobility trends, such as car-sharing or electric micro-mobility, the main requirement for engaging with these trends is proper guidance for the first use and ensured support afterwards [22, 79]. The guidance does not necessarily have to be provided by human personnel, but could also be provided in digital form [163]. In scenarios 2 (*Marcus Travels with Luggage*) and 3 (*Vera Uses Sharing Concepts*), this could be the first use of a car rental system or problems with a bike-sharing vehicle.

In order to maintain self-determined mobility, regular exercising and training are necessary. As indicated in scenario 1 (*Anna Travels to the Mountains*), mobility aids offer the potential of performing longer trips for people with limited physical mobility. However, in order to benefit from mobility aids, users need to know how to use them and to exercise regularly [357].

Similar holds true, when users often switch between vehicles from different manufacturers or at least different models (cf. scenarios 2 and 3). Functions beyond those directly related to driving or relying on the operation of HMI may remain hidden since users do not know how to operate them [138, 426]. Another drawback of these situations is the lack of user context information of the IVISs since no user data may be available.

3.4 User-Centered Requirements on Using Personal Mobile Devices for Mobility Assistance

In order to create mobility assistance systems that fit the individual requirements, we performed a systematic analysis of those requirements. For this purpose, the requirements have been clustered in the following categories as proposed by Vogelsang et al. [402]:

1. General travel-related requirements,
2. Travel task-related requirements,
3. Transport-related requirements, and
4. App-related requirements.

The results are depicted as clustered tree diagrams in Figures 3.7 to 3.11. The requirements are based on literature research (sources are started in the following paragraphs) and results gathered during studies conducted in the scope of this work. In particular, the findings from studies are reflected in the deepest level of detail in the tree diagrams.

In Figure 3.7, general travel-related requirements are summarized. For temporal data, users require real-time data. The positive effect of correct real-time information on public transport has been shown, for example, by Ferris et al. [122]. Not only the number of public transport journeys per week increased, and the overall waiting times decreased, but also the feeling of safety raised in their study. In general, time-efficiency is a determinant factor for most users, and outdated or wrong data quickly leads to frustration [141]. High-quality data is generally requested for spatial data. Users desire to reduce the physical and cognitive effort for intermodal mobility [141]. Especially when having a short transfer time, stress can quickly occur when the directions to get to the next vehicle are wrong. Quality, in that case, means that the data is complete, concise, and up-to-date [30].

Requirements for tasks occurring during the actual journey are summarized in Figure 3.8. Especially for longer journeys to unknown destinations and trips with transportation means users are not usually traveling with, the trip planning is an essential part. Users prefer trip planners that include all available means of mobility, as this transparency gives them the “illusion of control” [132, 249]. Also, a realistic comparison of travel times between taking a car, public transportation, going by bike, or walking has a strong influence on the route choice [343]. Especially with the rise of sharing concepts, users would prefer platforms that include the travel options of all available operators [40].

Another travel task-related requirement is the support of purchasing a ticket or performing a booking. That does not necessarily mean offering electronic ticketing. Providing information about total costs, ticket validity, or rental conditions can also heavily influence the choice of route and reduce the complexity when planning a trip [109]. When transfers are necessary, users require to know when and where the transfer should happen. Additionally, they need information on the duration of and the available time for the transfer, and whether the transfer is possible in a barrier-free way. Route guidance and navigation should be provided for all segments where the user has to travel individually. When electric-driven vehicles are used, finding compatible and free charging locations is an essential function [306].

Requirements related to the respective means of mobility are summarized in Figures 3.9 and 3.10. Most of the points have already been touched in the previous paragraphs, but are presented more into detail here. For example, when walking or biking, the path texture and the weather are more important than when traveling with public transport. For public transportation, the real-time data on the vehicle's location (address as well as current/next station), delay, and utilization can heavily influence the choice of route [122]. For sharing concepts, information on the number and the locations of available vehicles is required. Information on the equipment and vehicle state of the offered vehicles are also from interest to the users [298].

A convenient way to fulfill the requirements on real-time information is to provide a mobile application or online system that can be accessed via the user's PMD [268]. Requirements for such an application are summarized in Figure 3.11. For the design of the HMI, the principles of universal design [359] are a solid foundation to create an application that can fulfill the needs of the different user groups (e.g., people with digital experience, novice digital assistance users, or people with visual or auditory impairments). The usage of names, formulations, and symbols that are consistent within the information system and with the actual names and symbols used in the real mobility situations simplifies the navigation process. For mobility users, such a digital system must consider their context. That can be factors which directly influence the mobility, such as walking speed or accessibility needs, personal preferences (e.g., preferred transportation modes), or the availability of public transport subscriptions or driver's licenses [358].

Besides individual context, the journey and route context are also essential to provide proper or proactive support before or during a journey. Examples for information before journeys are reminders and notifications when delays or cancellations occur [434]. In order to provide proper information for the current or next trip step, the current step needs to be recognized automatically. With that data available, support for the next mobility step can be offered in time (e.g., instructions for using a sharing vehicle for covering the next segment). Navigational support from the current location to the next station or waypoint is also a central requirement. In order to offer the best benefit for the user, the provided information needs to match also the current mode of transport (e.g., parking information when driving a car, or the location of bike racks when traveling by bicycle).

> “The main determinants [for the choice of a trip and its mobility means] are time savings (travel and search time) and effort savings (physical, cognitive, and affective effort).”
>
> *Grotenhuis et al. [141]*

Overall, these requirements have in common that users can plan and conduct journeys efficiently with low effort.

3.5 Required Data and Possible Data Sources for Mobility Assistance Systems

As presented in Section 3.4, depending on the type and scope of a digital mobility assistance system, certain information is necessary. When looking at trip data, the most substantial part of the necessary data is temporal and spatial information. However, for the incorporation of personal context, e.g., to derive preferred routes, destinations, or modes of transportation, also health and social data are necessary. In the following, we compile a list of possible data sources by examining the context of mobility situation.

The context in mobility situations is often divided into *personal or trip characteristics* and *environment* [213, 364]. The traveling individual usually defines *personal or trip characteristics*. The personal characteristics include socio-demographic factors (such as age, gender, education, employment, or income), health, knowledge, values, attitudes, personality, as well as cognitive style [213]. The trip characteristics include the trip purpose (need or motive for the trip), the available time, the length of the trip, covered distance, the composition of the travel group, and the chosen means of mobility [124, 140]. This personal or trip characteristics domain also includes the trip and navigation history that can be used to derive preferences or to predict the behavior of users [345]. The *environment* describes the setting the individual user is interacting in and with, and includes both physical and social entities [300, 351]. That includes factors, such as the current location, weather, lighting, traffic conditions.

Krehl et al. [209] classified context relevant for traveling in five context *components* [185]:

- *Physical context*: e.g., location, altitude, orientation, movement, physical objects, weather, lighting, noise.
- *Social context*: e.g., presence of others, characteristics, roles and responsibilities, interactions.
- *Task context*: e.g., user task, multi-tasking, interruptions, the priority of task compared to the goal.
- *Technical context*: e.g., availability of infrastructure, the capability of software and hardware, sensors, actuators.

- *Temporal context*: e.g., current time/day/week/season, past and future events, duration of a task, available time for completing a task, hurried/normal/waiting.

In this classification, the health and mobility constraints are not explicitly named but are implicitly given via limitations in the physical capabilities of individuals. Compared to the clustering in *personal or trip characteristics* and *environment*, this approach is more general and not trip related. For example, *trip characteristics* would be composed of elements of the *task* and *temporal context*. In Table 3.2, we summarize the central data for trip planning assistance and name examples for data sources.

Table 3.2: Examples of data that can be beneficial for a digital mobility assistance system. The stated data sources shall give first ideas of how the information could be obtained.

Data	Description	Examples for Data Sources/Sensors
Location	The current location indoors and outdoors. Required for LBSs.	GNSS receiver, RF/light/audio beacons, optical markers with position data, (visual) odometry
Time	The current time and date of the timezone.	GNSS receiver, cellular network time, broadcast RF time signal, network time protocol, built-in real-time clock
Map data incl. enriched metadata	Maps for route calculation and navigation, including metadata such as accessibility or availability of public restrooms.	Commercial or open-source map data providers, own created maps (e.g., by SLAM [99]), crowd data
Movement and orientation	Determination of movement, the direction of movement, and the orientation of a person or object.	Gyroscope, accelerometer, magnetometer/compass, location trace, optical flow
Weather and temperature	The current weather situation and temperature of the surrounding.	Internet service (LBS), thermometer, barometer, wind sensor
Public transport information	Schedules, occupancy, real-time delay, and position of public transportation vehicles and lines.	Internet service by the operators, crowd data collection from people with devices using a certain public transportation line/vehicle
Traffic and parking space information	Information on the current traffic situation in the streets and available parking spaces.	Floating phone/car data [55], V2X data, usage prediction based on historical data, parking space detection sensors [233]
Health and fitness data	Data on the current health and fitness condition as well as the current level of stress.	Pedometer, heart rate monitor, connected scale, glucose sensor, training data of training applications, GSR sensor [13], facial expression evaluation [137], smart home sensors [239]
Preferred mobility options	Data on preferred destinations, routes, and means of mobility.	Travel history, user settings, social media likes and posts, ratings
Trip purpose and group	Information on the trip purpose and whether one travels with a group (and who). That also includes the available time for the trip.	Private calendar, option for route planning, voice/face detection
Driver's license, subscriptions, and payment	Overview of payment services one can use or is registered for. Availability, validity, and zones of available public transport subscriptions. Availability of driver's license.	Mobile digital wallet [14], settings in the user profile, setup and linked payment options
Accessibility	Data on the operational state of elevators, escalators, and boarding aids.	Self-diagnosis of technical systems with an Internet connection
Vehicles	Availability and state (e.g., charging) of vehicles that can be used for a trip.	Internet connectivity of vehicles, connected charging systems, self-diagnosis, booking systems, online fleet management [279]

Table 3.2: Continuation from previous page.

Data	Description	Examples for Data Sources/Sensors
Environment conditions	For example, the noise or the lighting of the surrounding, or the surface condition of the current path.	Light sensor, microphone, accelerometer, surface condition detection via camera [197]

By combining the available data and analyzing the history of data, comprehensive models of the user and typical trips can be created [35]. That allows adapting suggested trips and the support during trips to the requirements of the individual users in their different trip scenarios.

Today's large number of gathered data, together with the possibilities of analyzing large amounts of data (big data [62]) and automatically inferring implicit information (e.g., by machine learning approaches [322]) may cause severe ethical and privacy implications [381]. Principles of data minimization[12] should be applied whenever possible.

---

[12] https://www.iab.org/wp-content/IAB-uploads/2011/03/fred_carter.pdf, accessed September 4, 2019.

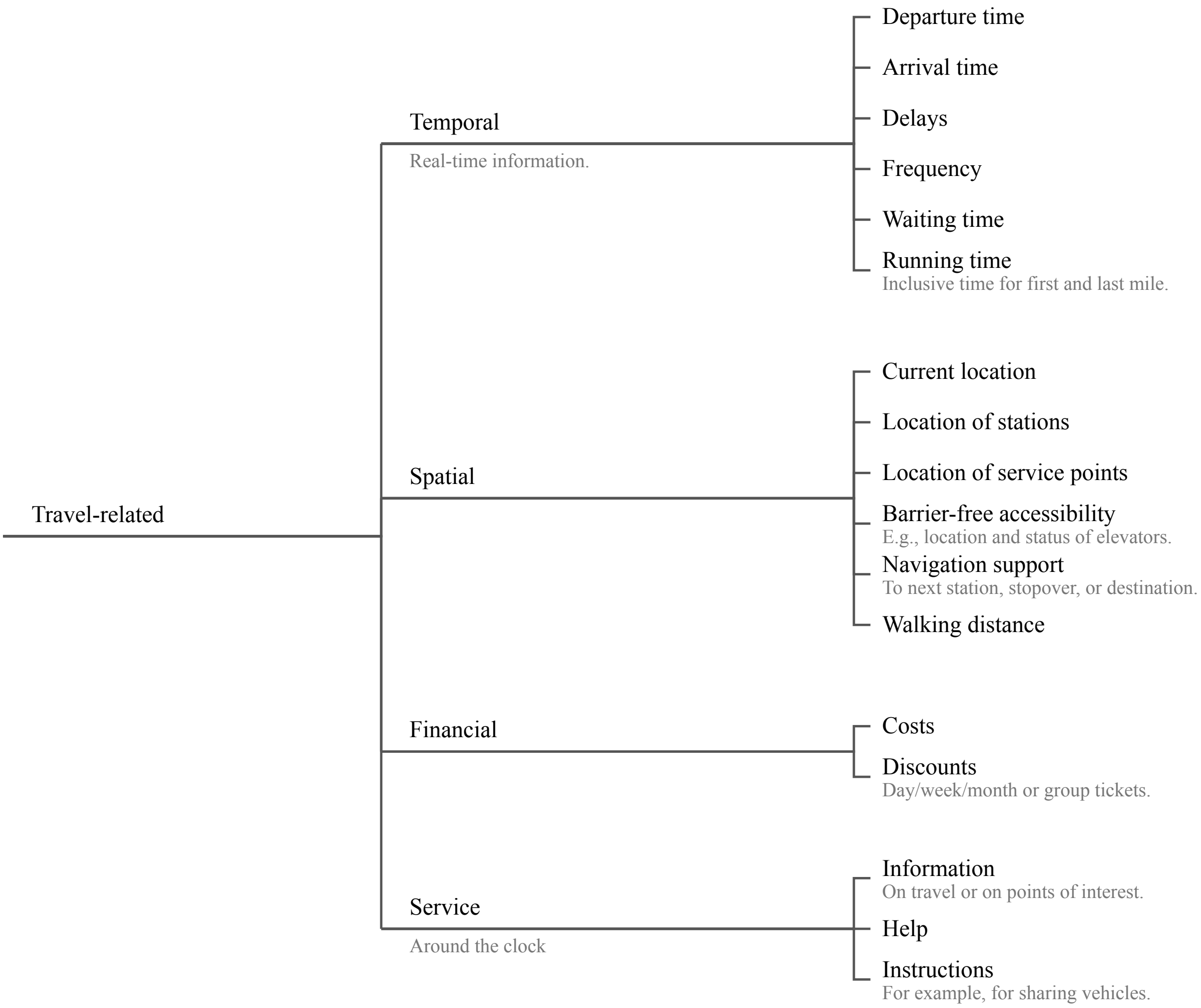


Figure 3.7: Overview of the information that is generally required for a journey. The requirements have been derived from literature research and experiences during studies conducted in the scope of this thesis.

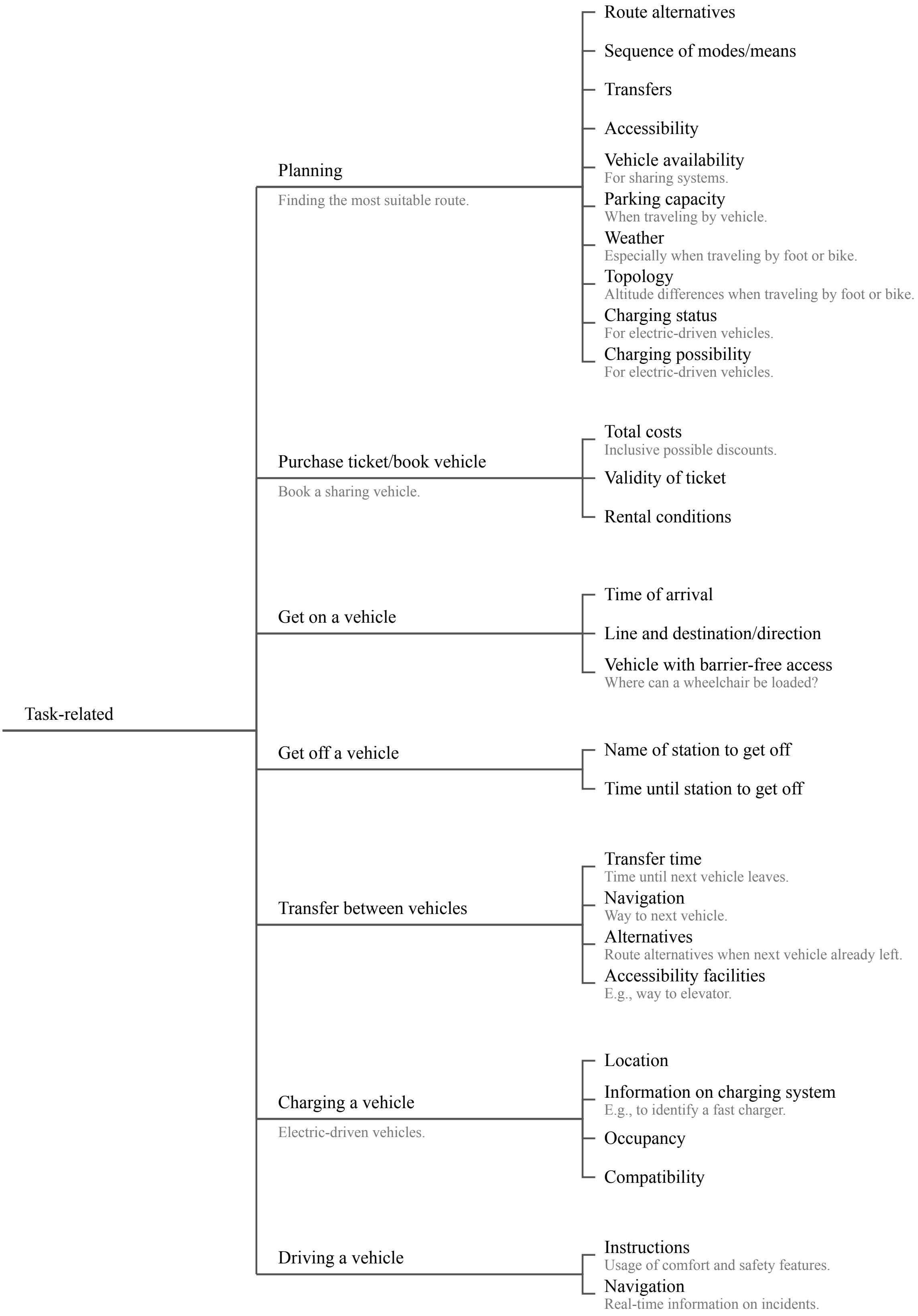


Figure 3.8: Required information that is related to tasks during a journey. The requirements have been derived from literature research and experiences during studies conducted in the scope of this thesis.

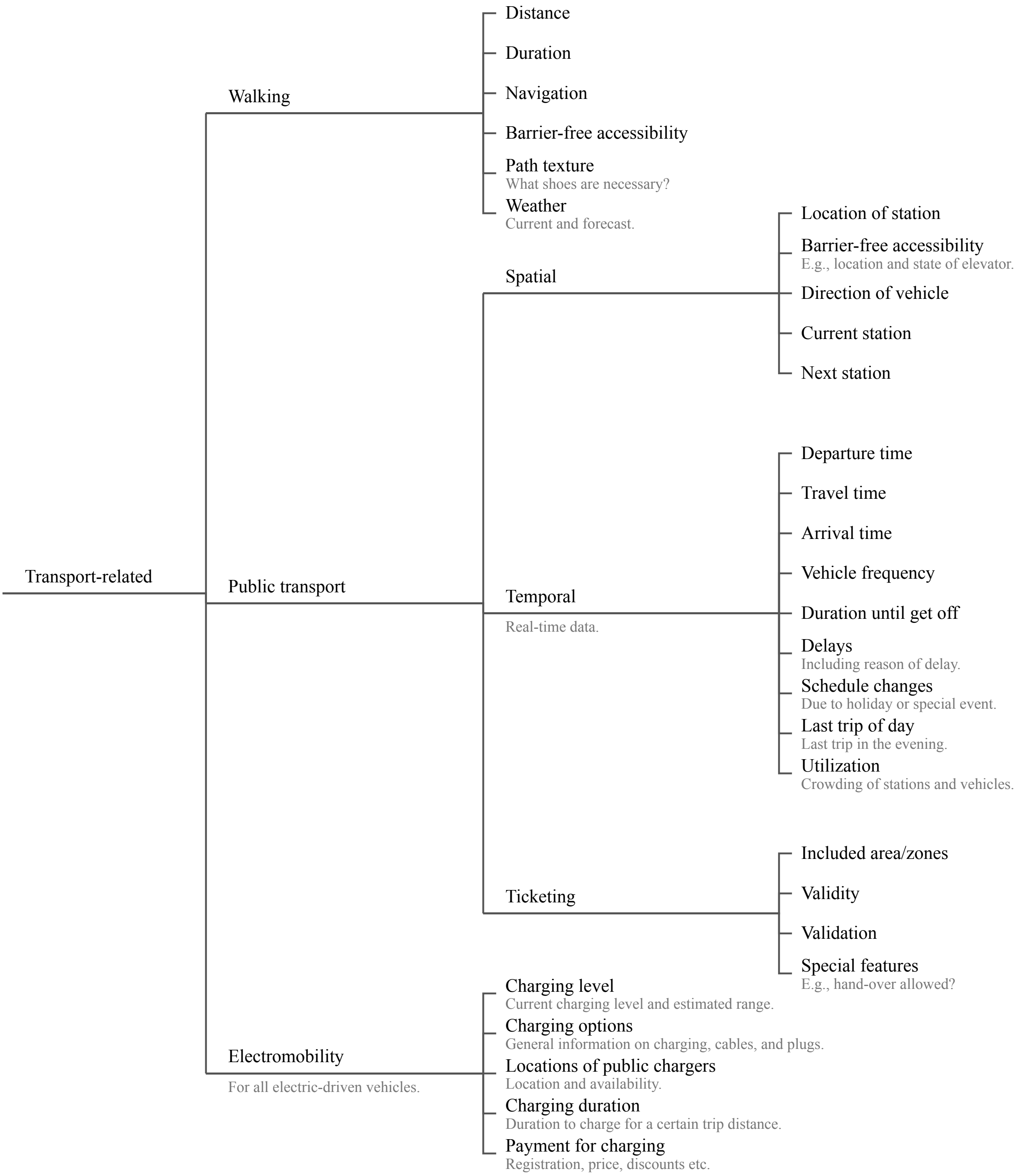


Figure 3.9: Depending on the mode of transportation or characteristics of the chosen mode, different information is required. These information demands are summarized in this chart. The requirements have been derived from literature research and experiences during studies conducted in the scope of this thesis.

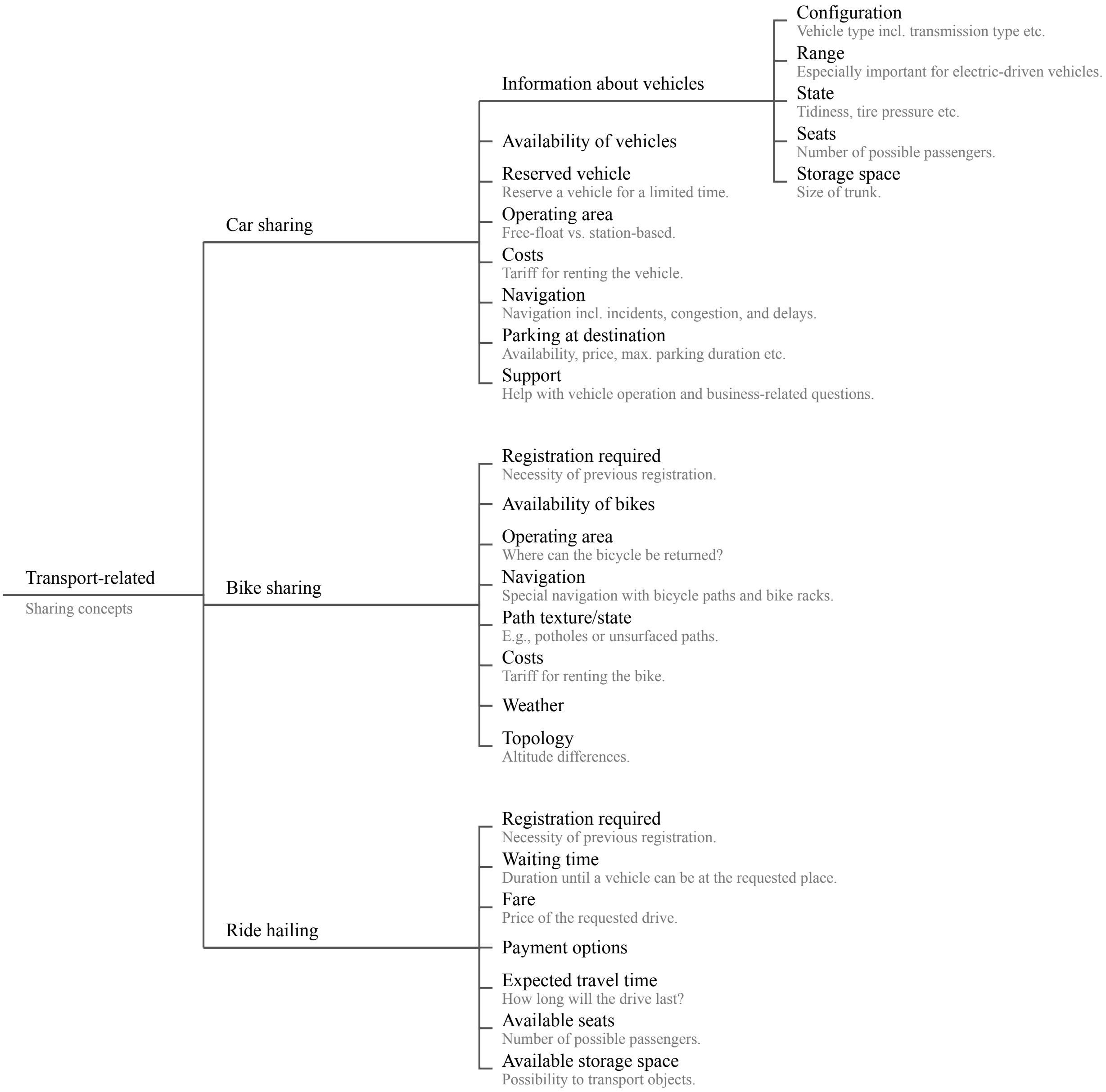


Figure 3.10: Possible requirements in sharing scenarios. The requirements have been derived from literature research and experiences during studies conducted in the scope of this thesis.

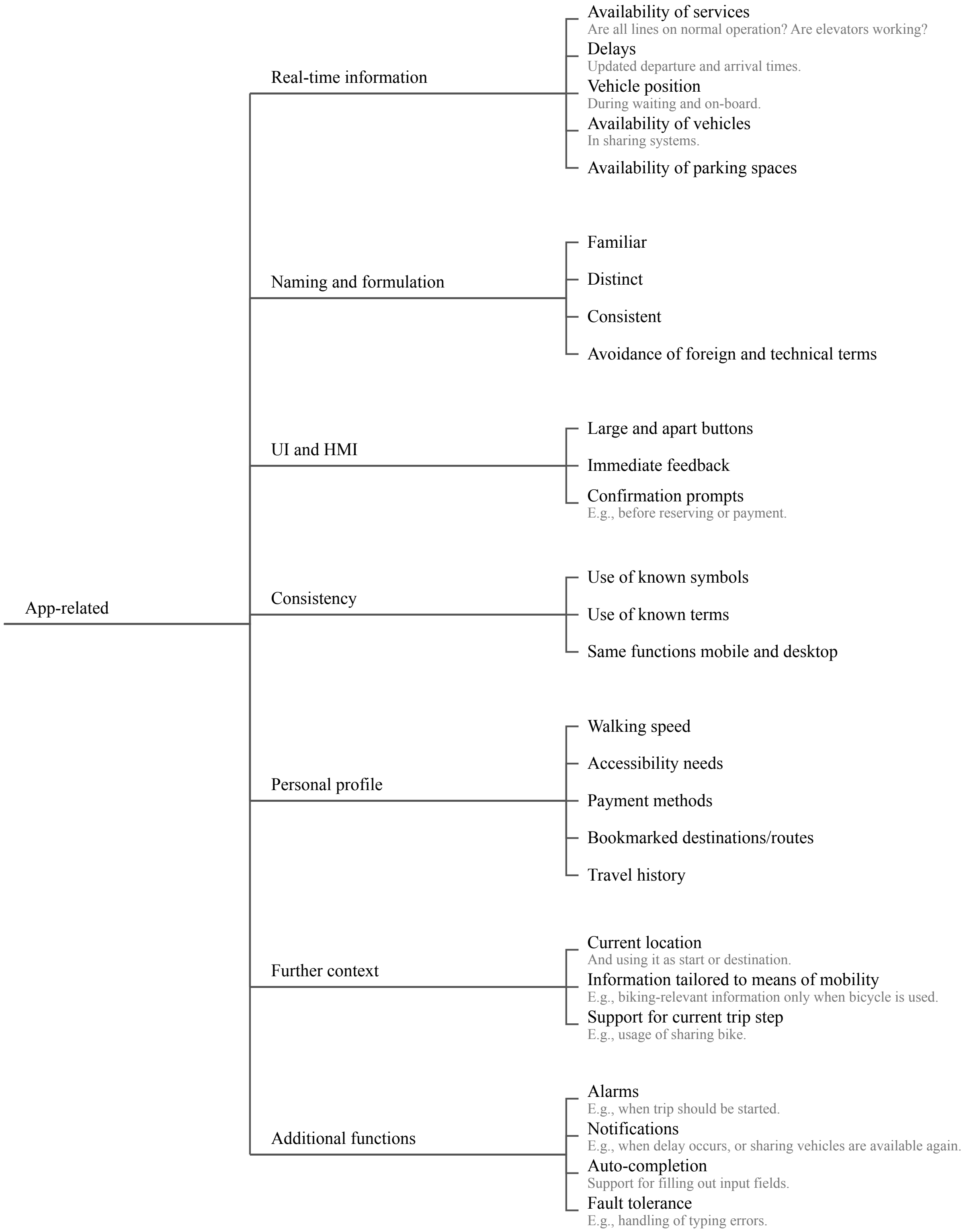


Figure 3.11: Users' requirements on applications that support mobility processes. Depending on the purpose of the application the specific requirements may apply. The focus of this requirement analysis was on a holistic trip planning application that also offers support during the mobility process. The requirements have been derived in a literature research as well as from observations and experiences during studies conducted in the scope of this thesis.

3.6 A Vision of a Seamless and Connected Mobility Solution

Based on the identified requirements, we carved out a vision of a connected mobility system that interlinks digital mobility services and with mobile-device based AMASs. It shall demonstrate the potentials of connected digital assistance. Our vision is based on a platform which interlinks not only people with each other, but also vehicles, public transport stations, parking lots, and other mobility-related systems and services. The integration of *things* into Internet-services is often referred to with the term IoT [206]. Adapting this term to our approach, one could say that our vision describes a service for the Internet of mobility (IoM).

A central goal of this dissertation is the optimization of the users' individual and personal mobility. In this vision, we highlight the potentials of connecting digital assistance and mobility services. For that reason, the platform supports numerous participants, so called *stakeholders*. An incomplete overview of possible stakeholders is depicted in Figure 3.12. Besides the potential end-users, also institutions, systems, and services can be part of the network.

Several factors are necessary to provide mobility-as-a-service (MaaS) [179, 188]:

- Integration of transport modes: All relevant modes of mobility shall be part of the MaaS system.
- Tariff options: Payment needs to be possible for a whole intermodal trip. Packets and options for different demand for mobility shall be offered.
- One platform: Users need a single point of entry and truth in a working intermodal mobility scenario.
- Multiple actors: The one platform shall integrate not only users and the means of transportation but also third-party operators etc.
- Real-time ICT integration: ICT is the primary access method to plan and book trips. Real-time information is required to make the system attractive to users.
- User-centered design: The transport solutions are made for its users. It offers the most suitable trips instead of the ones that make the most profit etc.
- User context & Personalization: Context is essential for a good MaaS experience. It allows narrowing trip options and helps to satisfy the users' needs by analyzing historical data.
- Customization: Besides reasonable, predefined solutions, users shall have the ability to mix and pick segments or offers from the proposed trips or tariffs.

In our vision, we assume that the user is accessing the platform with a PMD. The user will be employing a client application that allows for better integration in the mobile platform.

We published parts of this vision in 2012 [87].

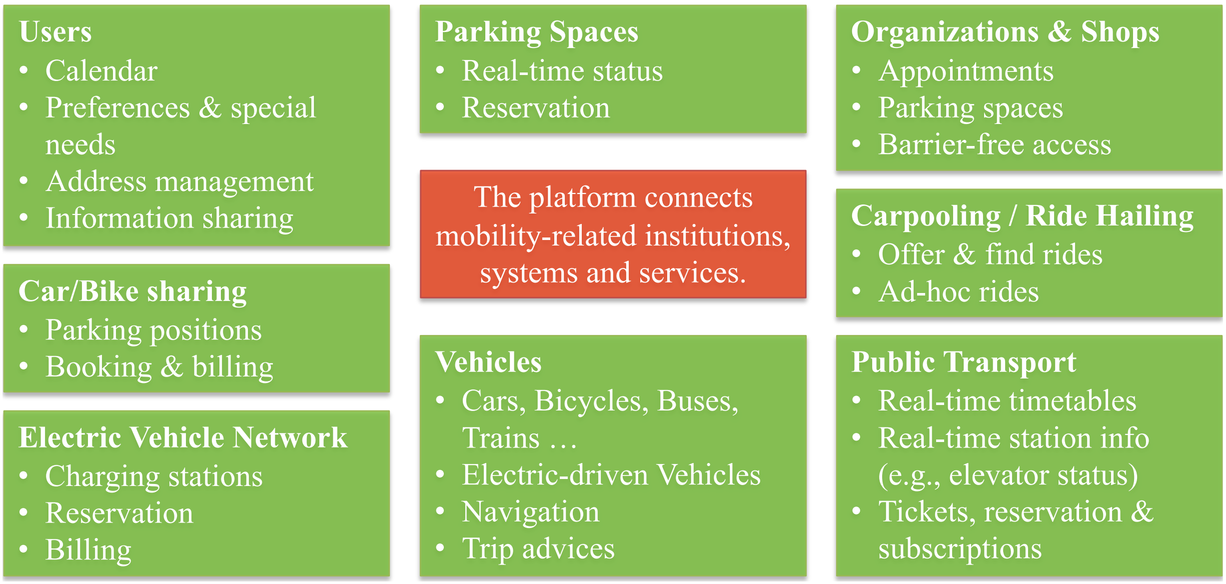


Figure 3.12: Overview of possible participants of a connected mobility platform. Besides the users, other mobility-related instances should be interlinked for seamless information sharing and arrangement of mobility processes.

3.6.1 Participants' Roles and Available Functions

The main functionality of our envisioned system is the support of the end-user by providing more efficient means of personal transportation across modality borders. In order to be able to assist the user optimally, a user needs a profile on the platform. By default, the profile is private, but parts can also be made publicly available so that friends can find each other. The profile consists of mobility preferences (cost limits, requirements, restrictions, etc.), and travel-related information. For example, users can configure whether they have a driver's license, need barrier-free access, or own a private car that they are potentially willing to share. Additionally, available public transport tickets and personal subscriptions can be set for calculating pricing alternatives. Other preferences, such as the preferred mode of transportation (e.g., with the private vehicle), can be used to refine the system's behavior.

A central part of each user's profile is a calendar. The calendar can be synchronized with standard online and desktop calendars. Users can also connect to friends and other known people. Depending on the degree of confidence, they can share their profile information as well as their calendar. The well-known means of sharing information on social networks are used to implement this feature, e.g., the circle model that was used on 'Google+.' This feature allows, for example, creating carpools by scheduling appointments next to each other. The user utilizes the platform to plan the trips. That can be done for future trips from a defined start point to a destination (for example, an appointment planned via the system), as well as for ad-hoc trips from the current location to any destination.

Organizations, authorities, and shops can also register at the platform and connect their calendar with their profile. This feature can, for instance, be a common base for scheduling appointments. The scheduling algorithm could take the user's journey into account and only offers appointments for defined slots. When trusted neighbors have an appointment nearby or even at the same place in the future, and the next appointment for the client falls in the same period, the system could offer the client an appointment so that they can create a carpool. Of course, the system would only suggest this when one of the clients plans to go there by car and is accepting carpooling for that journey. Additionally, the corporations or authorities could offer and reserve parking spaces for their clients for their next appointment. That would especially be easy when an intelligent parking solution is used.

Intelligent parking solutions could as well be directly linked to the platform. Parking space usage can be managed by participating organizations. When planning a trip, the user can, e.g., reserve a parking space for the desired time. Additionally, organizations can provide parking spaces for their clients. By binding the parking space reservation to the user's trip, the user's navigation application can show instructions for reaching the reserved parking space. Since the network knows about the special needs of the users, it could also take care of them. People with a mobility handicap can, for example, get a nearer parking space, and people with babies or toddlers could get assigned broader parking spaces so that the getting in and off would be more comfortable. When a user is traveling with an electric vehicle, the system could automatically choose a parking space with a charging station, when available and not reserved at the moment.

The incorporation of existing public transport options into the platform could make journeys more comfortable and less stressful. That could not only be helpful for people without private cars or driver's licenses but also save time and additional reduce CO_2 emissions. In cities, there is often heavy traffic, and usually, the parking situation is already at or over its limits. For that reason, it could be beneficial to park outside the inner city and to use public transport to get to the destination in the city — if a convenient travel alternative could be provided. In order to find the optimal intermodal route, the platform would estimate the traffic situation for the planned time of travel, e.g., by incorporating historical traffic data. When users have to transport something (for example, furniture from a furniture store), or when they do not want to take public transport, the platform would not consider public transport.

For users with special needs, the public transport operator could offer real-time information for elevators and other accessibility relevant systems (cf. Section 4.2). That way, the platform could also react during the trip and provide alternative routes and information to the user. Real-time information could also be provided by transport vehicles. That would the user allow, for example, the estimation of whether a connection could be reached when being already late, or whether the arrival will be delayed.

Car-sharing operators and carpooling initiatives or portals could also get part of the network. By providing the possibility to book or reserve cars or at least places in cars, these mobility alternatives could get a fixed part of mobility chains. For short-term journeys, car-sharing and carpooling are only attractive when reliable real-time information and binding booking is available. This information and booking functionality could be directly provided by the platform when the user plans a route. Besides, instructions and support for the handling of the booked vehicle could be provided (cf. Section 5.2).

Participation in the platform could also be interesting for electric vehicle charging station operators. They could, for example, provide a booking mechanism for their charging stations and make use of the platform's seamless payment possibilities for billing. Real-time information about the current price per kilowatt-hour could be displayed directly to the user when searching for a charging station.

3.6.2 Vehicles as Part of the Mobility Platform

A specialty of the platform is that also vehicles (conventional cars, electric bikes, or personal mobility platforms like a Segway or a Renault Twizy[13]) can participate in the social network-like service. Since the service can be accessed via all Internet-enabled devices, modern vehicles with mobile data connections can directly be linked with it. In contrast to safety-critical V2X applications, standard Internet protocol (IP) connectivity with higher delays over 4th Generation Mobile Telecommunications (4G) would be sufficient for the system. It is also thinkable that the user's PMD gets connected to the vehicle's infotainment system for providing the desired information from the platform (cf. Section 6.2.2).

When a regular user account is coupled to the IVIS, the proposed platform could provide the route chosen by the user for the vehicle's navigation system. When a parking space is assigned to the user for a trip, the reservation is automatically updated with the license plate information of the utilized vehicle. That ensures that the parking space is reserved for the user, independent from the actually used vehicle. Besides, the system could broadcast the estimated time when a user arrives at a destination. An example scenario for this functionality is the ability to check whether the pick up of a lift is on time or not.

An alternative to employing the IVI is the usage of the user's PMD as automotive HMI (cf. Chapter 6). By using the familiar HMI of the mobile device, the effort for the perception of and interaction with mobility data can be reduced. For this, a versatile and future-proof interface between the vehicle and the PMD is necessary (cf. Section 6.3).

Besides, cars could participate without being linked to a user. In that way, they could, for example, detect and report free parking spaces [57], or report traffic data to the platform's central route calculation system. Electric vehicles could use the system for requesting nearby charging stations that are in the range of the current battery level. Additionally, when a user plans a trip with a private electric vehicle that is assigned to the personal account, the current battery state reported by the car could be taken into account. That means that the system would automatically choose a

---

[13] https://www.renault.de/modellpalette/renault-modelluebersicht/twizy.html, accessed March 12, 2019.

parking place with a charging station, or suggests parking somewhere, where the user could get back home without charging.

Public transport vehicles running at regular service could also be linked to the respective connection and time slot. That would allow broadcasting information, such as the delay or the utilization, in real time. That could be valuable information for users that are already late and want to get their connection. For people in wheelchairs, people with baby carriages, or people with large luggage, the information about the utilization could also be critical, since often the number of places for such user groups are sharply limited. When other passengers in the transport vehicle are also part of the platform, the system could further try to create an estimation, whether there should be enough places, or not.

The flow of information is not limited to the direction from vehicles to other participants, but also the vehicles could be provided with information. For example, when an underground train arrives late and a bus on a line that is scheduled at 30-minutes interval is part of the trip for some travelers, the system could inform the driver about the underground's lateness and the expected time to wait. In that way, the driver of the bus could decide whether waiting to allow for transfer is possible or not. When users in wheelchairs or with carriages want to get on a vehicle that is not barrier-free by default, the platform could also inform the driver to prepare the loading ramp, to lower the bus, or to get ready to help someone with special needs entering the vehicle.

3.6.3 Accessing User Profile Information and Billing

For offering matching mobility services to a user, organizations and service providers would need access to some user data that is stored the profiles. One of the fundamental design principles of the system should be the protection of the user's privacy. Thus, only approved users and trusted services would be able to access the necessary parts of the personal data. For that reason, the system should have fine-graded user-managed access control [64]. A sample protocol that could be used for giving access to third parties is OAuth 2.0[14]. It provides authorizations flows for web, desktop, and mobile applications as well as for consumer media devices.

The linking can, for example, be realized by scanning a QR code with the PMD, or via near field communication (NFC). Thad could trigger an access screen that shows what service wants to access what kind of data. The user could then either accept or decline the request. In that way, enter the password in an insecure environment can be avoided. The coupling could either grant one-time access, for example, when a corporation wants to create an appointment in the client's calendar or not-time limited access. In the second case, the user could manage and revoke the access permission for each service at any time. The one-time access could, for instance, also be used for coupling car-sharing vehicles on a per-trip basis. This would allow using the platform on the vehicle's system as long as the car is booked.

---

[14] http://oauth.net/2/, accessed March 20, 2019.

Billing is another central part of the platform. Especially for people that are not used to the operation of ticket vending machines, or have difficulties with understanding network and fare plans, active support with billing could take away the fear from public transport of these people. Since most larger public transport associations are supporting online or mobile phone ticketing, the system could directly buy the tickets when the users agree in taking a route proposal. For systems without advanced ticketing, the public transport operators could provide step by step instructions for the most common available tickets. This step by step guide could then be displayed when the person enters the area where a ticket vending machine can be found. For car-sharing operators and carpooling scenarios, it would be possible that the payments could be carried out via the platform. The payment service could be realized by linking with immediate transfer services, online payment services, or common credit institutes.

3.6.4 Intermodal Route Calculation

In order to create intermodal trips, data from different sources have to be combined. Necessary routing information could, for instance, be derived from OpenStreetMap (OSM) data. The OSM project “creates and provides free geographic data and mapping to anyone who wants it”[15]. The data already includes barrier-free accessibility information for some buildings. Since everyone can contribute to the data, way and buildings could be added and corrected by everyone. That would ensure that also parking spaces from companies could be found by the system. The routing system could be based on one of the open-source routing implementations for OSM. For example, the *openroute service* offers full route calculation for vehicles and pedestrians[16].

For public transport, the respective data sources from the different transport operators and associations have to be queried. The popular Android application *Öffi* is already successfully using many existing application programming interfaces of public transport operators and demonstrates that this data is accessible and reliable[17].

Besides the route and duration under normal conditions, the system could also use other sources for determining a more comfortable route, or for creating a better estimation of a journey. For example, the system could include weather conditions when planning outside walking route parts [295]. Alternatively, it could make use of historical floating car data (FCD) for predicting the traffic for a specific day [315], similar to TomTom’s route planning assistant that makes use of gathered live traffic information from mobile phone operators and GPS navigation systems[18]. Since the user always carries the PMD while traveling, the algorithms could adapt themselves in various ways. For example, the system could optimize the estimation of the users’ walking speeds or driving behaviors by measuring the speeds and other sensors’ values.

---

[15] http://wiki.openstreetmap.org/wiki/Main_Page, accessed March 20, 2019.

[16] https://openrouteservice.org/, accessed November 4, 2019.

[17] http://oeffi.schildbach.de/faq.html, accessed March 20, 2019

[18] http://routes.tomtom.com/, accessed March 20, 2019

3.6.5 User Tracking for Advanced Services

When a user travels with the platform, location tracking can be used to offer advanced services. Those could be, for example, the notification of traveling or appointment partners, when the user is running late, or the on-the-fly alternative route calculation when changes on the further planned journey occur.

When traveling outside, the application could make use of the device's localization technologies. That could, for example, be the GPS system or localization via cell ID or Wi-Fi access points or other built-in radios of PMDs [63, 205, 310]. For detecting and supporting passengers traveling with the support of the platform in public transport, the vehicles and stations could, for example, be equipped with NFC service points. At these points, users could check-in and check-out with their NFC-enabled mobile device. Alternatively, free WLAN could be offered that can only be accessed when the device is linked to the platform.

Besides location tracking, incorporating the user's fitness could help to boost physical fitness. For example, when a user takes too few steps a day, the route planning could suggest adding additional walking segments to routes, when the user's health and travel conditions allow for this measure (cf. Section 4.3).

3.7 Example Scenario for Connected Mobility

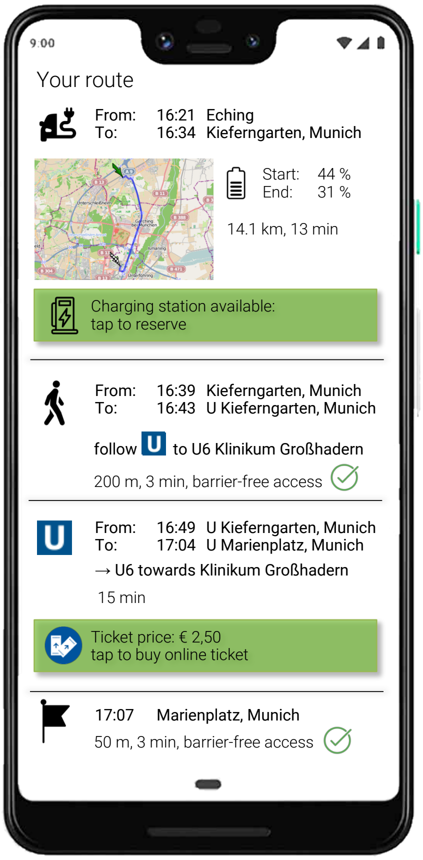
In Figure 3.13, a possible route suggestion is shown. For this scenario, a user with a private electric car wants to drive to the center of Munich, Germany. The user does not need barrier-free access or any other exceptional support. The user has further no public transport subscription.

At first glance, the output looks similar to standard public transport trip planners, such as Öffi[19]. However, the proposed platform combines multiple things: routing for a private vehicle, parking, and planning the final part of the journey with public transportation. Additional to the route, it also displays and incorporates the electric vehicle's battery state in the trip preview. Since the battery is charged enough to get back fully electric, the system does not output a warning but chooses a parking place that is equipped with charging stations. A charging station could further be directly reserved from the route preview.

Since the user has no subscription for the transport network, the system calculates the cheapest available fare and allows buying the ticket directly via the application. In case a user has planned multiple journeys within the public transportation network, the platform could suggest buying a day, week, or month ticket, whenever a cheaper alternative is available.

---

[19] http://offi.schildbach.de/, accessed April 3, 2019



Your route

From: 16:21 Eching
To: 16:34 Kieferngarten, Munich

Start: 44 %
End: 31 %

14.1 km, 13 min

Charging station available:
tap to reserve

From: 16:39 Kieferngarten, Munich
To: 16:43 U Kieferngarten, Munich

follow U to U6 Klinikum Großhadern

200 m, 3 min, barrier-free access ✓

From: 16:49 U Kieferngarten, Munich
To: 17:04 U Marienplatz, Munich

→ U6 towards Klinikum Großhadern

15 min

Ticket price: € 2,50
tap to buy online ticket

17:07 Marienplatz, Munich

50 m, 3 min, barrier-free access ✓

Figure 3.13: Our mock up shows how a possible route output could look like. It could, for example, offer possibilities for reserving a charging station for the electric vehicle and for buying a public transport ticket. Map source: OSM

3.8 Research Gaps for Mobile Device-Complemented Advanced Mobility Assistance Systems

Ehmke et al. summarize that most existing mobility assistance systems suffer from four major problems: they do not consider user context, are limited to certain (partner) services, have no measure of the expected service quality, and do not offer sufficient on-trip assistance [107].

The problem of missing user context in mobility assistance has already been identified by research several years ago and is currently finding its way into commercial products (cf. Section 3.5). The trip and user context are also a central part of our research and the created prototypes.

With the ongoing digitalization of mobility (cf. Section 3.1.3) and mobility-related services (cf. Section 3.5), there is excellent potential in seamlessly connecting different mobility services. That is also the foundation of the presented mobility vision in Section 3.6. Since there is already extensive research on the topic of connected mobility services [265], we do not focus on the interconnection of different services. Our research focuses on concepts that enhance selected, individual steps for planning, maintaining, and conducting mobility. However, we highlight how the individual parts can be incorporated in a comprehensive, seamlessly connected mobility solution.

The topic of *missing measure of expected service quality* shall be addressed in our research. Under *service quality*, we understand how satisfied users are with the AMAS they are using, not the service quality of the individually chosen mobility services. In our research, we distinguish between user *expectations* and the users' *perception* of service quality. One goal of our research shall be to investigate whether the perception of the service quality can be actively influenced and how users can be motivated to use a system they might not see a benefit from initially.

On-trip assistance has also been identified as a central requirement in our research (cf. Section 3.3.3). Like the user context, this topic has already been covered in the research. Especially in the automotive domain facing the trend of sharing, we see the large potential of using the users' PMDs for assistance, since this can add much additional context and allows providing known HMIs.

Together with the findings from the three defined mobility scenarios with our personas (cf. Section 3.3) and the identified potentials for intermodal mobility in Section 3.3.3, we selected the following research gaps that shall be investigated in depth in this thesis (**HRQ3**):

1. Mobility planning that considers the individual context of users in their current situation and enhances the trust in intermodal mobility.
2. Supporting the usage of mobility means to maintain self-determined mobility and to allow access to new mobility concepts.
3. Assisting with the handling of HMIs in vehicles by means of training.
4. Integrating the PMD in vehicles to provide user context and an HMI the user is acquainted with.

Our research results of context-aware and credibility-enhancing route planning are summarized in Chapter 4. Our novel assistance approaches for maintaining self-determined mobility and training the handling of automotive HMIs are presented in Chapter 5. In Chapter 6, we share our insights on integrating the users' PMD in the automotive domain.

3.9 Summary of Contributions

In this chapter, we examined the mobility process in depth to identify the fields that can benefit the most from AMASs. We now summarize our contributions to the individual covered topics of this chapter.

Mobility is a Continuous Process

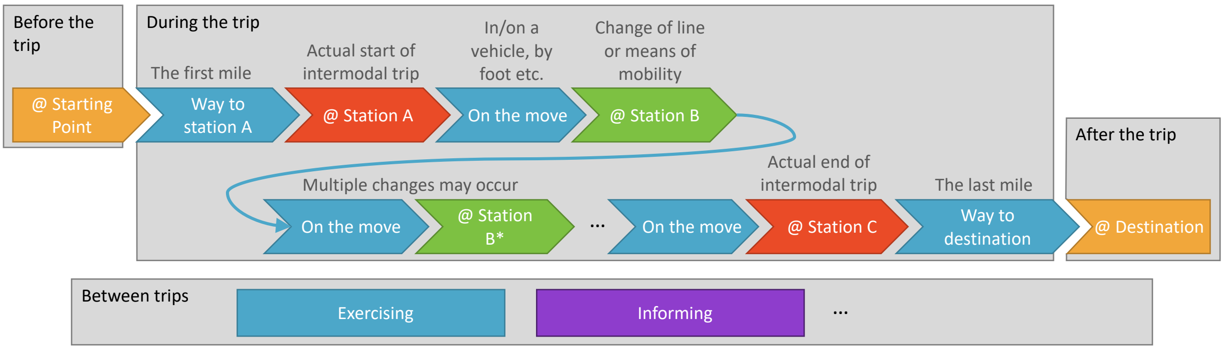


Figure 3.14: Overview of typical steps comprising intermodal mobility scenarios. During our process analysis, we identified that it is not only the steps during an actual trip that can benefit from assistance. The time between the trips is important in terms of actually maintaining the ability for self-determined mobility.

The mobility process description in Section 3.1.1 provides the structure for the systematic analysis of the different steps in mobility (answer to **HRQ1**). Our main contributions to the process description were the addition of the process step *between trips* and the introduction of stations where only transfer happens (*Station B*). The generic description is depicted in Figure 3.14. We identified that users are continuously engaged in mobility, whether it is conscious or unconscious. Examples are gathering information on mobility services (e.g., information on construction works causing delays or route deviations) or exercising to maintain the physical ability for self-determined mobility.

The Requirements on Information and Digital Services Act as the Basis for the Identification of Assistance Potentials

We provided the answer to **HRQ2** regarding the main requirements of mobility users on information and digital services in the form of tree diagrams in Section 3.4, clustered into four categories:

1. General travel-related requirements,
2. Travel task-related requirements,
3. Transport-related requirements, and
4. App-related requirements.

For directly mobility-related requirements, the main scope mostly encompasses spatial and temporal information. However, for example, data on the charging status of EVs, or the provision of instructions to use a car-sharing vehicle, are also points that can be necessary for certain user groups. In Section 3.5, we compiled a list of possible data sources that can be used to derive the data necessary to fulfill the requirements.

In particular, the points *context-awareness*, *consistent and appropriate data presentation*, and *need for instructions* influenced our choice of the research gaps that shall be filled by this dissertation.

The Identified Gaps Cover All Phases of Mobility

In Section 3.3.3, we derived global challenges and potentials for digital mobility assistance from the three scenarios we created to match our engaging personas. The selected research gaps, we contribute in this thesis are summarized in Section 3.8.

The answer to **HRQ3** on the steps of intermodal mobility that can benefit from a PMD-based AMAS is “all of them.” For that reason, we decided to contribute with our research to the points that (1) allow individuals to maintain their self-determined mobility, (2) support people to try out new forms of mobility, and (3) allow leveraging the available user and trip context as well as the knowledge of operating known HMIs in existing mobility forms (specifically in the automotive domain).

Chapter 4

Mobile Device-Complemented Intermodal Mobility Planning

4.1 Problem Definition and Research Questions

As stated in Section 3.3.3 concerning the challenges and potentials of intermodal mobility, a central challenge is trip planning. Having a trip-planning application that offers suitable routes via a user-friendly HMI is essential (cf. Section 3.4).

In this chapter, we set out specific requirements on functions and the HMI of intermodal route-planning applications on the user's PMD. This is done in a two-step approach: We first perform a lab study with elderly users who have limited knowledge of digital systems, in which we evaluate the usage of two already available route-planning systems. By examining the main technical barriers, we first gather partial answers to **HRQ4** (How can the complexity of operating mobility services and assistance systems be reduced for users?) and **HRQ5** (How can users be supported in accessing and using mobility services and means of mobility?).

In the second part of the chapter, we introduce our context-aware trip planning application Seamless Mobile that is based on our gathered requirements in Figure 3.11 and the results from the previous lab study. In this application, we integrated two approaches to influence the mobility behavior of the user:

1. Framing of shown trip information targeting the credibility of the data, and
2. Offering a fitness route to remind the user of regular training.

The results from a 2-week field study contribute to our **HRQ6** (How can users be motivated to actively deal with their mobility and assistance systems that can improve their mobility situation?).

This chapter is partly based on two papers we published in 2014 and 2015 [92, 94].

4.2 Optimization Potential in Existing Trip Planning Applications

In the context of the project PASSAge, we conducted a laboratory study to identify the essential elements of route planning applications. In this section, we summarize the collected quantitative and qualitative results.

4.2.1 Research Questions

The following research questions guided the conducted experiment:

> **RQ1**: What are the essential elements and functions of existing route planning applications?

With the continuous integration of additional features, the core functionality is often shifted into the background or gets more and more challenging to operate. For this reason, our goal was to identify the functionalities needed to plan an intermodal trip.

> **RQ2**: What improvement potentials can be identified in existing route planning applications?

We investigate the usage of the trip planning applications to identify what steps in the trip planning caused problems and ask the subjects what they found challenging and at which steps they would have needed assistance or would have expected another functionality.

4.2.2 User Study with Existing Trip Planning Applications

In order to get a different view on the existing applications, we performed the field study with elderly participants that are usually not considered as the primary target group of mobile applications [27].

Participants

15 participants (10 female, 5 male) aged between 66 and 93 years ($\mathrm{Mdn} = 73$ years, $\sigma = 7$ years) took part in this field study. The subjects were recruited from a rehabilitation sports group. 7 participants had a mobile phone, 3 of them a smartphone. Another 3 participants had experiences with the operation of PCs. 2 subjects stated to feel critical towards “new technology.” 6 participants stated to have problems reading small text, with one of them having no glasses available during the experiment. The participants did not receive any compensation for their participation in the study.

Task

The test sessions lasted between 20 and 35 minutes. It started with an introduction to the two major trip planning applications used in Germany: the *DB Navigator*[1] and *Öffi*[2]. After the introduction to the applications, the subjects had 5 minutes to try the apps on themselves. Afterward, two route planning tasks should be performed, from starting the app to an actual selection of a route from the current location to the given locations. A task was counted to be successful when a route to the exact destination address was selected (incl. correct street number[3]), and the starting point was somewhere close to the starting point. When the task could not be done within 5 minutes, the participants received support. The apps were used alternately for each task (within-subjects study) with a randomly chosen one to start with (counterbalancing).

Data Collection

The users have been asked to comment on their actions during the tasks (think-aloud method [397]). The task execution time was measured manually by the experiment operator in the background. Besides, after each task, a short interview was conducted to gather qualitative feedback. The interview focused on elements and functions in the application the users found necessary, helpful, interesting, or unnecessary. The elements and functions have not been named to avoid influencing. The interviewer only helped to identify the meant element or function, when the statements were unclear. Finally, the subjects were asked what they would change to optimize the application for their use.

4.2.3 Results of the User Study

Observed Operation Problems during the Experiment

The results from the task execution time measurements were two-fold. From the 30 executed tasks, only 18 could be solved in the 5 minutes without additional support from the experiment operator. The results are shown in Table 4.1.

The main reasons for failing the task were problems entering the addresses. We observed that many participants had problems typing on the touch display keyboard. The secondary functions of buttons appearing after a long press led to numbers and letters with diacritics. In many cases,

---

[1] https://play.google.com/store/apps/details?id=de.hafas.android.db, accessed March 11, 2019.

[2] https://play.google.com/store/apps/details?id=de.schildbach.oeffi, accessed March 11, 2019

[3] The starting point had to be around *Connollystraße 32, 80809 München*. The destination was *Tölzer Str. 13, 83607 Holzkirchen*.

	Öffi			DB Navigator		
		Task execution time			Task execution time	
	Completion	Mean	σ	Completion	Mean	σ
Task 1	3/7	204 s	133 s	4/8	189 s	146 s
Task 2	5/8	155 s	120 s	6/7	152 s	127 s

Table 4.1: Task completion rates and task execution times measured during the study with two existing trip planning applications. The task execution time only includes the required time for completed tasks.

the participants did not note this, which caused the route planning to fail. For 7 of the failed tasks, the subjects did not manage to enter the complete destination address correctly. The deviations reached from wrong cities over missing streets, to deviating or missing street numbers.

The concept of deleting entered letters was also not clear to several participants. One participant found a "workaround" by clicking on the *x* symbol within the text field, leading to a complete deletion of the field's content.

Another problem was the font size in the text input fields. Some participants could not read what they have typed. That led to situations where subjects had typed all the content but needed to start over again after the trip planning failed. When the applications showed error messages to the subjects, some subjects could not interpret them. One subject complaint aloud that the address would have been correctly entered, but the "computer cannot understand" it. When the experimenter looked at the entered input, it contained several serious typos so that it would also have been improbable a human could have understood what address would have been meant.

Two participants did not understand the concept of putting the start location and the end location into different fields. One of the participants entered the current location and the destination in the same text box. Another only entered the destination, assuming that the application then knows, she wants to travel there from the current location. However, as she entered the desired destination into the start field, the route planning failed due to "missing destination."

One participant failed the task as he entered the departure time menu and could not find the "way back" to the screen where he could start the route planning. Another subject got stuck on the route selection screen, as it was not clear to her that a simple tap on the route entry would have been sufficient to show the details. She searched for over a minute for a "button" on the screen.

RQ1: Results on the Importance of Elements and Functions

Table 4.2 shows the summarized overview of named functions and how the participants evaluated their importance. The numbers for the *importance* categories show how many subjects named the element or function and assigned it a certain importance level. No participant used the category unnecessary.

#	Element or function	Necessary	Helpful	Interesting	Unnecessary
I1	Possibility to book ticket directly in the application	7	1		
I2	Display of current vehicle delays	5	2		
I3	Map as overview	3	6		
I4	Auto-completion for station names	2	7		
I5	Inclusion of walking distances in trip	2	5		
I6	Notification about delays possible	1	4	2	
I7	Indication whether bicycle transport is possible/allowed	1	3	1	
I8	Use current location as starting point		7		
I9	Station overview (map)		1	3	
I10	Direction to and departure times of nearby stations			3	
I11	Saving a trip to personal calendar			1	

Table 4.2: Absolute frequencies of respondents' opinion on the importance of elements and functions of trip planning applications. The importance could be rated as *necessary*, *helpful*, *interesting*, or *unnecessary*. The subjects named the elements and functions themselves. There was no list given to them. The results are ordered by their rated importance. No participant used the category unnecessary.

The feature that has been named most as *necessary* was the ability to buy a ticket directly (I1). That was, at the first point, irritating for us. However, many subjects explained that buying a ticket at the ticket vending machines is very challenging for them and that there are often no more ticket counters at smaller stations. As the main problems, the overall operation of the UI and the destination entry were named. One subject noted that he often buys the ticket in advance to make sure she has a valid ticket before the trip. Concerns with buying the ticket in the app were that one "does not have a paper ticket" then and that the smartphone could run out of battery.

The feature that was rated second most as necessary was the real-time delay information (I2). Besides the information about the current delay of individual means of mobility on a trip, the subjects also highlighted the display of the information that the following train might be missed.

RQ2: Named Optimization Potentials

As central optimization potential, many subjects named the text input for the start and destination location. The ideas ranged from enabling voice input to selecting the address on a map view. The auto-completion of station names and addresses that was available on both application under test was mainly rated as *helpful* (I4). During the experiment, many subjects did not directly understand the meaning of the appearing text. That was enforced by the fact that the auto-complete suggestions were displayed in a smaller size. However, many subjects already named that the standard font size was too small for them.

These further points on optimization potentials have been named:

- Symbols are too small (e.g., bicycle carriage possible or second class).
- Icons are unclear (e.g., a star for remembering a station, the target sign to insert the current location).
- Information on the accessibility of vehicles and stations is missing.
- Information on the operation status of elevators is missing.
- Delay information is only available for long-distance trains.

The findings have been considered for the development of our trip planning application Seamless Mobile (cf. Section 4.4).

4.3 Extended Mobility Services and User Context at the Example of Fitness-Based Routing

As summarized in Section 3.8, a central requirement for new (extended) mobility services is their seamless incorporation with other, already existing, mobility services. For our trip planning application concept, we chose the topic of *physical fitness* as an example of an extended service since the promotion of physical exercise is also a central part of helping to maintain self-determined mobility. At this example, we demonstrate how the integration of extended services could look like and how user-context can be used to adapt to the individual situation.

4.3.1 The Concept of Fitness Route

Our *fitness route* concept is a novel idea of including the tracked daily fitness data in standard trip planning. In addition to the default trip parameters of start, destination, and travel times, it also incorporates the set daily physical activity goal, location preferences, and special needs, such as barrier-free access. With this data, the trip planning application calculates a route with additional walking segments so that the set physical activity goal (e.g., a certain number of steps) can be reached.

Our concept primarily aims at users that need to increase their daily physical activity. That can, for example, be the case for certain medical indications, such as type 2 diabetes, obesity, or lack of

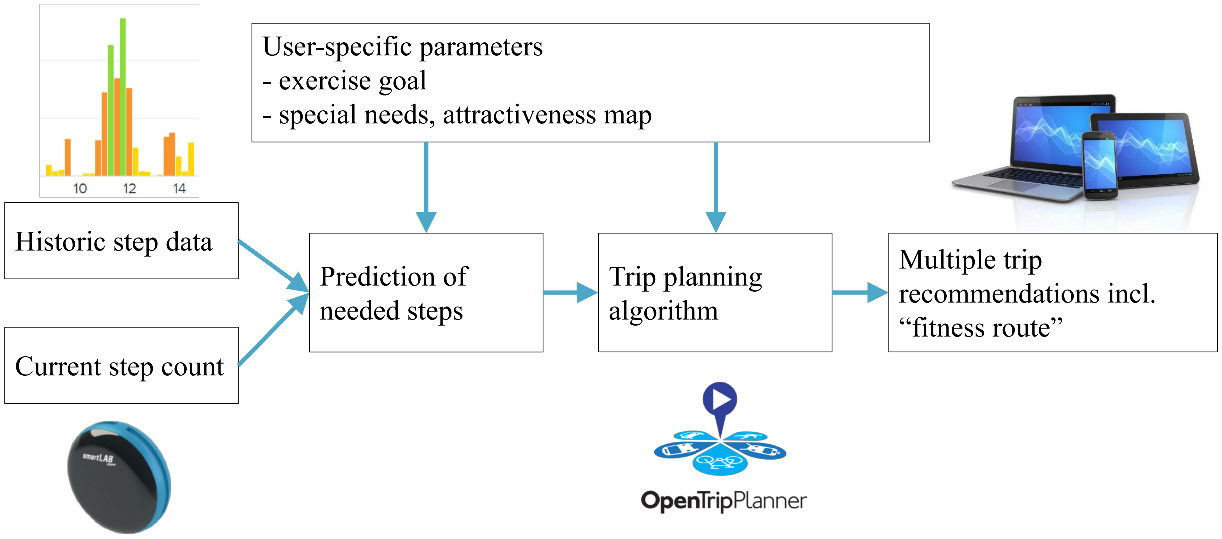


Figure 4.1: By comparing historical step data with the current number of steps, the step prediction algorithm determines the needed steps to reach the set goal. The trip planning algorithm calculates appropriate trips, including a “fitness route” with an extra walking segment. A prototype implementation of the system has been used as the trip planning back-end for the field study presented in Section 4.4.

exercise [361]. In those cases, patients often get prescribed a certain number of steps per day, for example, 10,000 steps/day for healthy ‘active’ adults [216]. Standard mechanical or electronic pedometers typically track the step count then.

The concept allows embedding exercising in daily trips. That is enabled by coupling the current step count and the step history with a trip planning application. In order to be able to respond to the individual needs of the users, each user has a profile and can specify exercising goals as well as special needs. The goal can either be a specific step count that shall be reached on average per day or a training program that gradually increases the exercise intensity to raise the initial daily step count average to the specified goal. Special needs define whether a user needs barrier-free access (e.g., no steps, maximum inclination, even floor surfaces) or needs to transport something (e.g., walking aids or a stroller).

4.3.2 Individual Maximization of Route Effectiveness and Attractiveness

The users can further specify preferred training environments, such as cultural sites (e.g., historic, arts), parks, or shopping areas. When a user wants to plan a new trip, the user opens the trip planning application and logs in into their account. The user’s current step count is fetched via the API from a user-specified cloud-based fitness tracking platform. By comparing the current step count with historical patterns, the trip planning platform calculates an estimation of steps needed to reach the specified goal on that day. Together with the defined needs, preferences, and entered trip parameters, the platform determines several appropriate trip recommendations, including a

Figure 4.2: The algorithm uses a user-dependent attractiveness map to determine where the most enjoyable walking segment can be included in the *fitness route*. The left image illustrates a walking segment in a cultural environment (C indicates cultural sites). In the right image, a walking segment in a park environment is depicted (P indicates park area). Walking segments are often inserted when transferring between different modes of transport. Map data: © OSM contributors; Tram and bus logos: Munich Transport and Tariff Association.

so-called *fitness route* with an additional walking segment so that the step count can be reached. Figure 4.1 depicts the procedure of the prototype implementation.

As users are more motivated when exercising is diversified but done in environments users are feeling well in [276], an *attractiveness algorithm* creates an attractiveness map for each user by comparing the environment nearby the standard routes with user preferences (see Figure 4.2). The attractiveness map is adapted after each trip such that often-visited places get lower attractiveness values, and new walking segments are returned for next similar route recommendations. For future extensions, the attractiveness values could also be adjusted by giving feedback after a trip or including recommendations of similar users.

4.3.3 Prototype Implementation of the Fitness Route Concept

Our prototype is based on the open-source trip planning platform *OpenTripPlanner* [161] and uses OSM data [147] for calculating the routes. Schedules for public transportation are imported from general transit feed specification (GTFS) files provided by the public transportation agencies. The attractiveness map is implemented statically (precalculated) and only distinguishes between cultural sites, parks, and shopping areas. These maps are generated from the density of entries in the respective categories from the OSM data. The *OpenTripPlanner* platform performs a multi-factor optimization with user-dependent constraints [81] to allow for barrier-free access when needed and to minimize trip duration and number of transfers. The optimization also considers our contributed algorithms to maximize attractiveness and to reach the determined step count. The historical and current step count is retrieved from a fitness platform that allows real-time data gathering from coupled pedometers.

The calculation of possible walks is based on the time-dependent model of de Jonge and Teunter [77]. In the prototype, the walking segment is statically configured to be between $200\,\mathrm{m}$ and $1000\,\mathrm{m}$. The algorithm assumes that 50 % of the target steps shall be done before 1 p.m. For routes during nighttime (from 9 p.m. to 6 a.m.), the system does not suggest fitness routes.

4.4 Seamless Mobile – Prototype of a Context- and Service-Enriched Trip Planning Application

In this section, we introduce the prototype of our mobile trip planning application and present the results of a two-week field study we performed with it. Besides considering the gathered user requirements in Section 3.4, we included our novel fitness-routing concept. In addition, we conceived a nudging approach to influence the credibility of shown routing data.

4.4.1 Research Questions

In order to align the research with our formulated HRQs, we formulated the following RQs:

RQ1: Can the credibility of the shown trip data be enhanced by framing?

When optimizing a trip with respect to the number of necessary transfers or to be barrier-free, the generated routes might not look comprehensible at the first view since they are often not the shortest ones. For that reason, users need to be convinced of the correctness and the overall quality of the shown data. For that reason, we investigate whether the credibility of the shown data can be influenced by applying an approach of framing.

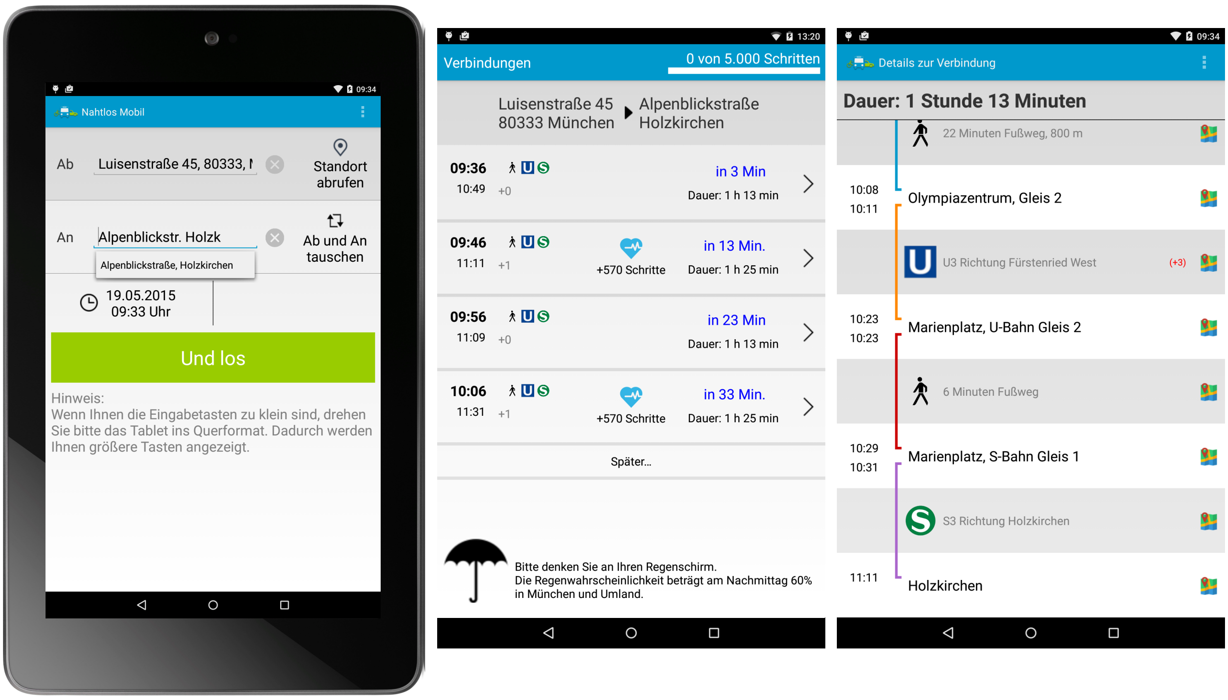
RQ2: Do the participants choose the extended mobility service *fitness route*?

We investigate in the study with our prototype, whether the people accept and use the integrated fitness-routing service.

RQ3: Does the *fitness route* provoke a positive effect on daily steps?

Here, we compare the daily steps taken before using our prototype and during the usage of the prototype. We investigate whether the subjects that have selected the routes with additional walking segments take more steps then.

The answers to this section's research questions contribute to **HRQ6** (How can users be motivated to actively deal with their mobility and assistance systems that can improve their mobility situation?).



Ab Luisenstraße 45, 80333, M

An Alpenblickstr. Holzk

Alpenblickstraße, Holzkirchen

19.05.2015
09:33 Uhr

Hinweis:
Wenn Ihnen die Eingabetasten zu klein sind, drehen Sie bitte das Tablet ins Querformat. Dadurch werden Ihnen größere Tasten angezeigt.

Luisenstraße 45 80333 München ▸ Alpenblickstraße Holzkirchen

09:36 10:49 +0 in 3 Min Dauer: 1 h 13 min

09:46 11:11 +1 +570 Schritte in 13 Min. Dauer: 1 h 25 min

09:56 11:09 +0 in 23 Min Dauer: 1 h 13 min

10:06 11:31 +1 +570 Schritte in 33 Min. Dauer: 1 h 25 min

Bitte denken Sie an Ihren Regenschirm.
Die Regenwahrscheinlichkeit beträgt am Nachmittag 60% in München und Umland.

Dauer: 1 Stunde 13 Minuten

22 Minuten Fußweg, 800 m

10:08
10:11 Olympiazentrum, Gleis 2

U3 Richtung Fürstenried West (+3)

10:23
10:23 Marienplatz, U-Bahn Gleis 2

6 Minuten Fußweg

10:29
10:31 Marienplatz, S-Bahn Gleis 1

S3 Richtung Holzkirchen

11:11 Holzkirchen

Figure 4.3: The Seamless Mobile app prototype was developed based on the findings of the user study on essential elements of trip planning applications as well as on the requirements gathered from literature research. The left screen shows the main screen that was reduced to the elements necessary to plan a route. In the center, the route overview is shown. When selecting a route, the route details are shown as depicted in the rightmost screenshot. The prototype was available in German only, a design prototype translated to English is depicted in Figure 4.4.

4.4.2 Prototype Application Seamless Mobile

In order to evaluate the approach of fitness-based routing and to optimize the credibility of the shown journey, the mobile app prototype Seamless Mobile for the Android platform has been developed as a research vehicle. Figure 4.3 depicts the main interaction screens. The substantial differences to other trip-planning applications are larger font sizes and the textual explanations for all icons. The main screen (left screen in the figure) has been reduced to the essential functions that are necessary for trip planning. For the start and destination, text completion based on data from the *OpenTripPlanner* back-end is enabled. The current location can be automatically set as the start. On the test device for the study, we also enabled *Google Voice Typing*[4] to allow speech to text for all text boxes. In the screen for selecting the departure time, it can also be switched to arrival time mode.

The trip overview screen, depicted in the middle screenshot of Figure 4.3, provides an overview of all calculated trips. Routes with fitness route (additional walking segment, cf. Section 4.3) are

---

[4] http://eguides.sprint.com/support/eguides/samsunggalaxytaba/content/samsung_galaxy_tab_a_ug/google_voice_typing.html, accessed February 15, 2019.

marked with a blue heart in the center. The screen displays the live step data from a connected pedometer via a back-end service[5] on the upper right. For each trip, the intermodal chain in the form of symbols depicting the means of mobility is shown. Below the symbols, the current delay of the first vehicle of the trip in minutes is displayed.

When a trip is selected, the detail view is opened. The colors of the different segments correspond to the line colors (when available). Each public transportation segment shows directly available information on platform and vehicle direction. When a symbol is provided for a certain kind of transportation means or line, the symbol is shown for easier recognition and navigation. Delays are also shown in the form of red numbers. When a delay gets too large, the trip can be automatically updated. The system tries to use the next vehicle in the next segment. If no next vehicle is available or the delay when taking the next vehicle is getting larger than 15 minutes, the application suggests calculating a new route with the same destination and the current location as the start. By touching the map symbol on the right, a map view is opened. When activating the map view for a station, the station and its surroundings are shown on the map. A marker indicates the station and, when the corresponding data is available, its entries. When the map symbol is touched for a travel segment, the course of the line is indicated (straight line, when no coordinates are provided), or, when walking, the way to walk is shown. From the map view, the pedestrian navigation of Google Maps[6] can be launched. However, when switching to the Google Maps navigation, the walk route can derive from the shown route in the map view, since different data has been used in our back-end for calculating this route.

The mobile application had several preferences that could be set by the users:

- Daily step goal: Defines a daily goal. The default value for the prototype was 5,000.
- Mobility aid required: Users can select between *no mobility aid*, *rollator*, and *wheelchair*. When a *rollator* or *wheelchair* is selected, the application automatically switches on the barrier-free flag.
- Barrier-free required: Also, when no mobility aid is required, users can select that barrier-free routes shall be calculated.
- Step length: Users can configure their average step length to get a better estimation of the required steps. The default value for a user without a mobility aid selected is $0.64\,\mathrm{m}$ [168]. For mobility aid users, the default value is $0.30\,\mathrm{m}$ [299].
- Fitness route preference: Users can select between *park*, *cultural*, and *shopping* areas for their preferred areas in which an additional walking element shall be added when possible (fitness route, cf. Section 4.3).

---

[5] In this project, the health tracking portal https://hline-online.com of the HMM Diagnostics GmbH was used, as the company was one of the partners in the project PASSAge.

[6] https://play.google.com/store/apps/details?id=com.google.android.apps.maps, accessed June 21, 2019.

As a technical preference, the ID for assigning a pedometer to the application could be set. We preset this ID and locked the setting for the study devices.

4.4.3 Individualized Route Creation

The context is essential for creating and suggesting suitable intermodal trips (cf. Section 3.2.2). The fitness-based routing is an example of context information that directly influences the trip planning.

In Figure 4.4, a journey overview screen is shown. In the upper right corner, the current count of today's steps, as well as the target for the day, are shown. The progress bar is used to visualize the progress better and to add a game-like element (cf. Section 2.4.2). Below, the suggested trips are shown. The second trip is a so-called *fitness route* where an additional walking segment has been added to the route. The blue heart in the line indicates this. The estimated number of additional steps is displayed below. The step count is derived from the distance and the step length that has been configured individually by the user. A default step length of $0.64\,\mathrm{m}$ has been configured [168]. For users of mobility aids, the default step length was set to $0.30\,\mathrm{m}$. In the shown case, the user was dependent on a rollator. For that reason, the fitness-based routing algorithm has created a barrier-free segment, which is indicated by the rollator symbol in the trip summary. In that case, the walking segment has been added for a transfer near a public park, since the user has chosen that being in nature is a preference. The walking segment was created by getting off the bus a station earlier before the actual transfer station.

4.4.4 Reliability and Confidence

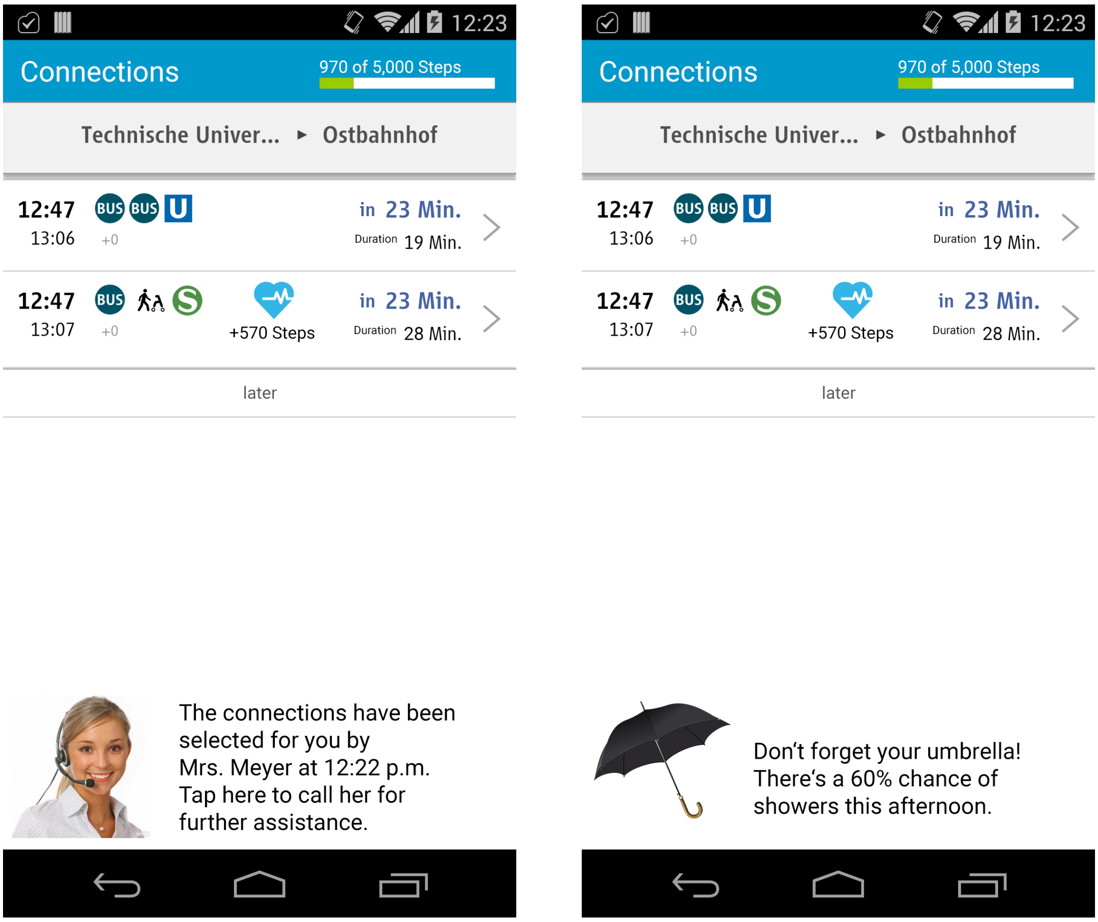
One of the identified barriers was *lack of trust*. That means that users do not accept the presented trip suggestions or do not trust the shown information for a trip [25]. For counteracting this barrier, the approach of providing full data transparency was employed. In addition, a framing approach was evaluated. For that, we implemented two framing concepts:

1. Personal recommendation: the user shall believe that a human has curated the shown journeys.
2. Presenting checkable and comprehensible data in the form of rain probability.

Figure 4.4 shows examples of the two concepts. The personal recommendation is a static text with different 'fake' contacts (list of random German names with stock images) and the current time. The rain probability is queried via a weather API[7]. Depending on the rain probability, the application suggests to carry an umbrella or displays that no rain is expected for the journey.

---

[7] The AccuWeather API was used in the application: http://apidev.accuweather.com/developers/, accessed March 6, 2019.



The connections have been selected for you by Mrs. Meyer at 12:22 p.m. Tap here to call her for further assistance.

Don't forget your umbrella! There's a 60% chance of showers this afternoon.

Figure 4.4: The added contents in the bottom part of the connections overview were displayed in a field study for evaluating the effect on trust and confidence in the above-displayed routes. The depicted screens are manually translated design screens. The original layout and sizes are depicted in the actual screenshots of the prototype in Figure 4.3.

The hypothesis was that personal recommendation leads to higher confidence and trust in the presented routes. That was based on research results by Burgoon et al. [51]. They concluded that “human partners are judged higher on credibility than computer partners” [51, p. 566].

Randomly, either no framing content, personal recommendation, or the rain probability was shown. From time to time, the application asked the user to evaluate the perceived credibility of the presented journeys on a 5-point Likert scale via a modal popup. The items ranged from 1 *strongly implausible* to 5 *strongly credible*.

4.4.5 User Study with the Seamless Mobile Prototype

The user study was conducted as a field study. We installed the mobile app prototype on a 7 inch Android tablet PC (Nexus 7, model 2013). The devices had an active mobile data connection. They were equipped with a specially developed application launcher that had larger symbols and texts. Besides the trip planning application, the rollator training app (cf. Section 5.4) and several news applications had been installed.

The participants received an introduction to the general operation of the tablet computer. A short, printed manual summarized how to switch the device on and off, how to charge the device, and what can be done in case of common problems (e.g., charging when the device could not be turned on). A telephone number was also provided to the participants in case they have further questions or problems.

Task

The subjects were asked to use the developed trip planning application for their daily traveling for two weeks. They should perform the planning with the application and use the application to get information during journeys. In addition, the participants should wear provided pedometers when they performed outside trips.

Data Collection

The data collection for the app usage was based on data logging on the tablet PC as well as on server-side logging at the trip planning platform. Client-side logging focused on the usage of the application. The server-side logging targeted the planned and selected trips. Besides, the step count was logged via the connected pedometer the participants should wear on their shoes (except for the one wheelchair user).

After two weeks, the participants returned their devices. At this point, a short interview was conducted. The goal of the interview was to gather qualitative feedback on the application. We also asked for possible effects of the application on their mobility behavior.

Participants

13 subjects (9 female, 4 male), aged between 63 and 77 years ($\mathrm{Mdn} = 68$ years, $\sigma = 4$ years), took part in the study. They were recruited in a rehabilitation sports group in Munich and a senior club[8]. 9 subjects had a mobile phone. 5 subjects had a smartphone and used it regularly. 3 subjects had physical impairments and required a mobility aid (rollator) to cover longer distances; 1 subject had to use a wheelchair. The participants did not receive any compensation for their participation.

---

[8] The senior club *50plus Verein e.V.* from Holzkirchen brings elderly people together and organizes events targeted at elderly people.

4.4.6 Results of the Study with the Seamless Mobile Prototype

Usage of Route Planning

The analysis of the log data from the *OpenTripPlanner* (server-side) and the mobile application (client-side) has revealed the following usage of the app prototype in the two weeks:

1. Overall, 359 trips were planned successfully. For another 94 trip planning requests, the start or the destination could not be determined from the provided data, for example, because of typos or incorrect addresses.
2. From the 359 trips, 144 requests had different start and destination address combinations (considered as unique trips). The other 215 planned trips were repeated routes with identical (about 1/3) or different travel times.
3. For 87 planned trips, the requested travel time was more than 1 hour in the future.
4. The detailed route description was opened for 92 routes. 40 of these routes were fitness routes, i.e., routes with an additional walking segment.
5. 38 requests were not successful since there was no Internet connection.

The *OpenTripPlanner* platform stored anonymized logs for all queries. These logs have been analyzed to identify the main problems of the 94 unsuccessful requests (1). Similar to the observations in Section 4.2.3, the main problems were again related to the input of address data:

- Missing spaces in addresses (e.g., no space between the street name and house number or city)
- Input and typos that made it impossible to recover the typos in addresses (e.g., missing characters, spelling errors, and a few words that looked like gone wrong auto-correction)
- Incomplete addresses (e.g., there were several requests with less than 4 characters)

In addition, we noticed that many requests had numbers or letters with diacritics in the addresses. These problems, however, have been caught by the platform as far as possible. The problematic secondary functions of input keys had been identified in the field study with established applications (cf. Section 4.2).

In the post-study interview, the participants were asked about their experiences with the application. As the numbers and analyzed errors for failed trip planning indicated, the subjects named the text input to be their primary challenge. Only two participants made use of the voice input feature that has been shortly explained in the introduction of the trip planning application. Their feedback was that the speech to text mechanism was working in most cases. One subject summarized that she had several situations where the system "understood something that was not a bit related to [address names]." That is due to the missing *address context* of the voice typing system.

The design was evaluated to be appealing. The provided functions were rated to be enough for daily trips. One subject was missing the option to provide an arrival time, which was available in the application, but not directly accessible on the main screen. Although we tried to make all icons large enough, one participant named too small icons as a problem.

The feedback on the automatic re-calculation of routes when the delay becomes too high was diverse. While two subjects found this a positive feature, another subject reported this to be confusing. Overall, the display of the delay information and delay handling received some negative feedback, since this real-time information was not available for certain lines (especially bus lines). One subject suggested adding some symbol or explanation that there is no real-time delay information available for the displayed segment. Although all subjects were told that personal preferences could be made in the settings (accessible via the context menu on the main screen), only 5 of the 13 subjects changed some preferences.

RQ1: Results on Trust and Credibility

In Definition 5 (Section 2.4.3), we defined credibility as a perceived quality that is heavily influenced by its presentation and the context of the presentation. In this study, the context was artificially altered by the additionally shown framing content. The results in this section indicate the credibility of the shown trip suggestions depending on the applied framing condition.

Overall, 104 credibility ratings were reported back in the logs. The absolute frequencies of the ratings for the different framing conditions are summarized in Table 4.3. In general, all subjects stated that the rain probability was enriching information.

#	Statement	SI (1)	I (2)	N (3)	C (4)	SC (5)	M	σ
E1	No framing was applied.	2	4	10	12	6	3.47	1.11
E2	Personal recommendation was displayed along with the journey data.	4	3	11	10	6	3.32	1.22
E3	Rain probability was shown with the trips.	2	2	5	15	12	3.91	1.11

Table 4.3: Absolute frequencies of respondents' opinion on the credibility of the shown journey data in dependency of the applied framing. The credibility is rated from *strongly implausible* (SI), *implausible* (I), *neutral* (N), *credible* (C), to *strongly credible* (SC). M stands for the average value and σ for the standard deviation.

The Shapiro-Wilk test [334] shows that all three credibility ratings are not normally distributed ($\alpha = 0.05$, $p < 0.01$). For that reason, the Mann–Whitney U test is used to analyze whether one framing causes higher perceived credibility than another. The only significant difference can be found between the personal recommendation (**E2**) and the rain probability (**E3**) with $p = 0.026$. Thus, the perceived credibility of the rain probability framed journey data is higher than the ones with a personal recommendation. With a probability of $p = 0.058$, the difference between no framing (**E1**) and rain probability (**E3**) is not significant. Still, it shows a slight tendency towards higher credibility of data framed with the rain probability.

The results show that the hypothesis of generating trust and credibility by making believe that a human is part of the technical process of trip planning was not correct. Subjects rated the presented trips more credible when the rain probability was shown.

In the post-study interview, we asked the subjects also about the framing conditions. The following points summarize the feedback:

- One participant found it positive that the routes were created or at least checked by a human operator.
- One study participant complained that he could not reach the shown contact person when he called the provided support telephone number.
- Two subjects doubted that there was really a human that compiled the route suggestions. Their feedback was that "[the route suggestions] appeared so fast," and one proposed route suggested to travel via a stopover in the opposite direction that "no normal person would do."
- All but one found the rain probability valuable additional information. The skeptical one complained that the app told that there should not be rain, but when she traveled, it rained.
- A subject was confused that there was no "rain warning" shown, although it already rained outside.

The overall conclusion of the personal recommendation framing condition is that the randomly shown contact people were too unapproachable. The fast – quasi instant – presentation of trip suggestions made it appear to not having been compiled by a human. For the rain probability framing condition, the feedback was quite positive. However, it has been shown that this information should be very reliable for not plunging the users to trust the other presented data.

Further qualitative feedback revealed that the inclusion of the user context could also have been an essential contributor to credibility. Two participants named that the display of their mobility aid (one rollator user, one wheelchair user) in the route description was a selection criterion for them. One rollator user stated, "when I saw the rollator symbol in the route description, I always chose one of these routes." That is an interesting finding since walking – or, in that case, the rollator symbol – was only shown when a longer walking segment was part of the route (e.g., in the proposed fitness routes). The participant further stated that she never had problems on the "rollator routes."

From the numbers gathered in the credibility ratings and the qualitative feedback, we conclude that framing is a possible measure to increase the perceived credibility of the displayed data. In this study, the self-verifiable rain probability worked better than personal recommendations. However, it is more important to have correct and complete data as well as taking the individual context into account.

Results on Fitness Route Usage and Effects on Users' Mobility

The analysis of the *OpenTripPlanner* logs revealed that 7 of the 13 subjects had a detailed look at a total of 40 fitness route trips. From these 7 participants, four had selected park areas as their favorite environment to do a short walk. The other three had no preferred walking area selected, which leads to an unweighted calculation of additional walking segments (cf. Section 4.3).

RQ2: Choice of Fitness Routes

Based on the 40 selected fitness trips, we correlated the gathered step data of the pedometers from the respective tablet PC and pedometer combination. Since the subjects did not always wear their pedometers on the shoes they wore for a trip, we cannot finally determine the number of conducted trips. A correlation (based on planned time and estimated duration) was found for 4 planned trips; however, according to the feedback in the interviews, there should have been at least 11 trips. Details on the 4 fitness trips are presented in Table 4.4. The actual steps and the duration have been determined by taking into account the data between two longer breaks, which were considered to be the segments where the subjects were in vehicular transportation.

Trip #	Distance	Mobility aid	Configured step length	Calculated steps	Calculated duration	Actual steps	Actual duration
T1	$469\,\mathrm{m}$	-	$0.69\,\mathrm{m}$	679	$361\,\mathrm{s}$	822	$397\,\mathrm{s}$
T2	$838\,\mathrm{m}$	-	$0.64\,\mathrm{m}$	1309	$643\,\mathrm{s}$	1247	$590\,\mathrm{s}$
T3	$548\,\mathrm{m}$	-	$0.64\,\mathrm{m}$	857	$422\,\mathrm{s}$	914	$669\,\mathrm{s}$
T4	$219\,\mathrm{m}$	rollator	$0.30\,\mathrm{m}$	731	$378\,\mathrm{s}$	776	$438\,\mathrm{s}$

Table 4.4: Four fitness trips could be correlated from planned trips to step data gathered by the worn pedometers. An average walking velocity of $1.30\,\mathrm{m/s}$ was used in the application [36]; for users of mobility aids, the gait speed was set to $0.58\,\mathrm{m/s}$ [299]. The actual steps and duration are an estimation by counting the steps and calculating the duration between two longer breaks in the step data (vehicle driving segments).

For the 4 trips, the average distance of the additional walking segment was $519\,\mathrm{m}$ ($\sigma = 255\,m$). Only one subject (**T1**) had set an individual step length; all others kept the default values. The deviation of the calculated steps to actual steps was, on average, 0.07 ($\sigma = 0.11$). For the duration, the deviation is higher ($\mathrm{M} = 0.19$, $\sigma = 0.28$) due to the outlier in **T3**. Without **T3**, the average deviation is 0.06 ($\sigma = 0.13$).

As elaborated in Section 2.4.3, providing suitable default values for the average user is important. Due to the small number of samples, we cannot finally conclude that using the default value for step length would be sufficient. However, the data indicates that a suitable assumption was made.

RQ3: Effect on Daily Steps

The step counts have further been investigated whether there was some change over time recognizable, but no significant effect could be detected. There was a slight tendency of fewer steps on weekends and days with longer periods of rain in the study region. However, since most of the subjects did fix the pedometer permanently to one pair of their shoes, the step data was incomplete and, thus, we did not further analyze the data.

In the interview, the subjects were asked about the fitness route and the overall effect of the application on their mobility. All participants found the concept of the fitness route positive. 9 subjects stated to have used the feature. That contradicts the data in the logs showing that only 7 subjects did open the details of fitness routes. One rollator user highlighted that he always used the fitness route when it was offered. According to the subjects' estimations, the fitness route should have been selected at least 11 times. The distance of the additional walking segments was rated as appropriate. One subject stated that the fitness route sent her along a very muddy way, and suggested to be able to select that only paved ways should be taken. Another participant explained that she wanted to use the fitness route but could not understand the displayed route and, thus, walked to the known bus station on her own. Another subject said that at "the first time, it felt strange to leave the bus one station before the station that is located directly opposite my house." But it made her aware of this possibility to get more exercising. "Later on, I did not need the [fitness route] suggestions anymore," she further said, since she then added herself extra walking segments to her usual routes.

As reasons for not choosing the fitness route were mentioned the following points:

- Longer duration: Subjects did not want to spend the extra time. This time was often not only caused by the walking segment but also through additional waiting time, since, for example, direct connections at transfer points were intentionally missed by the fitness route planning algorithm.
- Bad weather: Rainy weather, slippery road conditions, and mud after a rain was the main reason for most of the subjects not to take the fitness route. One participant noted that she takes public transportation on purpose when the weather is bad and, thus, she does not want to walk then.

- Physical fitness/health: It was stated that the trip itself is already very stressful and physically taxing. For that reason, another walking segment has not been chosen.
- Transport of goods: Two subjects stated that they would not take the fitness route when they have to transport something (e.g., purchases).
- Unaware of function: although the *fitness route* functionality was explained beforehand and a printed manual was available, three subjects did not notice the fitness route.
- No fitness route offer: One participant said that he never saw a fitness route from his home to the next city. That may be the case, e.g., when the distance between stops is very long (e.g., when there is only one stop in the city, or when the first stop in the city is already the most suitable stop to exit. Currently, the fitness route algorithm does not add extra ways at the end or the start of the trip, when those would lead to longer public transportation time.

4.4.7 Discussion of Study Results and Improvement Potential for Seamless Mobile

The major challenge for the participants was the text input. Our observed results match with the related research on the text input performance of older users [281]. In order to reduce the complexity of operating mobility-related HMI (**HRQ5**), it is essential to limit the necessary text input to the minimum as well as offering other input modalities. When offering voice input for spelling the addresses, the interpretation system should be linked to the database of existing addresses in order to derive the hit(s).

From the logs and the feedback, we saw that only 5 of 13 subjects changed their settings, although the menu had been shown to the subjects, and the possible mobility settings had been explained. Since these settings have a high impact on the kind of route calculation, for example, concerning accessibility when a mobility aid was selected, or the suggestion of fitness routes when the preferred area is set, these settings should be centered. A possibility would be offering a setup wizard that is automatically triggered on the first use [45]. That could be coupled with the behavioral economics approach of *setting defaults*, for example, to set a reasonable high daily step goal (cf. Section 2.4.3). For settings such as the preferred area for fitness route calculation, the user could be informed about the possibility to adapt upon first use. Another possibility could be to gather more context on the user and to adapt settings automatically [237]. For example, when a user regularly takes the elevator, which can be detected by smartphone sensors [427], then the route calculation could be adapted to prefer barrier-free routes. Besides the settings, users were also partially unaware of the fitness route functionality. For such features, there could also be a hint displayed when a first fitness route suggestion gets on the screen.

A drawback of showing weather data could be that trips are canceled due to the bad forecast. In that case, an unintended behavior of the nudging may be triggered [26]. However, although research from Cools and Creemers [67] has shown that making changes in activity-travel behavior is indeed significantly based on the type of forecast weather, “the different methods of acquiring weather information (exposure, media sources, and perceived reliability) did not appear to impact the probability of behavioral adaptations." [67, p. 19]. For that reason, we assume that this information would lead to canceling only a few trips. We assume that the quality of the forecast has a more substantial impact. The subjects named several times that the displayed rain probability was wrong. LeClerc and Joslyn [217] have shown that there is a so-called "cry wolf effect" by wrong weather forecasts. When raising too many false alarms, people tend to ignore the weather forecast and doubt the credibility of the source. In our nudging case, this could affect the trip data presentation negatively. However, since the nudging approach in the application has shown not only a rain warning but also the rain probability, the effect was already reduced. In order to further reduce the negative effect, the probability level from which on the rain warning is displayed could be adapted [217].

Using the personal contact could trigger a loss of trust when people get to know that actually no human was involved in the process of the trip suggestion compilation, and – in the worst case – this person does not even exist. As stated in the results, the subjects did not believe that a human created the choice of routes for them. However, having someone to contact in case there is a question or problem was mentioned to be good. For younger users, text-based chatbots are a viable alternative [422]. For elderly users, digital chatbot support can also be an alternative when they support voice communication [356].

4.5 Summary of Contributions

In this chapter, we have reported on the importance of different extended functions in trip planning applications and on two approaches to influencing individual mobility. In the following, we summarize the key findings and recommendations of this chapter:

- The major challenge for the elderly subjects was text input. The integration of other input modalities, such as voice input or selection of locations on a map, can reduce the effort needed.
- From the existing extended services in trip planning applications, subjects rated *purchasing of tickets* and display of real-time delay information as the most important.
- The primary missing information was general information about barrier-free access, and, if this info was available, there was no real-time data on the operation status of means for barrier-free access.
- We recommend automatic re-calculation of routes in case of excessive delays that cause the participants to feel as if they are losing control.
- Presenting checkable content, such as the weather forecast for the next few hours, next to trip planning results has the potential to enhance the credibility of data.

- Visualizing the considered user context (e.g., displaying a mobility aid symbol for users of mobility aids) in the route suggestions greatly enhances the credibility of the displayed routes.
- For the fitness route concept, no direct effect on increasing the daily step count could be identified. However, the subjects stated they had used the function and that the function continuously reminded them to move a bit more.
- User preferences remained mainly unchanged. Thus, reasonable defaults have to be set, or, in case the data are necessary, some active inquiry has to be implemented.

Chapter 5

Mobility Compass – Usability Aspects in Physical Mobility

5.1 Problem Definition and Research Questions

A 2017 study on automotive dealerships revealed that "consumers may remain underinformed or misinformed about the ... technologies" [3]. On the one hand, this refers directly to the understanding of how the different functions work and what limitations the systems have. On the other hand, it also concerns the operation of the functions a vehicle is equipped with. That leads to situations with, in the best case, limited comfort, or, in the worst case, to accidents caused by incorrect usage or inactivated functionalities. For the example of automotive user interfaces, we investigate in this chapter how the awareness of functionality can be increased and how users can be better trained for the operation of HMIs they are not used to.

The second mobility-related training aspect we investigate in this chapter is physical exercising with a mobility aid. The goal is to show how exercising can be combined with training in the correct usage of a rollator.

The usability problems we cover in this chapter can be separated into general and mobility-related ones. Specifically, we examine the following general usability issues:

- Limited awareness of available functions: Users do not have an overview of the offered/supported functionalities.
- Constantly growing design space: The amount of functionality is steadily increasing (cf. Section 5.2.1). The digitalization of functions leads to functional extensions where users do not expect it (e.g., activating the triple-turn signal by softly touching the steering column switch for the turn indicators).
- Incomprehensible implicit interaction paradigms (e.g., suppressing of functions as a result of situational awareness algorithms).

The mobility-related usability issues comprise:

- Lack of physical fitness.
- Missing consistency of interaction methods (e.g., latching flash indicator switches and tip switches) and manufacturer-specific labeling for non-standardized vehicle functions (e.g., for driving assistance or infotainment functions).
- No HMI for mobility aids at all because they are still mainly analog devices.

In the first part of this chapter, we introduce and compare two approaches to training users in the operation of mobility-related HMIs. In the second part, we share the results of our PMD-based physical exercising assistant for mobility aid users.

The research in this chapter contributes to answering our following HRQs:

- **HRQ4**: How can the complexity of operating mobility services and assistance systems be reduced for users?
- **HRQ5**: How can users be supported in accessing and using mobility services and means of mobility?
- **HRQ6**: How can users be motivated to actively deal with their mobility and assistance systems that can improve their mobility situation?

This chapter is partly based on seven papers we published between 2012 and 2015 [88, 90, 91, 93–96].

5.2 Mobile Device-Based Training of Automotive User Interfaces

5.2.1 Assessment of Vehicle Functionality and Driver Behavior

An analysis of the in-car design space by Kern and Schmidt shows the enormous increase of mainly comfort functions and, with that, control elements in the last few years. The analysis highlights that the development is not only driven by car manufacturers but also the drivers demand increasing comfort. With longer commutes, a car becomes more than just a means of transportation. It can be seen as a “multi-functional living space” where people consume media, communicate, or even work [192]. With the increasing number of control elements, a one-to-one mapping is no longer possible, and the introduction of multi-purpose input/output-devices was necessary. The different functions are no longer apparent, and a certain amount of experience and training is necessary. For our concept, we assume that especially secondary (mostly safety increasing functions, e.g., activating turning signals or windshield wipers) and tertiary driving tasks (comfort functions including infotainment system) need to be trained [385]. The primary task of driving should be well-practiced and equal between different car types and makes (the difference between automatic and manual shifting is not considered here).

Even though tertiary tasks are not essential for operating a vehicle, they are performed regularly during the drive and thus heavily influence the driver and the driving performance. In a mental workload experiment, Lansdown et al. [214] examined possible safety impairments of drivers when facing multiple simultaneous tasks. The results show that operating secondary and tertiary tasks leads to increased workload, which results in decreased headway and higher brake pressure. Drivers often compensate for the higher mental load by reducing their speed. Higher mental workload is especially the case when drivers operate functions in a cockpit they are not used to [344]. In those cases, visual distraction is the primary reason for the higher workload [214].

Wu et al. [418] have analyzed the vehicle entry and the start process, including the necessary adjustments that are essential for a safe drive. Surveys have shown that many people do not make the necessary adjustments (e.g., seat, rear-view mirrors, steering wheel) before they start the drive. In many cases, this is made up during the first few meters of the drive, and sometimes the adjustments are entirely skipped. However, wrong adjustments are often the cause of accidents [376]. There are multiple reasons why people make inconvenient adjustments or even skip the adjustment step [181]. Besides being in a hurry, some drivers also have problems with the operation of the different levers for manual or powered adjustments of the seat, rear-view mirrors, or steering wheel position. In addition to adjusting safety- and driving-relevant elements, a more relaxed journey is also possible when other secondary and tertiary comfort functions are controlled before the drive starts. Examples are the input of the destination in the navigation system, setting the temperature for the automatic climate control, or choosing the desired radio station.

5.2.2 Gamified Training Concept

Our training concept aims at novice and advanced beginner drivers of vehicle models. The main scenario covered in this work are users of the younger generation that regularly change car models, for example, because they are using car-sharing vehicles in their daily mobility. The concept is based on a mobile application that can be used on the move.

Exploration Mode and Quiz Mode in the Virtual Cockpit

Especially users that are avoiding manuals prefer the *trial-and-error* method for gaining proficiency [253, 290]. However, this method causes unnecessary distraction and, thus, safety risks when performed in moving vehicles. In our concept, this method is addressed by a one-to-one mapped virtual representation of the vehicle's interior. That way, users can explore the cockpit and the functions of the different controls before they enter the vehicle. The exact content and training depend on the respective vehicle models. In our scenario, a user plans a multimodal trip with the help of a mobile application. In this application, the car-sharing vehicle could, for example, be directly reserved. While the user is on the way to the car, the application could automatically load the respective training for the reserved vehicle.

The *exploration mode* offers a cockpit and a function view. In the cockpit view, a virtual representation of the real cockpit is shown. The users can freely roam and find the input elements themselves. When clicking on an element, a visual explanation shows how to operate the input element and what functions are connected to it. The visual explanation is either a still image or an animation. When an input element can be operated in multiple ways, the ways are explained one after the other. The functions view consists of a list indicating what functions have been found so far. Missing objects are greyed out, and, when clicked, users get a hint on where to find this function in the cockpit view. When clicking on an already discovered element, the visual explanation is shown, and the element can be highlighted in the cockpit view. The function view serves as a reference list where users can lookup functions.

The *quiz mode* supports establishing the explored functions and the layout of the vehicle cockpit. The quiz mode makes use of both the cockpit and the function view. The tasks in the quiz consist of finding the element for operating a given function in the cockpit view or choosing a function from a single choice list for a control element that is highlighted in the virtual cockpit. The time for answering a question is limited. Points are awarded for the right answers, and bonus points can be earned by answering quickly. A quiz consists of five questions. The achieved points are accumulated. The app saves and displays the highest score in order to allow the placement of the current round's results.

Employed Game Elements

As defined in Section 2.4.2, when using game elements, there should be comprehensible goals and rules. The *goal* of the application is to inform the user about the vehicle functions and the operation of those. The goal is stated in the application's description and is identifiable in the tasks (explanation of the functions and their operation). The *rules* are also in the respective mode descriptions. The tasks are intentionally kept very simple (e.g., clicking on identified control elements in the virtual cockpit), which allows for easy identification of the next actionable steps. Feedback is given via a progress gauge that indicates how many elements still have to be found. In the quiz mode, the user also receives feedback on the progress, and a score is awarded for correct answers. The score is kept in a high score list to allow for ego-involvement [210], which shall motivate to repeat levels to improve the score. In a later version, it is also planned to be able to compare the score with other users. Before the user can access the quiz mode, milestones have to be reached, which can be seen as intermediate goals that guide the user.

However, the scoring mechanism is not central to the application; users can also advance with low scores. That is to avoid outshining the underlying non-game training context, which is of higher importance than the game mechanics. We avoid the extensive use of a badge system as badges are often seen as very generic and organization-centered [101]. For example, a badge for taking a quiz ten times will shift the focus away from intentional repetition to a mechanic, dull task.

5.2.3 Implementation of the Prototype

In order to evaluate the gamified training concept, we built a prototype for the Android platform. We implemented the exploration mode and quiz mode. The exploration mode includes the virtual cockpit and function view. The quiz is started from the application's main menu, which is depicted in Figure 5.1. For the driving simulator evaluation, we had access to a real chassis-based BMW series 5 (model 2005) driving simulator. The training modes were created to match the interior and functions of the experiment environment. The cockpit view is a realistic recreation so that the driver can make a connection between the view in the application and the real cockpit (see Figure 5.2); only the steering wheel was shrunk so that it does not cover other control elements. The user can interact with the cockpit through the standard Android interaction gestures. A total of 32 elements were implemented. In the exploration mode, the progress indicating the found elements is shown in the top right corner. When an element has been found, a white outline is added to mark the already explored ones. Each control element has an own description page with a textual and visual explanation of the element and the connected functions (see Figure 5.3). The function view lists all available functions. Functions that have not yet been explored in the cockpit mode are grayed out. When clicking on a grayed-out function, a message with a hint where to find the element in the cockpit pops up. When clicking on already explored functions, the explanation is started.

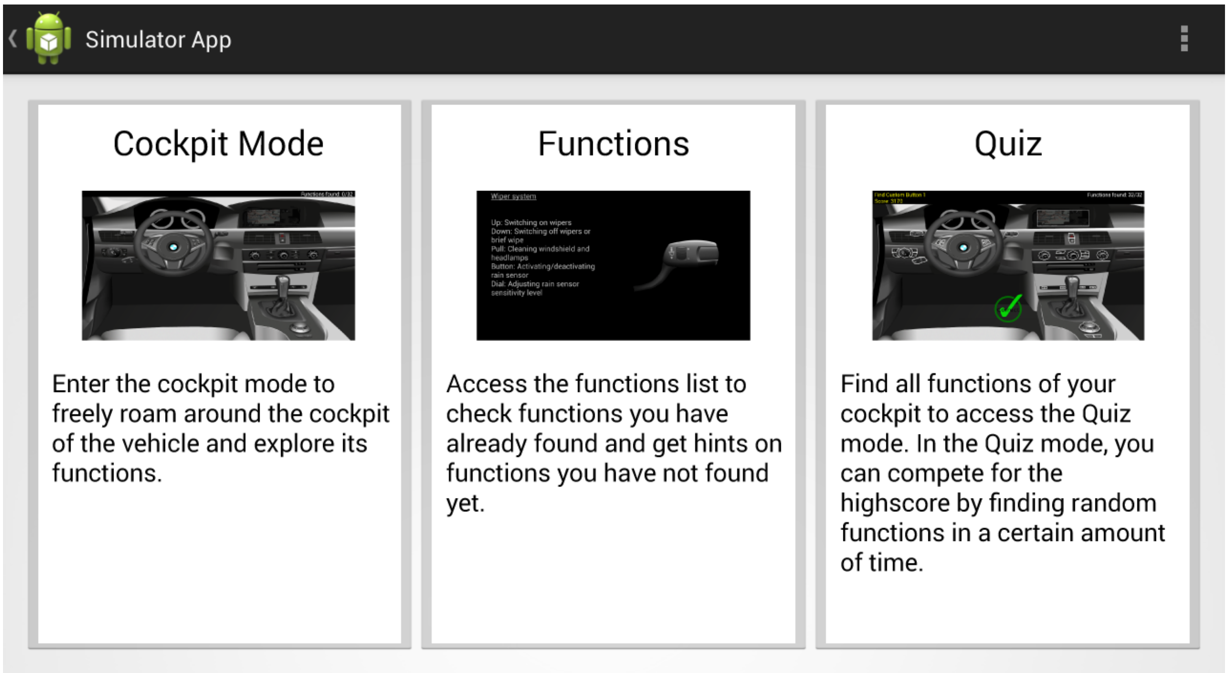
The quiz mode is realized as an overlay of the cockpit view (see Figure 5.4). The current quiz task and the score are displayed in the top left corner. Visual and auditory feedback for indicating right and wrong answers is given when a user clicks on an element. When the quiz is over, the app displays a scoreboard presenting the final score (points for correct answers + time bonus − points for wrong answers). Besides, the high score is shown, and the user is informed when a new high score was reached.

5.2.4 User Study with the Mobile Device-Based Automotive Training Prototype

We evaluated the described training concept regarding its effects on driving performance and function operation in a driving simulator experiment.

Research Questions for the Experimental Evaluation

The study was conducted to provide answers to the following RQs:



Cockpit Mode

Enter the cockpit mode to freely roam around the cockpit of the vehicle and explore its functions.

Functions

Access the functions list to check functions you have already found and get hints on functions you have not found yet.

Quiz

Find all functions of your cockpit to access the Quiz mode. In the Quiz mode, you can compete for the highscore by finding random functions in a certain amount of time.

Figure 5.1: The main menu of the mobile training application. It allows access to the exploration mode ('Cockpit Mode' and 'Functions') and the quiz mode.

- **RQ1**: Is the influence of secondary and tertiary tasks on the driving performance a significant problem?
- **RQ2**: Is the training effect of the mobile app similar to the effect of gaining experience in the real car?
- **RQ3**: Does the use of the training application influence the detection rate and operation of vehicle functions?
- **RQ4**: Will subjects perform safety-critical actions or even follow dangerous recommendations while driving in order to get a higher score from the training system?
- **RQ5**: How does gamification affect the training?

In order to measure the effects of the gamified training application, the participants were randomly divided into two groups (between-subjects design [61]):

1. Without any training (control group).
2. 10 minutes of training with the mobile application (experiment group).

Task

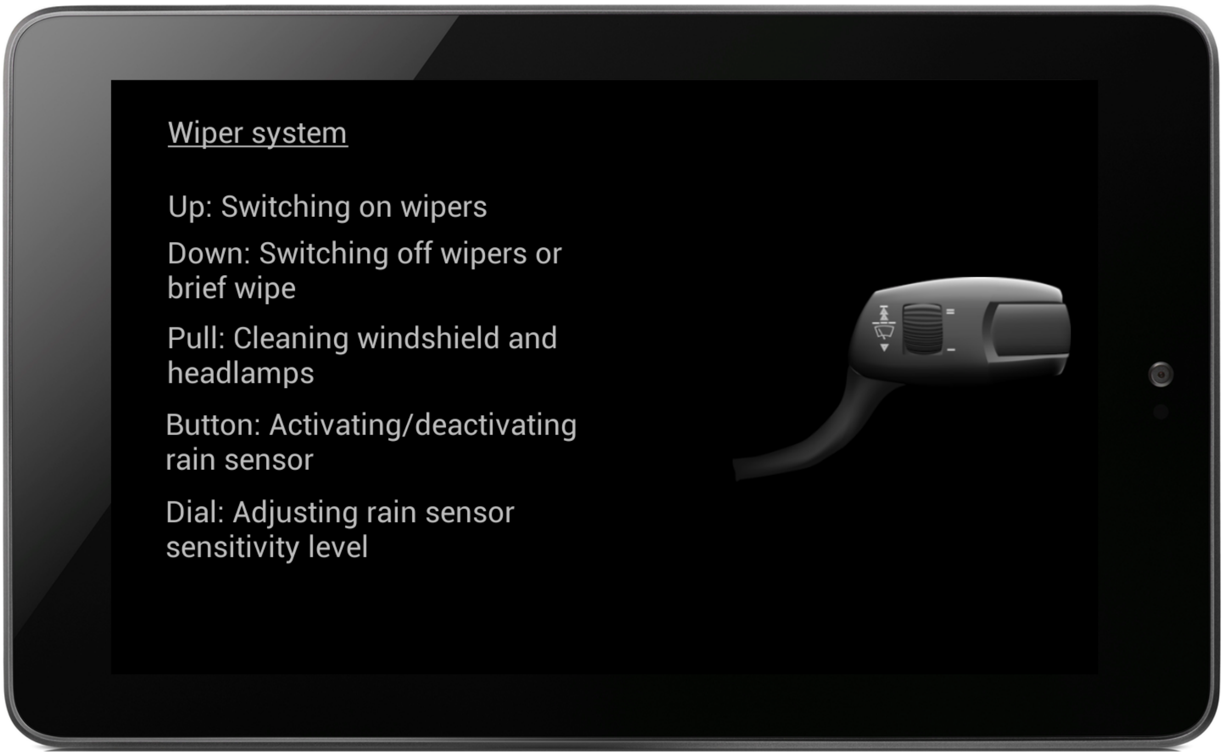
The experiment was performed in a real car cockpit-based driving simulator (BMW series 5, model 2005). Figure 5.5 depicts the simulator. The driving task was the so-called lane change task (LCT)

Figure 5.2: The cockpit mode of the mobile application. By clicking on an interactive element in the cockpit, the application shows usage details (see Figure 5.3), and awards points to the user for newly found functions.

by Daimler [151, 260]. The maximum speed was set to 60 km/h. The secondary and tertiary operating tasks to be performed by the subjects were shown on the lower part of the dashboard and were triggered automatically based on the driven distance. The subjects were instructed to focus on their speed, to perform the lane changes indicated by the simulation tool, and to keep their track. Although the participants should focus on driving safety, the displayed operating tasks should be performed as fast as possible. The operating tasks are summarized in Table 5.1.

The experiment began with a brief introduction for both groups. In a pre-experiment questionnaire, demographic data, driving experience, and experience with technical systems such as smartphones were gathered. Afterward, the experiment group got a short introduction to the mobile application prototype, which ran on a Google Nexus 7 tablet PC. Then, the subjects could freely explore and use the gamified application for a maximum of 10 minutes. The subjects in the control group immediately progressed with the driving task.

The driving task consisted of four laps (each 3,300 m, ~3.5 minutes) in the LCT simulation. In the first lap, subjects got an introduction to the simulation environment and the LCT. In the second lap, baseline data on the driving performance was recorded. In the baseline lap, no extra operating tasks had to be performed. For the last two laps, subjects had to perform the additional operating tasks (cf. Table 5.1) in parallel to the normal driving task. After the third lap, a summary of their operating performance in the form of an automatically calculated score (composed of accomplished task score and time bonus) was presented to the subjects. Before they started the



Wiper system

Up: Switching on wipers

Down: Switching off wipers or brief wipe

Pull: Cleaning windshield and headlamps

Button: Activating/deactivating rain sensor

Dial: Adjusting rain sensor sensitivity level

Figure 5.3: The details view explains the usage of the different interactive elements. There is also a walk-through for the vehicle's infotainment menu. The example in this figure shows details on the wiper stalk switch.

fourth lap, the experimenter told the subjects that the score is rather low, and that they could get into a high score list when they perform the operation tasks faster and more accurately in the next lap. After each lap, subjects had to do a subjective assessment of their mental workload with the NASA task load index (NASA-TLX) questionnaire [153].

Data Collection

The metrics included quantitative data such as required distance for task completion, lane deviation, subjectively perceived workload, and qualitative data such as ratings on a questionnaire. The NASA-TLX questionnaire measured the perceived workload. An additional questionnaire asked about previous knowledge of the subjects and let them rate statements concerning their motivation as well as their perception of the gamefulness of the overall experiment.

Participants

For the first test, we recruited 30 subjects between 19 and 28 years ($\mathrm{Mdn} = 25$ years, $\sigma = 3$ years). There were 5 female and 25 male participants. Most of the participants were students or research assistants. The average experiment duration was 35 minutes. Subjects received direct

Figure 5.4: The quiz mode is based on the virtual cockpit view. The current task is shown in the top left. Besides, the reached points in this round and the number of found functions are displayed. The found functions are highlighted by a white border. In the shown case, the user just found the so-called “custom button 1.”

compensation for their participation in the form of a € 5 gift card for an online retailer after the completion of their task. The average driving experience was 6.0 years ($\sigma = 2.53$ years). The subjects were randomly assigned to the experiment (participants P16 to P30) and the control group (P1 to P15). A Student’s t-test ($\alpha = 0.05$, two-tail) [338] on the driving experiences of the control and the experiment group showed no significant difference ($P(T \leq t) = 0.069$). Besides, there were no significant differences in experience with and interest in technical devices between both groups. One subject (participant P2, control group) works as a part-time chauffeur for a BMW fleet service and, thus, is very acquainted with the cockpit of the simulator. Two subjects (P8 and P20) dropped out after lap 3 but completed the post-experiment questionnaire.

5.2.5 Results of the Driving Experiment

The presentation of the results focuses on the parts relevant to providing answers to our research questions. The calculation of the mean lane deviation in meters was done with the *LCTAnalysis* tool. Instead of working with absolute numbers, we refer the results to baseline measurements that were performed in the second lap.

Figure 5.5: The user study on the effects of the gamified automotive user interface training took place in a driving simulator. It is the real cockpit of a BMW 5-series. The training application controls parts of the dashboard and the display on top of the center stack, and can log most controls by monitoring the vehicle's bus system.

RQ1: Effect of Secondary and Tertiary Tasks on Driving Performance

In comparison to the second lap (baseline, $\mathrm{M} = 0.81\,\mathrm{m}$, $\sigma = 0.23\,\mathrm{m}$ for the control group, $\mathrm{M} = 0.85\,\mathrm{m}$, $\sigma = 0.22\,\mathrm{m}$ for the experiment group) without additional operating tasks, the lane deviation increased for the control group, on average, about 48.7 % ($\sigma = 0.43$) for the third lap, and 39.6 % ($\sigma = 0.46$) for the fourth lap. The experiment group had slightly better results. Their lane deviation increased by 42.1 % ($\sigma = 0.27$) for the third lap and 23.7 % ($\sigma = 0.27$) for the fourth lap. However, no significant differences could be found between the results of both groups (lap 3: $P(T \leq t) = 0.65$, lap 4: $P(T \leq t) = 0.26$). In order to answer **RQ1**, the significance of the lane deviation increases for all subjects was again checked with a two-sample t-test ($\alpha = 0.05$, two-tail). The significance can be confirmed for lap 3 ($P(T \leq t) = 7.83 \times 10^{-7}$) as well as for lap 4 ($P(T \leq t) = 3.1 \times 10^{-3}$), both compared to baseline.

The task completion rates were almost equal for both groups (see Table 5.1). The only significant

Task	**Lap 3**		**Lap 4**	
	Control n = 15	Exp. n = 15	Control n = 14	Exp. n = 14
T1: Increase volume via steering wheel controls	93.3 %	93.3 %	100.0 %	100.0 %
T2: Change radio station via steering wheel controls	80.0 %	73.3 %	78.6 %	78.6 %
T3: Play CD: Sheryl Crow	80.0 %	73.3 %	100.0 %	92.9 %
T4: Activate Active Cruise Control	33.3 %	60.0 %	35.7 %	71.4 %
T5: Start Navigation to ‘Home’	73.3 %	66.7 %	100.0 %	78.6 %

Table 5.1: Task completion rates for operating tasks. There were $n = 15$ participants in both groups for the third lap. For the fourth lap, in each group, one subject decided to end the driving experiment early ($n = 14$ in the fourth lap).

Lap	**Task**	**Control Group**		**Exp. Group**		$P(T \leq t)$
		Mean	σ	Mean	σ	$\alpha = 0.05$, two-tail
Lap 3 (n = 15)	**T1**	56.7	31.2	61.4	26.5	0.67
	T2	90.2	36.6	103.1	40.0	0.43
	T3	303.9	161.6	334.7	34.4	0.60
	T4	165.5	136.0	186.6	110.2	0.77
	T5	344.1	115.6	412.9	112.1	0.18
Lap 4 (n = 14)	**T1**	44.0	24.4	48.9	16.5	0.54
	T2	47.1	30.8	62.2	37.8	0.32
	T3	182.8	91.2	167.4	49.2	0.59
	T4	36.2	25.6	40.3	20.4	0.74
	T5	164.0	120.0	140.7	76.7	0.58

Table 5.2: Task completion distance in meter (in columns *Mean* and σ). The tasks were triggered automatically at given distances. All participants drove 60 km/h. No significant differences could be found between both groups. The results ($P(T \leq t)$) from the two-sample t-test are given in the last column. The decrease of task completion distance from lap 3 to lap 4 is significant for tasks T2 to T5 ($P(T \leq t) < 0.05$).

difference can be seen for task T4. The completion rate for the active cruise control task is twice as high for the experiment group as for the control group. In Table 5.2, the task completion distances are given for both laps. There is no significant difference between the groups, so that one can say that the training application did not influence the detection and operation of vehicle functions (**RQ3**). However, the decrease of the completion distance from lap 3 to lap 4 is significant for tasks T2 to T5.

In order to complete all tasks, 109 control actions need to be performed per lap. During lap 3, the control group performed on average 141.2 ($\sigma = 22.5$) actions. With an average of 137.8 ($\sigma = 22.1$) actions, the experiment group's result is not significantly different. That means that using the training application has no provable effect on the trial-and-error behavior of the users. In lap 4, the numbers increased to an average of 159.1 ($\sigma = 26.8$) actions performed by the control group and 142.7 ($\sigma = 18.4$) actions for the experiment group. However, the increase

S#	**Statement (S)**	**Control Group**		**Exp. Group**	
		Mean	σ	Mean	σ
S1	The operating tasks were too difficult for me.	2.07	0.59	1.87	0.74
S2	My goal was to drive safely.	3.27	1.03	3.67	0.98
S3	My goal was to accomplish the tasks quickly.	4.34	0.62	4.27	0.70
S4	My goal was to reach a high score.	4.07	1.03	4.20	0.77
S5	The experiment felt more like a game for me.	3.47	0.92	3.34	1.05

Table 5.3: Mean and standard deviation (σ) of rated statements concerning the driving experiment. The statements had to be rated on a 5-point Likert scale with 1 *strongly disagree* and 5 *strongly agree*. No significant differences between the groups can be observed.

of performed control actions from lap 3 to lap 4 is not significant ($P(T \leq t) = 0.065$). We then looked at the individual results of the participants. Two participants only solved a single task (T1, T4) each. They performed 90 (participant P8, control group) and 102 actions (P19, experiment group), respectively. P8 had the second-highest absolute lane-deviation value and the highest mental workload value. She reported to have experienced a high level of stress and, thus, decided to drop out of the experiment after lap 3. P19 had the third-lowest lane deviation in lap 3 and stated that his focus was on driving safely. In the fourth lap, he performed 169 actions, and, opposed to the general trend of decreasing lane deviation, his lane deviation value rose by 18.5 %. P3 had the highest increase in control operations between the two laps. In lap 3, he only had 101 actions and could solve two tasks. With 223 actions in lap 4, he had the highest overall amount of operations per lap but only could complete three tasks. With the rise of control operations, the lane deviation also increased by 35.6 %, which led to the highest absolute lane deviation in the study. For checking whether there is a linear relationship between the change in numbers of operations and the change in values of lane deviation for the two laps, the Pearson product-moment correlation coefficient was calculated. After removing the values of the two dropouts (P8, P20) and an extreme outlier (P2, a part-time chauffeur with perfect knowledge of BMW vehicles), a moderate positive correlation was determined ($r(24) = 0.53, p = 0.004$).

The results from the subjective assessment of the mental workload with the NASA-TLX (weighted score from 0 to 100) correlate with the average lane deviation of the LCT. No significant difference was found between the groups. For the second lap (baseline without operating task), an average NASA-TLX score of 24.7 ($\sigma = 13.9$) was calculated. The third lap (first experiment lap with operating tasks) had an average score of 57.0 ($\sigma = 21.3$), the fourth lap resulted in an average score of 39.4 ($\sigma = 18.4$).

In addition, the subjects rated statements on the driving experiment on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). The results are summarized in Table 5.3. The goal was to measure whether the usage of the mobile application changes the perception of the driving task. However, no significant differences between the groups could be observed.

5.2.6 Results of Training Application Evaluation

In the end, the subjects in the experiment group ($n = 15$) rated statements on the mobile application on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). The fun factor of the application was rated with an average score of 4.20 ($\sigma = 0.56$). The usefulness of the application was confirmed with an average rating of 4.27 ($\sigma = 0.46$). The subjects can further think of using such an application for unknown cars (mean $= 3.80$, $\sigma = 0.77$). Participants thought that the use of the application made the operating tasks easier during the driving experiment (mean $= 4.47$, $\sigma = 0.52$). Regarding the motivation, the subjects stated with an average score of 4.73 ($\sigma = 0.46$) that the quiz mode with the ability to make a high score motivated them to improve their first score.

5.2.7 Discussion and Lessons Learned

RQ2: Training Effect in Comparison to Real Driving Experience

From the results in Tables 5.1 and 5.2, we can see that the use of the training application had no significant influence on secondary and tertiary task completion and driving performance. However, the learning effect leads to a significant reduction of task completion distance for T2 to T5 when comparing the results from lap 4 to those of lap 3 (see Table 5.2). The gained experience in lap 3 leads to a lower lane deviation, higher task completion rate, and lower task completion distance in lap 4. For that reason, the training effect of the mobile application is not comparable to the influence of gaining experience of real driving.

For future experiments, the learning effect of repetitive experiment conditions needs to be considered. The LCT is known to have an evident learning effect, and performing the driving tasks again also enforces the learning effect, as shown by Petzoldt et al. [303]. In a follow-up study [304], they also determined that there are learning effects when making the participants work on realistic secondary tasks in addition to the primary driving tasks. Moreover, there were indications for a learning transfer between different tasks if they are similar to some degree. Some operating tasks from our study were not sufficiently distinct to counteract this effect, especially both tasks operated on the steering wheel (T1, T2). For further studies, one should consider the previous experience of participants with both the LCT and the operating tasks to be completed.

RQ3: Effect of Training on Detection Rate and Vehicle Operation

The only task that produced a higher completion rate in the experiment group as opposed to the control group was the active cruise control task (T4). We believe this to be grounded in several factors. One factor is the general distribution and availability of cruise controls in cars the study participants had previous experience with. In the 2014 DAT report [110], a representative survey among 2,688 car buyers yielded that cruise control equipment was built into 47 % of existing cars, 44 % of new cars, and 31 % of pre-owned cars in Germany in 2013. In contrast to that, radio equipment was built into 97 % of existing cars, 98 % of new cars, and 95 % of pre-owned cars. Another factor is the difference in positions and shapes of the cruise control interfaces. Available solutions range from stand-alone levers (e.g., below the turn signal lever), combinations with the turn signal or windscreen wiper levers, to on-the-wheel buttons. Placement of controls for the other tasks (T1-T3, T5) is less scattered: radios, CD players, and integrated navigation systems are commonly found in the central stack. Steering wheel radio controls can only be arranged on the surface of the wheel. All this suggests that there is more to be learned about unknown cruise control interfaces than unknown radio interfaces for drivers in an unfamiliar car model. Possible reasons for this can be:

- Missing of a mental model for the function [196]: When one is not familiar with the function, one cannot derive the function from the offered controls.
- No consistency of HMI between different manufacturers or vehicle generations: Non-standardized functions have manufacturer-specific labeling and differing interaction concepts.

While we did not see a difference between the numbers of performed actions for the two groups, we could prove a moderate linear correlation between the lane deviation and the number of performed actions. In addition to the observation that secondary tasks in general cause higher lane deviation, this shows that also the amount of performed actions is a decisive factor. That means that trial-and-error is not a desirable behavior for finding functions while driving and that the overall amount of necessary secondary operating tasks should be kept low. In order to reduce the number of necessary secondary operations, our concept offers the preset mode that shall guide the drivers through the process of adjusting comfort functions before starting a trip.

RQ4: Negative Behavior through Score Mechanism

For evaluating the game element ‘score’ and, thus, ‘competition,’ a score was computed during the driving experiment and displayed to the subjects after completing a lap. We further intensified the ‘competition’ after the third lap by saying that they can enter a high score list when they get more points in the fourth lap. From the values in Table 5.3, it can be seen that, on average, the subjects concentrated more on the operating tasks and their score than on driving safely. Although both groups had only slightly the feeling that the experiment is more like a game (see Table 5.3), they disregarded the instruction that the main objective was to drive safely. When we asked the subjects why they had concentrated on the score, they mainly named the competition as the decisive factor. The high score list influenced even subjects who stated in the pre-experiment questionnaire not to be very competitive. That shows that competition is a very motivating factor for users to lose focus from the primary driving task. That also coincides with the observations of Deterding[1], which

---

[1] https://www.slideshare.net/dings/pawned-gamification-and-its-discontents, slide 41, accessed March 12, 2019.

means that competition for safety-critical applications should be avoided. As a lesson learned, we believe more thought will have to go into the balance between certain gamification elements and the matter of driving safely in future research. The main intention of our gamified mobile training solution is the reduction of stress and accident risks for driving with unfamiliar car models. With game elements that move safe driving out of focus for drivers, such a training tool could cause an effect in the opposite direction.

RQ5: Effect of Gamification on the Training

Subjects stated in the final interviews that the mobile application had both informative and game character. Especially the cockpit view and the function list have been seen as an information source. The quiz mode was rated to be more like a 'learning game.' However, when we observed the users interacting with the mobile application, we noticed that the informative character faded into the background. Most subjects tapped systematically or entirely randomly on the virtual cockpit in order to find all functions. Instead of reading the information, subjects tried to keep the game flowing. When a function was found, the description was often just quickly scanned, and possible recommendations or usage hints were overlooked. When we mentioned this in the interview, the subjects stated that their goal was to activate the quiz mode quickly. A solution could be to implement a short compulsory break that allows the user to read the text. Another idea is to cut down the amount of information presented at a time. Alternatively, the textual explanation of functions could be enhanced with interactive graphics, video snippets, or audio.

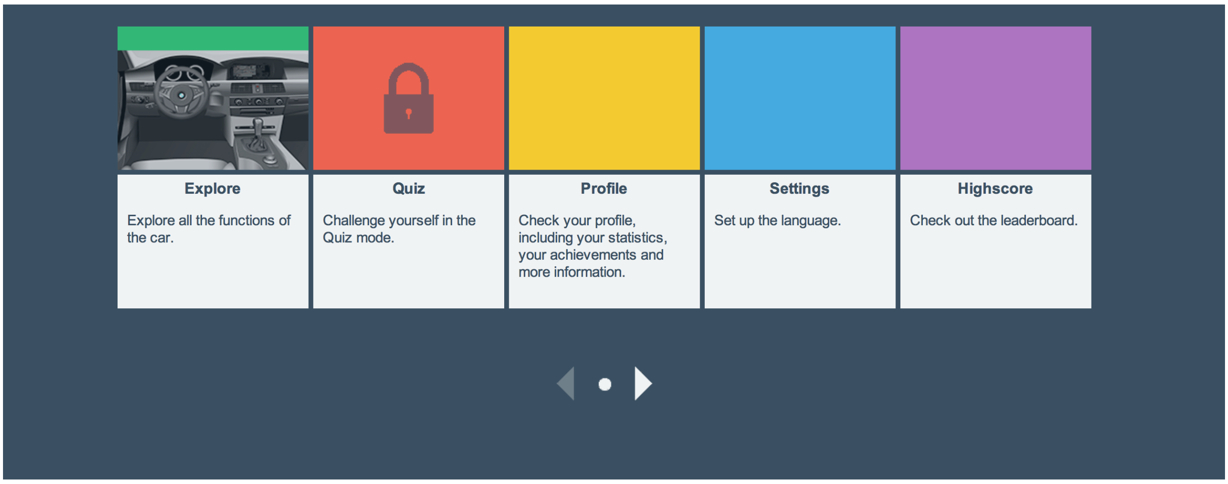
The main lesson learned from the evaluation and the tests during the development is that the concept should be developed iteratively and that after each slight change of the game mechanics, a test is necessary. Even the change from one game element to another can be critical and needs to be evaluated thoroughly, as it might influence the focus of the users' attention.

5.3 In-Vehicle Training of Automotive User Interfaces

We decided to implement an in-vehicle training to examine whether there is a difference between exploring the vehicle functions virtually on a mobile device's screen and experiencing the functions in the real environment.

5.3.1 Concept and Prototype Implementation of In-Vehicle Training

The in-vehicle training was running on the driving simulator's IVI system. Figure 5.6 depicts its main screen that was displayed on the central information display (CID) of the driving simulator. The control PC was not only connected to all displays (CID and instrument cluster), but also to the driving simulator's controller area network (CAN) bus. That way, almost all interactions with



Explore

Explore all the functions of the car.

Quiz

Challenge yourself in the Quiz mode.

Profile

Check your profile, including your statistics, your achievements and more information.

Settings

Set up the language.

Highscore

Check out the leaderboard.

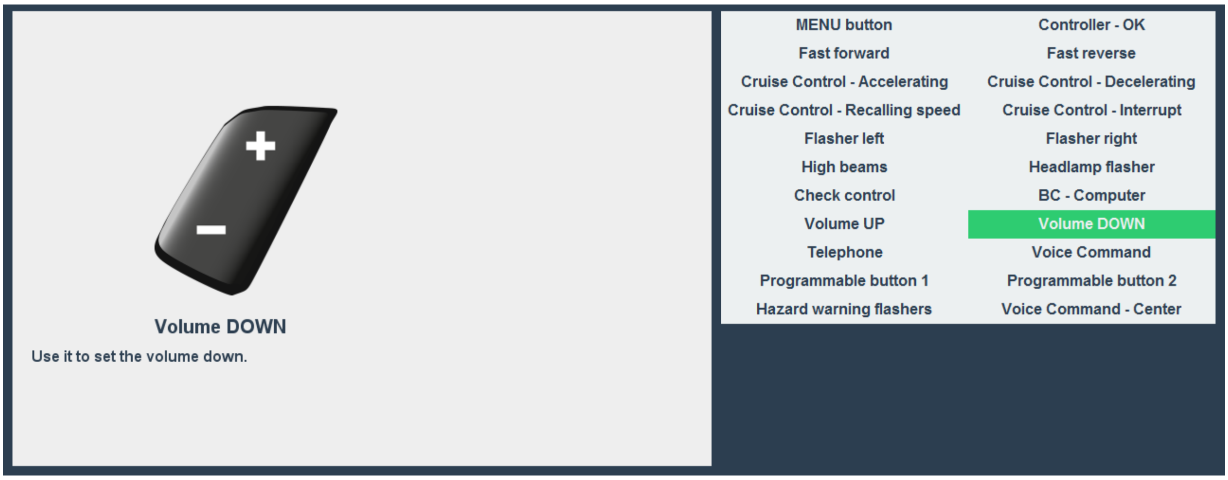
Figure 5.6: The in-vehicle training was running on the vehicle's infotainment system in the driving simulator. This figure depicts the main screen of the training application that was shown on the CID. On this screenshot, the quiz mode is still locked. It can only be used after successfully exploring all elements in the explore mode.

input elements could be registered by the training application. The training application can be controlled via the push-and-rotary switch of the IVI system.

Similar to the mobile application-based training, the in-vehicle training also consisted of two central modes: an *explore mode* and a *quiz mode*. The *explore mode* provides an entry point to the vehicle's functions. The explore screen is depicted in Figure 5.7. The list on the right-hand side of the screenshot enumerates all functions that can be explored in the training system. It is just a subset of all vehicle functions but is enough for the evaluation of the approach.

To 'explore' a function, the user has to interact with the associated input elements. Examples for input elements are the direction-indicator control or the buttons on the steering wheel. When a function on the explorable list has been found, the screen shows a short introduction and operation hint on the left-hand side of the screen. A short auditory output accompanies a successful finding. Besides, the element is marked green as already found. The found elements are stored persistently for each profile. That means elements that have been found once are successfully explored. When a function is activated again, although it is already marked as found, the hint screen is shown again. As soon as all elements on the list have been explored, the *quiz mode* gets unlocked. That is indicated by a popup with an opened lock to reward the user for the progress directly.

The goal of the *quiz mode* is to test one's knowledge of the vehicle's functions and their operation. In the context of our research, we designed it also as a method to foster competitiveness by creating a means of comparison with other users via a high score list. The quiz mode is only available after having explored all functions in the explore mode. It starts with a short welcome screen that also presents the task of the users: find and activate the mentioned functions as fast as possible. Then the quiz starts by presenting the quiz tasks.



Use it to set the volume down.

Figure 5.7: In the explore mode, the user had to find and interact with all mentioned elements in the right list. Since the training application was connected to the driving simulator's CAN bus, it could evaluate almost all interaction with input elements.

A sample quiz task where users had to identify user interface elements depicted on the left side and several possible answer options depicted on the right side is shown in Figure 5.8. As soon as the task is displayed, the user has 20 seconds to solve it. The remaining time for the task and the overall score for this quiz round are also displayed. When the correct function is activated, the user gets a basic score of 1250 points. The awarded time bonus points depend on the remaining time in seconds that is multiplied by 100 points. As soon as a task is successfully solved, the whole screen gets green. Besides, a random auditory message is played via the integrated TTS system. The messages are praises, such as, "Well done!", "Great!", or "Good job!". The effect of these auditory messages is also investigated in the user study. When a user activates a wrong function during a task, 250 points get subtracted from the round's score (analog to the quiz in the mobile app-based training). The score can also become negative. Instead of a green-colored screen, the screen's background becomes all red in case of negative points.

A quiz round consists of four tasks. After the fourth round, a summary of the quiz results is shown. That also includes the listing of basic points, time bonuses, and negative points contributing to the overall score. In addition, the summary screen also indicates whether a new achievement has been unlocked for a user.

Each user has a profile that is created by the experiment operator during the introduction. Each profile has at least a name assigned to it. Besides, a profile picture can be defined. For each profile, the progress of the explore mode and the reached scores in the quiz mode are stored. The profile screen is depicted in Figure 5.9. On the left-hand side, the name and the profile picture are displayed. Below, there is a graphical representation of the six achievements that we implemented: *found all functions in explore mode*, *finished the quiz mode at least once without a negative score*, *finished five quiz rounds*, *has beaten the average score of all users in a quiz round*, *placed in the top 10 of the high score list*, and *ranked number one in the high score list*. The detailed overview

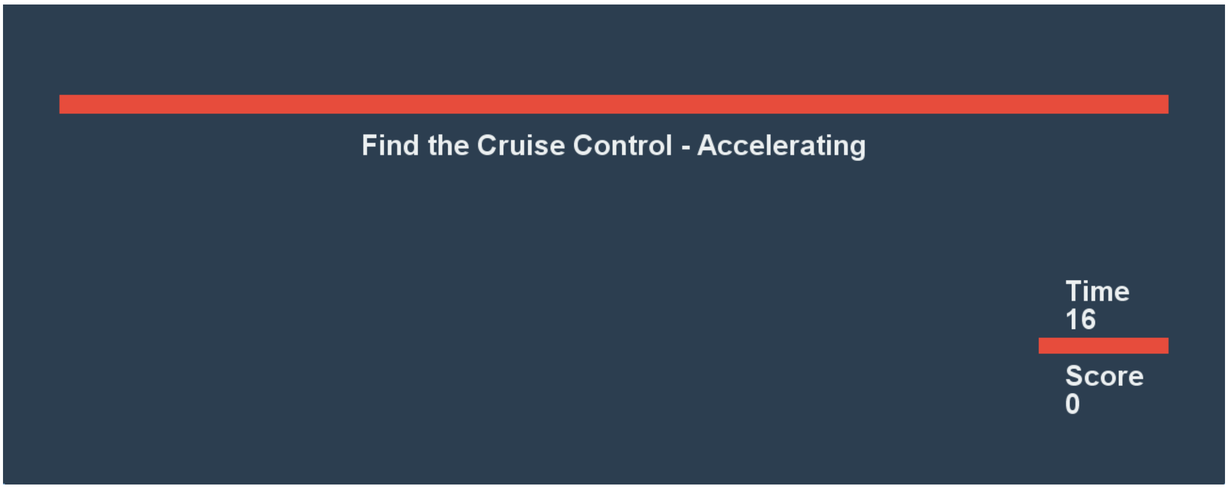


Figure 5.8: After having explored all included elements, the user can start the quiz mode. The goal of the quiz mode is to find and interact with the mentioned element as fast as possible. Depending on the required time to find the correct element, a certain amount of points is added to the score. When wrong buttons are pressed, points are subtracted from the user's score. The displayed time is a countdown from 20 s that automatically starts when the task appears. For identifying the correct function, the user is awarded a basic score of 1250 points plus a time bonus that is the remaining time in seconds multiplied with 100 points. Triggering wrong functions leads to subtraction of 250 points.

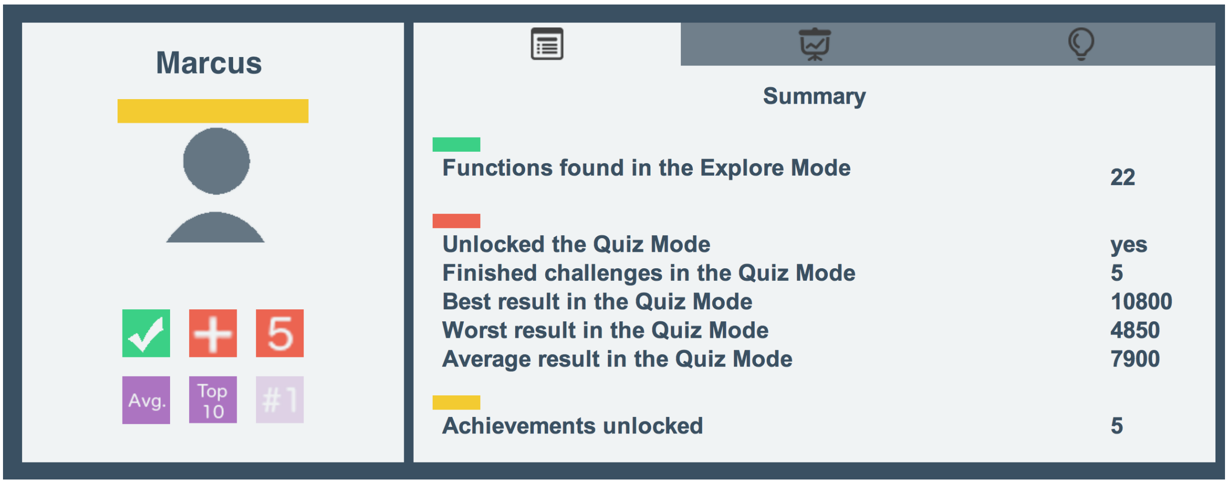
of the achievements is also presented on the last tab of the profile view. Opposed to the mobile application, we integrated the achievements to foster competitiveness and create a slight game character.

The profile screen also summarizes the best, the worst, and the average score of the taken quiz rounds. A graph shows the historical development of the score over the taken quiz rounds.

Via the main menu, the user can also enter the high score list. It shows the top ten scorers. Only the best result of a user is considered for the high score list to avoid having a *good player* in several positions. Initially, the high score list was filled with fake profiles. We derived the scores for the fake profiles from test rounds during the development.

5.3.2 User Study with the In-Vehicle Training Prototype

After the implementation of the in-vehicle training, we conducted a laboratory user study in the same driving simulator as for the mobile app-based training application.



Functions found in the Explore Mode	22
Unlocked the Quiz Mode	yes
Finished challenges in the Quiz Mode	5
Best result in the Quiz Mode	10800
Worst result in the Quiz Mode	4850
Average result in the Quiz Mode	7900
Achievements unlocked	5

Figure 5.9: Each user had a personal profile for which statistics for the explore and the quiz mode are shown. Besides the worst and the best result, there was also a trend chart showing the results from the different quiz rounds.

Research Questions

The following three research questions were in the focus of the experimental evaluation of our in-vehicle training application:

- **RQ1**: Does the gamified in-vehicle training improve the operation of vehicle functions?
- **RQ2**: Is there a difference in the driving and function operation performance between the participants that trained with the mobile application and the ones that used the in-vehicle training?
- **RQ3**: Does the game character of the in-vehicle training have a negative influence on the driving and function operation behavior?

While **RQ1** is targeted at the general effect of the training, **RQ2** is focused on the comparison with the mobile application-based training. **RQ3** aims at the effect of the gamification that has been reinforced compared to the app-based training. Especially when the training is executed in the same vehicle that is later driven, we expect to find an influence on the behavior of the participants.

Study Method

The study was set up analog to the study for the mobile application-based training presented in Section 5.2.4. In this study, another group with different training but the same evaluation method is introduced (between-subjects design).

Task

As for the mobile application-based training, the subjects first had to fill out a questionnaire to gather their demographic data, their driving experience, their usage of functions in modern vehicles, and their affinity to technical devices. The subjects also had to rate their competitiveness.

After filling out the questionnaire, the subjects received a short introduction to the driving simulator. Then, the developed in-vehicle training system was started, and the subjects had 15 minutes to discover and use the training application. There was no specification of what should be done in the 15 minutes. The participants only knew that they should train themselves. It was also possible that subjects shortened the training duration when they stated to have trained enough.

The actual driving tasks were equal to the mobile device-based training presented in Section 5.2.4. The subjects had to drive four laps (each 3,300 m with a mean duration of 3.6 minutes, $\sigma = 0.6$ minutes) in the LCT simulation [260]. The first lap was again an unrated round for getting accustomed to the driving simulator and the LCT. Then a control-lap without secondary tasks followed. In the third lap, secondary tasks had to be solved. After the third lap, the subjects were told that their performance could be improved to trigger their competitiveness. Then the fourth lap followed in which again secondary tasks had to be performed. After each lap, the subjects had to fill out the NASA-TLX questionnaire [153].

In a post-study questionnaire, the subjects gave feedback to their goals during the driving experiment.

Data Collection

The metrics included required distance for task completion, lane deviation, subjectively perceived workload, and ratings on a questionnaire. The NASA-TLX questionnaire measured the perceived workload for each lap. An additional questionnaire asked about previous knowledge of the subjects and let them rate statements concerning their motivation as well as their perception of the gamefulness of the overall experiment. During the experiment, a researcher controlled the sequence and observed the subject from behind.

Participants

This study is strongly related to the study conducted for mobile device-based training (cf. Section 5.2.4). For that reason, the following group naming is introduced for further reference:

- *Control*: the control group with data presented in Section 5.2.4.
- *App*: the experimental group that trained with the mobile application (cf. also Section 5.2.4).
- *In-vehicle*: the experimental group that trained with the in-vehicle training application

The experimental group *in-vehicle* consisted of 10 people (3 females, 7 males), aged between 18 and 31 years ($\mathrm{Mdn} = 21$ years, $\sigma = 4$ years). The subjects were mainly engineering students or research assistants. The average driving experience of the group members was 4.4 years ($\sigma = 3.78$ years). Subjects received direct compensation for their participation in the form of a € 5 gift card for an online retailer after they took part in the study.

In order to ensure the comparability of the three groups' general driving performance, the driving experience has been tested pairwise for significant differences with the Student's t-test ($\alpha = 0.05$, two-tail). There was neither a significant difference between the control group and the in-vehicle group ($P(T \leq t) = 0.082$) nor between the app and the in-vehicle group ($P(T \leq t) = 0.601$).

As for the study on the mobile app-based training application, the subjects also filled out a questionnaire on their experience with and interest in technical devices. There were no significant differences between the three groups, as could be expected due to the similar recruitment process in the same community.

5.3.3 Results of the User Study and Comparison to the Mobile Device-Based Training

The task completion rates are shown in Table 5.4. As for the mobile app-based training, the only significant difference to the control group is in the completion of the adaptive cruise control (ACC) activation task (T4). An explanation is that for functions that require more previous knowledge, the training has a higher effect than for rather apparent functions, such as the volume control on the steering wheel (T1). Besides the significant difference, there is a general tendency to higher completion rates for the trained groups. For that reason, we conclude that the in-vehicle training has a positive effect on the operation of vehicle functions (**RQ1**) in comparison to the control group that did not perform any training.

For the task completion distance, no significant difference could be found between the groups. However, as in the mobile application study, there was again a significant difference for the task completion of tasks T2 to T5 between lap 3 (first lap with secondary tasks) and lap 4 (second lap with secondary tasks). The total number of performed actions during the laps with secondary tasks was also insignificant between the groups and the laps. When looking at the individual operation counts, one participant (P36) of the in-vehicle training group had noticeably more operation actions. In lap 3, he performed 167 actions ($\mathrm{M} = 138.2$, $\sigma = 23.4$) and 181 in lap 4 ($\mathrm{M} = 135.1$, $\sigma = 28.3$). Although he finished all tasks in both laps well below the average task completion distance, he had more unnecessary actions than all others. His lane deviation values were overall the second-lowest of the group but increased by 13.4 % from lap 3 to lap 4. In the post-study questionnaire, he had the highest rating for the goal of achieving a high score (E4) and performing the task as fast as possible (E3). He was also the participant with the highest number of completed quiz rounds.

Task	**Lap 3**			**Lap 4**		
	Control n = 15	App n = 15	In-Vehicle n = 10	Control n = 14	App n = 14	In-Vehicle n = 10
Task 1 (T1): Increase volume via steering wheel controls	93.3 %	93.3 %	100.0 %	100.0 %	100.0 %	100.0 %
T2: Change radio station via steering wheel controls	80.0 %	73.3 %	90.0 %	78.6 %	78.6 %	50.0 %
T3: Play CD: Sheryl Crow	80.0 %	73.3 %	100.0 %	100.0 %	92.9 %	100.0 %
T4: Activate Active Cruise Control	33.3 %	60.0 %	90.0 %	35.7 %	71.4 %	100.0 %
T5: Start Navigation to 'Home'	73.3 %	66.7 %	90.0 %	100.0 %	78.6 %	100.0 %

Table 5.4: Task completion rates for operating tasks. The in-vehicle group (with n = 10 subjects) was added to the results from the control and the app-based training groups. The control and the app group had $n = 15$ subjects in lap 3 and $n = 14$ in lap 4, since in each of the groups, one participant decided to end the lap early.

#	**Statement**	**Control Group**		**App Group**		**In-veh. Group**	
		Mean	σ	Mean	σ	Mean	σ
E1	The operating tasks were too difficult for me.	2.07	0.59	1.87	0.74	2.10	0.57
E2	My goal was to drive safely.	3.27	1.03	3.67	0.98	3.50	0.71
E3	My goal was to accomplish the tasks quickly.	4.34	0.62	4.27	0.70	4.10	0.88
E4	My goal was to reach a high score.	4.07	1.03	4.20	0.77	3.90	1.29
E5	The experiment felt more like a game for me.	3.47	0.92	3.34	1.05	4.20	0.79

Table 5.5: Mean and standard deviation (σ) of rated statements concerning the driving experiment. The statements had to be rated on a 5-point Likert scale with 1 *strongly disagree* and 5 *strongly agree*. The only significant difference is in E5 (game character) between the app and the in-vehicle group ($P(T \leq t) = 0.038$, two-tailed t-test, $\alpha = 0.05$).

In Table 5.5, the results from the post-study questionnaire are summarized. The subjects rated the statements directly after the driving experiments on a 5-point Likert scale from 1 *strongly disagree* to 5 *strongly agree*. As for the mobile app-based training, the goal was to measure whether the preceding training affects the perception of the actual driving task. The only significant difference that could be found was for the game feeling (E5) between the app and the in-vehicle group ($P(T \leq t) = 0.038$). The difference between the control group and the in-vehicle group was not significant ($P(T \leq t) = 0.051$).

5.3.4 Discussion and Lessons Learned

RQ1: Improvements through Gamified Training

As the analysis of the results on the task completion rates in Table 5.4 has shown, we could detect an improvement of operation for non-basic functions like the ACC activation task (T4). For that reason, we can confirm that the in-vehicle training can improve the operation of vehicle functions. That is comparable to the results of the mobile application-based training presented in Section 5.2.7.

RQ2: Difference between App-based and In-vehicle Training

Between the app-based and the in-vehicle training, the differences in task completion rates and task completion distance are insignificant but show a weak tendency for better performances of subjects in the in-vehicle training group. For the overall driving performance measured by the lane deviation results of the LCT, no difference, and no tendency could be determined. That means that both systems generated a comparable training result. There is no difference in driving and function operation performance between the two training approaches.

RQ3: Negative Influence of Gamification on Driving Behavior

The last focus point of our research was on the influence of the game character on the driving and function operation behavior. Overall, we could not find significant differences between the three groups. However, we think that statistics over a larger experiment group should answer such a question. As stated in the paragraph on the performed actions, we noticed one participant (P36) with a very high number of performed actions, a high rating of achieving a high score, and the largest number of completed quiz rounds. We assume that the subject has a strong competitive character trait. That gamification – especially leaderboards and rewards – can trigger the competition character, has been shown, for example, in research of Jia et al. [178] and Nov and Arazy [289]. The results show that extroverted, competitive people use game elements that allow comparison with others as a stage to present them and their performance. Although we could not measure the effect of prior gamified training in the vehicle that is driven afterward, we see potential that for a few people, this may trigger a game feeling and, thus, may affect the driving performance negatively. However, by coupling our gamified automotive user interface training with a gamified safe driving approach [372], the effect for this group of people could probably be counteracted.

We noticed that 4 subjects, including the mentioned participant with competitive character traits (P36), took pictures of the scoreboard with their smartphones. Several subjects also stated that they would like to have the possibility to share their achievements and scores directly to social networks or messenger applications. The possibility to share the score and the rank in the high-score list was mainly mentioned by subjects that were placed on the top three ranks when they finished the experiments. Research on gamification and motivation also shows that the possibility to share results can lead to higher motivation and cause better performance [252, 327].

5.3.5 Mobile Device-Complemented Online Mode in Real Vehicle

Besides using the IVI, the user's PMD could also be coupled to the bus system of a real vehicle [415]. That would allow for further training modes:

- *Online exploration mode* and *online quiz mode*: The operation of certain control elements could be detected on the vehicle's bus system and sent to the training app running on the user's PMD.
- *Background assessment mode*: The application could monitor the operation behavior of the users and, at the same time, record accelerations and speed while the user is driving. After the drive, the application could analyze the recorded driving and operation behavior. It could give hints on what should be trained in more detail or what operations should be avoided next time.
- *Preset mode*: The preset mode would allow restoring saved presets (e.g., adjustments of powered rear-view mirrors, and seats, or settings of the audio system or automatic climate control). That could either be done by sending stored information on the vehicle's bus system when allowed, or by reading the sensor values on the bus and giving feedback when the saved values are reached.

We present a system architecture for the PMD integration in Section 6.3. That way, a future-proof and flexible connection between the vehicle system and the PMD can be established.

5.4 Improving Mobility and Handling of Mobility Aids

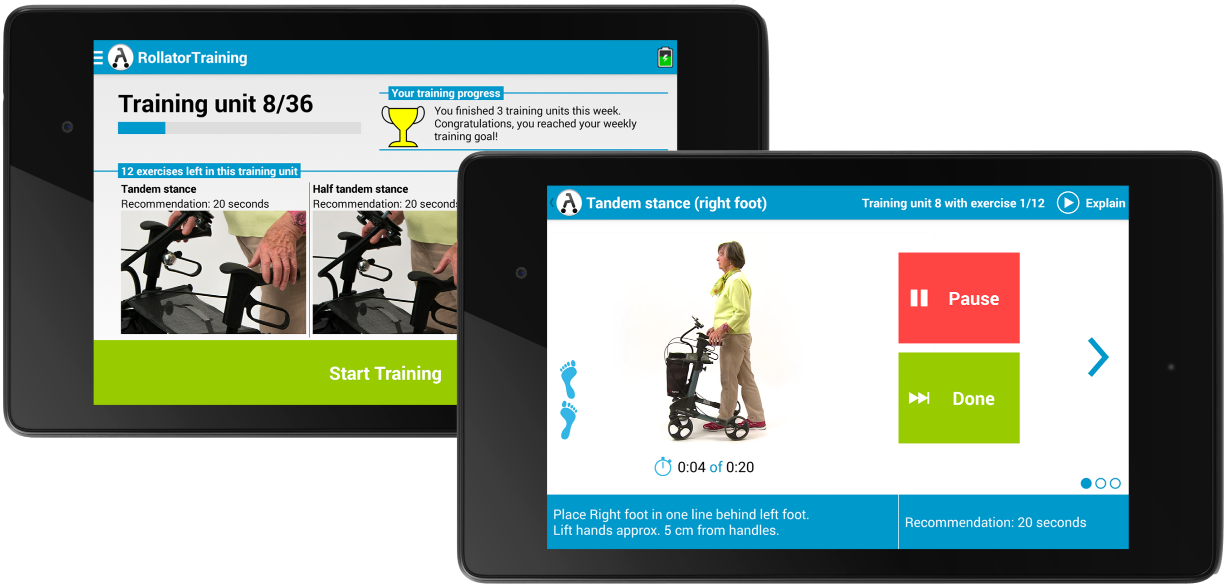
Our concepts of automotive interface training have the goal of providing a better understanding of the operation of offered functionality and assistance. In this part of our work, we investigate how PMD-complemented AMAS can be made broadly accessible to the user group of elderly users.

A 2014 report on app users revealed that there are only a few apps for older people [220] that cater for impairments many seniors suffer from (such as less acute vision or reduced tactile sense) or for missing prior knowledge (such as special gestures or typing on a soft keyboard). For that reason, many older adults cannot benefit from the large amount of available mobile apps that could support their activities of daily living or their health.

Developing mobile applications for elderly people is especially complex since their abilities and experiences are quite diverse. With increasing age, bodily changes negatively influence sensory-perceptual processes, motor abilities, response speed, and cognitive processes [71]. The severity of these age-related functional limitations varies widely from person to person, which leads to different requirements on the user interface. Another difficulty is the different amount of prior knowledge of computer technology. Many of the current seniors have never worked with computers and are unaware of the possibilities and boundaries of modern technology. Since both factors – the functional limitations and prior knowledge – vary over a broad range, it is necessary to follow worst-case assumptions for the design of digital applications and to adapt the evaluation process to the individual abilities of the subjects [174].

5.4.1 Research Focus

In order to give an overview of central challenges that may occur in the development process of mobile applications for older people, we share our insights from the development and evaluation of a mobile physical training app for seniors who use the mobility aid rollator [95, 96]. Besides, we describe the measures we applied to adapt to elderly users' abilities. The measures can be seen as recommendations for the development of future mobile (fitness) applications. The physical fitness context was chosen as it is an important topic for most elderly rollator users, which should avoid acceptance problems due to doubts on the usefulness of the application.



You finished 3 training units this week. Congratulations, you reached your weekly training goal!

Place Right foot in one line behind left foot.
Lift hands approx. 5 cm from handles.

Figure 5.10: The main menu of the mobile training app summarizes the current progress and previews the next exercises (left). Advanced functions are hidden in the app drawer. The exercise instructions are presented via videos, textual, or audio descriptions (right).

5.4.2 Mobile Training App Concept

Regular physical training is necessary for rollator users to prevent falls and to improve their ability to walk. The goal of the application is to provide an appropriate training program, which can be performed independently and integrated into daily life [92].

The developed mobile application is an interactive physical training app, where the rollator is used as training equipment (see Figure 5.10). The app includes exercises for coordination, strengthening, and flexibility to increase strength and performance and to reduce the risk of falling. Sports scientists compiled the set of exercises. Instructional videos and photos of key positions, along with written and spoken exercise descriptions, were implemented to support a correct exercise execution (see Figure 5.10, right). The app reminds the user to exercise regularly (recommendation: three times per week) and additionally visualizes the current training progress. A virtual trophy is used to enhance and maintain the motivation if the training session is completed successfully (see Figure 5.10, left). The duration of a training session is between 15 and 20 minutes and includes initially ten exercises. The number of exercises and their intensity increase with the training progress.

5.4.3 Evaluation of the Training App

We performed a field study with the rollator training app to investigate the potentials and challenges of PMD-guided exercising for older people. The study was guided by the following research questions:

- **RQ1**: Do older users accept and make use of the mobile training application?
- **RQ2**: What needs to be considered when making a field study with older users?
- **RQ3**: Does the interaction with the training app change over time?

Within the **RQ3**, we also investigate motivational aspects for keeping up with the training program.

Task

During the 12-week study period, 7-inch tablet PCs with universal mountings that could be fixed at the rollator were provided to the participants. The task was to perform an exercise unit with the provided mobile application three times a week for the next 12 weeks. The exercising time and day were up to the participants. The participants were told to skip exercises they cannot perform or feel unsafe with.

Data Collection

For the evaluation, technical data, as well as data on physical performance, were collected. The technical data consists of application log data (e.g., frequency of use, duration per exercise, and activated functions) and subjective assessments of the training sessions. In order to detect changes in physical performance, tests for strength, balance, and walking ability were performed at the beginning and the end of the exercise period by the involved sport medicine specialists.

Participants

The participants were recruited by a preventive and sports medicine specialist in retirement homes she already had worked with on preventive fall programs. The selection criteria were the dependency on a rollator (i.e., seniors with limited walking abilities) and an adequate physical fitness level to perform the exercises.

Ten seniors (1 male, 9 female) aged 75 to 89 years ($\mathrm{Mdn} = 82$ years, $\sigma = 5$ years) used the app and trained independently for 12 weeks. Since all participants had no experience with smartphones or tablet PCs, three training sessions took place before the independent training, where functions of the devices were explained, and the correct training technique was taught. The participants did not receive direct compensation for their participation but were given flowers and sweets at the end of the experiment.

5.4.4 Results on the Usage of the Training Application

With the help of the gathered log data, **RQ1** on the usage of the training application and the motivation aspect of **RQ3** can be answered. The analysis of the logged data revealed that only one subject regularly met the recommended exercising repetitions over the 12 weeks. Most other subjects only used the application regularly in the first few weeks. In the after-study interview, many of them stated that they knew many exercises by heart then and performed them without the app. Almost all users exercised at the same time of day. It could also be seen that some subjects regularly skipped exercises. One subject once even skipped 9 out of 11 exercises in one training unit.

For evaluating the physical effects, the functional strength of the lower extremity was measured by the Chair Stand Test (CST) [244]. The patients were asked to complete five rapid chair rise cycles up from a standard chair. Before training, six participants were able to complete the test successfully. After the end of the training, seven participants were able to stand up five times. The average improvement of the participants was from $29.5 \pm 17.1\,\mathrm{s}$ to $17.7 \pm 6.4\,\mathrm{s}$. The static balance measurement (modified Romberg, *mRomberg* [143]) was tested with three measurements according to the Short Physical Performance Battery (SPPB) [143]. The participants were instructed to stand with their feet side by side, in semi-tandem, and full-tandem position.

Each test position had to be held for ten seconds. The summary of the total balance time in all three tests was used for the analysis (max. reachable 30 seconds). The balance performance in the *mRomberg* increased on average from $19.4 \pm 9.4\,\mathrm{s}$ to $28.8 \pm 3.1\,\mathrm{s}$.

5.4.5 Challenges and Recommendations

Based on the experiences during the development and evaluation of the mobile training application, the following challenges have been identified. The summary is not limited to usability aspects [172] but also includes factors that may influence the acceptance of the application and the results of the evaluation.

Deviant Interaction

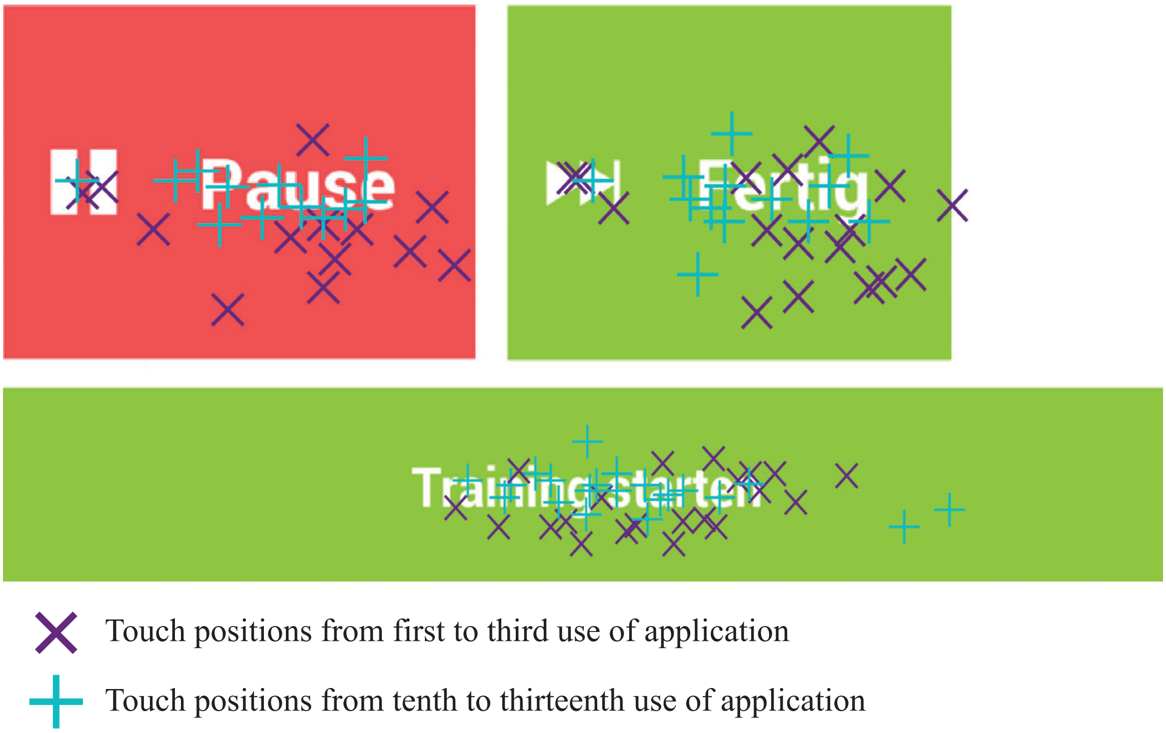


Figure 5.11: During the evaluation, the touch positions were recorded in order to check whether interactive elements could be detected. The analysis revealed that experienced users (tenth to thirteenth use of the app) more likely press at the center of the elements, whereas novice users (first to third use) avoid tapping on the text. In contrast to Figure 5.10, the texts are in German as they were during the evaluation.

In order to evaluate whether users recognize the interactive interface elements, whether the elements' sizes are large enough, and whether the interaction changes over time (**RQ3**), the app recorded the touch positions in the different screens. During the analysis of the recorded touch position data, we noticed that many users did not press at the center of the elements. In particular, touch events were recorded on the right-hand side of the elements, which can be probably explained that most subjects operated the application with their right hand. A temporal analysis of the recorded touch positions also revealed a position shift over time.

In Figure 5.11, a representative excerpt of recorded touch positions for three buttons is visualized. In contrast to Figure 5.10, the labels are in German as the evaluation was performed with the German version of the application. The figure shows touch positions of the first three app uses as well as positions from the tenth to the thirteenth use. When comparing the touch positions, it can be observed that inexperienced users avoided clicking on the text. However, as soon as the users are acquainted with the app, the touch positions are shifted towards the center of the element and are no longer around the text. A possible explanation could be that users do not have to read the labels in detail anymore as they know what happens when they click on the color-coded buttons.

This behavior was not expected. Consequently, we enlarged the central elements to offer enough space to press below and next to the text. For smaller screens, touch coordinate correction can be applied. Henze et al. [158] have shown that at specific positions on a hand-held touchscreen device, accuracy problems arise and trained a function to shift the coordinates and reduce the touch error rate. Since elderly users may have a different mental model of mobile applications, they can show different interaction patterns compared to younger users that are familiar with modern technology [430]. For that reason, it is advisable to observe or record interactions during the evaluation in detail. The temporal analysis can be useful to reveal changing requirements with the level of experience.

The following three sections provide answers to **RQ2** on the difficulties when performing a user study with people that are not used to digital systems and may have physical, visual and auditory limitations.

Fears and Trust

Especially users with little or no previous knowledge of mobile device and PC use had inhibitions to perform experiments without exact instructions. Besides the fear of causing irreparable damage to the system, some subjects were also afraid to embarrass themselves. Even though the experimenter emphasized that only the applications are tested and not the subjects, many participants felt like being in an exam situation.

As part of the iterative development, we performed short laboratory studies with subjects from the target group. In order to create a relaxed situation, we started the evaluation with semi-structured interviews while guiding users through the app, which served at the same time as an introduction to the app. When performing task completion experiments, we defined a maximum duration, after which we helped to solve the task to keep the subject's motivation. The subjects well accepted the measures. However, it was challenging to perform valid task completion experiments.

During the 12-week evaluation, the subjects were provided with a tablet PC for free. However, the fear of causing damage to the device or losing it prevented some of them from regular exercise. Only after presenting a liability exclusion, these users could be moved to use the application at home. The three introduction sessions were also very important to many users and helped to dispel their doubts about whether they can use the application alone. Another important support measure that many subjects made use of were printed manuals with descriptions of central functions and the regular availability of a contact person. For example, we had equipped the tablet PCs with adhesive labels indicating the position and orientation of the power switch and the charging plug (cf. Figure 5.12a). In the beginning, lost labels led to situations in which some subjects could not use their devices anymore. By calling the support contact, these issues could be quickly fixed. In order to create a suitable exercising environment, we also provided mountings with strong clamps. The mounts are depicted in Figure 5.12b. They could be fixed to any solid part of the rollator. The flexible gooseneck allowed adjusting the mobile device's position so that it could be controlled comfortably without obstructing the exercise. By offering these support possibilities, many small issues that prevented subjects from using the applications could be solved.

Trust was another important factor during the evaluation. Subjects that knew the experimenter before and, thus, had a higher level of mutual trust rated the trustworthiness of the app and its exercise content higher than subjects without prior contact did. At the same time, the subjects that had a better bond of trust with the experimenter expressed their opinions more openly. When performing an evaluation, this bias should be considered but could also be exploited. When choosing the participants, one could distinguish between a more open qualitative and a low-biased quantitative evaluation.

Reduction of Complexity

An early prototype of the app required the input of the age and the selection of preferred training days. However, initial experiments revealed that the input of data (text, selection of dates and times) was a significant problem for many elderly novice users. For that reason, this step was removed, and default values were set. As a consequence, the amount of data input should be kept to a minimum. In many cases, default values can be used, which could be changed in the settings if it is desired or necessary. Other supportive measures are auto-completion that can compensate for minor typos or the possibility to create favorites to reduce repeated data input.

A good approach to reduce the mobile application's complexity is to analyze which functions are actually used. When a function is only rarely used, the reason for not using it should be examined. Possible results could be that the function is not necessary for the users or that it is currently complicated to find or use. In general, the primary function should be at the center of attention and stand out against auxiliary functions. For example, the main screen of the rollator training app offers only a single visible element for starting or resuming the current training unit. All other

(a) Adhesive markings indicated the position of the on/off switch (white) and the position and direction of the charging plug (blue).

(b) All subjects received tablet PC mountings that could be clamped on any solid component of the mobility aid. That allowed for hands-free use of the training application, but ensured a clear view and proper control of the mobile device.

Figure 5.12: The study on the rollator training was performed with standard off-the-shelf tablet PCs. A fitting mount with a clamp for attaching it to the rollator provided an optimal training environment.

functions are accessible via the hidden app drawer menu. The display of single exercises was initially divided into two steps. In the first step, the users should watch the training video and read the instructions. By clicking on the start button, the exercise was started, and a stopwatch was displayed. However, observations of training sessions and the analysis of recorded log data have shown that many users started exercising already in the introduction part. That caused situations where the stopwatch had to be started after the exercise execution, followed by an immediate click on the finish button to jump to the next exercise. For that reason, we combined the instruction and execution step, which then only required a single click to get to the next exercise. The stopwatch function can still be used but is implemented as an auxiliary function that can be started on demand.

Fidelity of Prototype

The evaluation of early prototypes was arduous. Since most of the elderly subjects had no experience with smartphones and tablet PCs, the mock-ups without functionality or even paper prototypes were too abstract for them. Due to the missing experiences, they could not imagine how the functional prototype would work. For that reason, low-fidelity prototypes were then evaluated by experts. However, it is advisable to create a functional digital prototype as early as possible in the process to gather results from the target group. In doing so, it is essential to match the prototype's level of detail with the prior knowledge and experiences of the potential users. We also noticed that an incomplete or imperfect prototype could have a negative influence on the future acceptance of an application. Another difficulty was the dissociation of the element under evaluation. Most subjects did not understand the difference between software and hardware during the evaluation. For example, subjects named the slippery surface and the weight of the used tablet PC as negative points of the app. That needs to be considered when questions on stability or similar areas that can refer to hardware as well as software are part of the evaluation.

Training Motivation

Regular training is necessary to achieve a sustained health benefit. For this reason, the application must promote long-term training. If the participants themselves determine success in training, such as improvements in balance or strength, the training motivation will increase. An integration of exercises, which have a fast and positive training effect, is therefore advisable. In addition, motivation can be reinforced by integrated virtual rewards. In the training app, trophies were displayed when the participants reached the predefined training goals, which was also named as an essential motivational factor in the after-study survey (**RQ3**). Additionally, variety in training sessions can trigger curiosity and, thus, further boost the participants' motivation [353].

5.5 Summary of Contributions

In this chapter, we reported on two training assistance solutions for maintaining self-determined mobility. Though the automotive user interface training focuses on the handling of mobility means and, in particular, the HMI, the focus of our rollator training concept is on the support of physical exercising. The key results from our conducted studies with the prototypes and our derived recommendations can be summarized as follows:

- Complexity reduction needs early feedback from the targeted user group. In general, the necessary input should be reduced as far as possible. When possible, the assistance systems shall be configured with reasonable default values so that the user only needs to adapt the value in special cases.

- The necessary prototype fidelity depends on the users' experience with PMDs and digital technology in general: Users with little or no experience need more mature and stable prototypes because they cannot imagine how the solution may look when ready.
- Besides, inexperienced elderly users require visible options to request additional support. The availability of a sole contact person and printed manual reduces their fears of causing irreparable damage.
- Training motivation can be enhanced by starting with exercises that show immediate results (e.g., balance or strength) and by varying exercises that trigger curiosity.
- Gamified training of mobility-related user interfaces is especially beneficial for less known or less common functions.
- The HMI training does not necessarily have to be performed with the actual HMI, but can also be practiced with a realistic simulation on the user's PMD.
- Game elements have a stronger involvement effect on younger subjects than on elderly subjects.
- Users with stronger competitive character traits get more involved in gamified training. That leads, however, to the conclusion that safety-critical tasks should not employ competitive game elements for motivation.

Chapter 6

Mobility Assistance in the Automotive Context

6.1 Problem Definition and Research Questions

After having explored PMD-complemented AMAS for trip planning in Chapter 4 and for mobility-related training and exercising in Chapter 5, we focus in this chapter on *real-time assistance* during the trip.

For our investigation, we have chosen the automotive domain because it is one of the sectors in mobility with the most advanced digitalization, as shown in Section 2.3.4. The chosen use case is V2X communication because it offers real-time data provision and is one of the key enabling technologies for autonomous driving, intelligent traffic management, and road safety [108].

The first issue we look into is the role of the PMD and its general integration possibilities in the automotive domain. Besides interaction possibilities, we also elaborate on bridging the gap between the long life cycles of mobility means and the short life cycles of consumer electronics (CE) products. In the next step, we report on a possible architecture and evaluate work splits for a future-proof PMD integration in the vehicle's V2X system.

On basis of the created architecture, we implemented two PMD-based AMAS: a V2X warning and incident overview app, and a GLOSA application. We report on our findings from the studies with the two applications with the focus on HCI aspects and extended service integration. We finally share our test environment that allows for joining simulation and reality.

The research presented in this chapter contributes to answering the following HRQs:

- **HRQ4**: How can the complexity of operating mobility services and assistance systems be reduced for users?
- **HRQ5**: How can users be supported in accessing and using mobility services and means of mobility?

6.2 Engineering Principles for Mobile Device Ecologies

When a mobile device user enters a car, the “anywhere, anytime” paradigm of mobile interaction seems to end. Although many automotive manufacturers already integrate connected IVI systems in their cars, these systems often have a minimal function set (especially at the time of conducting this research). Many systems are focused on driving-related information and only offer some basic user interfaces with considerable restrictions on interactive capabilities. In many compact cars, there is often no head unit at all. Integrating mobile devices into the vehicles’ IVI systems can help with providing natural user interfaces (NUIs) and enable access to contextual information and extended services.

In the following subsections, we give examples of how natural user interfaces of mobile devices could be used in the automotive domain and provide an overview of possible architectural integration methods. That means, we investigate HCI from a technology perspective.

This chapter is partly based on four papers we published between 2011 and 2013 [84–86, 89].

6.2.1 Benefits of the Integration of Mobile Devices

As shown in Section 2.1, people of all ages nowadays use PMDs. One success factor is the good learnability of their UIs [65]. Norman, in his article “Natural user interfaces are not natural” [288], supports the proliferation and provision of natural user interfaces. However, he also highlights the fact that natural user interface paradigms are still not standardized and, therefore, people need to get accustomed to each system they use. It can be observed that most users are more familiar with the handling of their mobile devices than with handling different IVISs. One possible reason is that until now, only expensive cars in the premium segment feature interactive capabilities. Especially while driving, it is important that the user can interact with the IVI without having to concentrate on the handling itself. That comprises finding the correct interface, locating the appropriate user interface elements, and selecting the desired options using the available controls. That can, for example, be achieved when the user’s PMD is used for interpreting the gestures or voice input. Sonnenberg claims that “[t]he system shall respond in a clear, predictable and consistent way [...]” [370]. We believe this can be achieved with current and future mobile devices, since the user is familiar with their mobile device’s system, and can comprehend and predict the behavior of it.

Another benefit of using mobile devices together with – or as a replacement for – embedded in-vehicle infotainment is the ability to bridge the life cycle gap between automotive and consumer devices. By now, the life cycles of automotive hardware and software can be measured in years and decades. Vehicles are easily used for ten years and longer. In contrast, the life cycles of smartphones and tablet PCs are measured in months or years. In 2018, mobile device owners in the United States replaced their hardware on average after 25 months of usage[1]. The life cycle of

---

[1] https://www.cnbc.com/2019/05/17/smartphone-users-are-waiting-longer-before-upgrading-heres-why.html, accessed August 10, 2019

mobile applications can be measured in weeks or months today. At the same time, applications installed in automobiles often do not even receive one single update. Automotive manufacturers try to keep up with the innovation cycle of consumer devices by introducing remote software update mechanisms. However, an affordable possibility for upgrading IVISs is not yet in sight, nor realistic. One reason is the variability of automobiles through purchasable extras, which causes differences in cabling and on-board components. In general, only newly released models benefit from new systems and technology. In addition to the lack of update possibilities, the specialized solutions for the in-car systems are often costly. A simple embedded navigation system for a premium car can easily cause up to 3,000 Euro extra costs for a new car. The following yearly map updates cost, on average, between 150 and 200 Euro. Assuming a car lifetime of 10 years, the user could also use the money to buy a new up-to-date mobile device (including up-to-date maps) every year. Despite having updated software, the user would also have new hardware and could directly benefit from updated interaction possibilities, and thereby NUIs.

Natural user interfaces comprise not only gestures and interactive voice response (IVR) systems. These two classes of user interfaces are important and prominent, but given the definition of NUI, there are additional factors to be accounted for. The inclusion of contextual information is also essential for making interaction more natural than with traditional user interfaces. Especially mobile devices, as ubiquitous personal devices, can access, calculate, and provide a lot of information and data of their owners to adapt and contextualize in-vehicle infotainment systems ("always-on" paradigm). They are configured and adjusted to fit the user's needs and have the (digital) contextual information available. A simple but striking example is the user's language that could be derived from the language set on the mobile device and thus be set for the in-vehicle interfaces. In general, much of the initial configuration of a car can be derived from past data or current (mobile or wearable) device information. Most users also use their mobile devices as their calendar. Thus, the PMD could derive where the user probably wants to go or when the arrival should be – a well-known use case, but still not easily achieved in an automotive context. The navigation system of the mobile device can access the contact list and could automatically calculate routes to friends or meeting partners, adding up-to-date traffic information. Whereas saying, "Navigate me to John Doe's working address" would confuse a classical in-vehicle navigation system, a mobile device-based system could use its additional context-information to interpret the user's command correctly. The mobile device, a personal assistant, never leaves our side. For this, early work showed that the user's device could be used as a proxy of the user's location [18]. It could also be used for storing in-car preferences, such as the preferred seat adjustment or temperature. That would simplify the changing of vehicles (e.g., for car-sharing or rental cars) but also changing drivers in a vehicle.

As a kind of digital memory, the mobile device could enable a more energy-efficient and more comfortable driving. For example, the known route, the driver's known way of driving, which could be stored on the mobile device, and information from digital maps could be used to predict the charge levels of hybrid electric vehicles. Thereby a system could increase fuel efficiency or, in case, of electric cars, their range. Based on these predictions, the charge profile could be optimized: for example, driving up a hill could consume the whole battery charge, since it would get charged again during driving down.

Coupling the mobile device to the IVI would also enable transferring data between the systems. For example, when a user cannot park their car near the destination, the navigation task can be split up. In the first step, the system navigates to a parking lot, and when the user leaves the car, the mobile device automatically shows instructions to the destination. By using the Internet connectivity of the mobile device, this could even incorporate public transport. At the same time, the mobile device can automatically remember the position of the parked vehicle and lead the user back to it afterward, possibly using offline stored maps and routing information in case of no data connection.

6.2.2 Integration of Mobile Devices

The integration of the mobile device into the vehicle's digital ecosystem is a key point in order to create a system that can benefit from the coupling. Besides thinking about the physical connection (concerning the lower layers of the ISO/OSI model [432]), one has also to consider the data interface, e.g., the syntax and semantics of the exchanged data. For the physical connection, there are, in general, two possibilities: *wired* and *wireless*. The following list (not concluding) describes wired connections that are commonly supported by mobile devices:

- Universal serial bus (USB): Up to $480\,\mathrm{Mbit/s}$ (for USB 2.0) or $5\,\mathrm{Gbit/s}$ (for USB 3.0) bidirectional multipurpose link with charging support.
- Mobile high-definition link (MHL): Charging and, at the same time, 1080p high-definition (HD) video and digital audio output via a single low pin-count interface.
- High-definition multimedia interface (HDMI): Uncompressed HD video (inclusive 3D video) and digital audio output.
- Audio Line-In/Line-Out: Analogue audio input/output.

Modern docking (and charging) stations allow a secure connection from the mobile device to the different wired outputs. Most mobile devices further have an option to detect whether they are docked to a car docking station or a regular desk docking station. That allows, for example, automatic switching to a car optimized user interface, often featuring larger icons or to the ability to switch off animations, which could distract the driver.

On the wireless connection side, the most common links are:

- WLAN: Multipurpose network connection with a theoretical maximum throughput of $780\,\mathrm{Mbit/s}$ (for Institute of Electrical and Electronics Engineers (IEEE) 802.11ac, $5\,\mathrm{GHz}$)
- Bluetooth: Different protocols allow various communication types, for example, audio distribution or IP networking.

- NFC: Simplifies device pairing and enables secure data transmission (up to 424 kbit/s) for a minimal distance.
- Other short distance networking standards following IEEE 802.15.4, such as ZigBee
- Mobile Networks: Telephony and data services, such as 3G, 4G or, 5G.

Land und Leute, Umwelt und Gesundheit, Wissen und Bildung sind die Schwerpunktthemen.

Figure 6.1: *paragon's cTablet Docking Station* enables docking the tablet PC *Samsung Galaxy Tab 7.0"* in two standardized car mounting bays. Source: *paragon AG*

Although inductive charging solutions are available for several years now [171], there are still many mobile devices that cannot be charged wireless. A wired connection with charging support is preferable for longer journeys, also with respect to safety regulations in most countries regarding the use of mobile devices when driving. Dependent on the required data exchange between the mobile device and the car system regarding data and connection parameters, one (still mostly manually) has to choose the appropriate connection type. When the mobile device shall be used as an input and output unit to the car's system, bidirectional multipurpose links, such as USB, WLAN, or Bluetooth, are the right choice. For the output of multimedia content, MHL, HDMI, or WLAN with Digital Living Network Alliance (DLNA) software support could be used. It is to be noted that standards agreed over the respective domain (mobile devices, automotive context) are still rare. A combination of different connection links allows high flexibility and performance at the same time. Especially when services should be provided for all car occupants, a wireless data or multimedia connection (usually by an in-car WLAN hotspot) is the most convenient solution. The same applies for shorter trips since the driver can leave their mobile device in the pocket. When, in the future, femtocells get integrated into vehicles, the mobile network could also be used for the coupling by providing the network for the car occupants.

The *cTablet Docking Station*[2] from *paragon AG* is shown in Figure 6.1. It allows connecting a 7-inch Android tablet PC to the car via two standardized car mounting bays at the vertical center stack. The device is charged via USB, and the connection to the car's system is established using Bluetooth. The example shows another key issue of the integration of the mobile device in the vehicle: when the mobile device should be used as head unit and, thus, provide the natural user interface with respect to human-computer interaction (not with respect to the driving task), it is important to put it to a place where the driver can interact with it in a natural way with eyes still being mainly on the road. Kern and Schmidt [192] present an overview of the design space for driver-based automotive user interfaces. These investigations provide a good starting point for thinking about a suitable position where the mobile device could be placed in the car for interaction. This design space has, so far, not been defined conclusively. When the mobile device's display is used for output, it should be placed somewhere at the dashboard (vertical part of the car) where the driver can look at it without looking too far away from the street. The mobile device can also be used as an input device only. For example, it could be mounted at the horizontal center stack, and the user can perform multi-touch gestures on the blank screen with only the touch sensor active.

Another critical challenge is the establishment of in-car data interfaces. Since automotive innovation cycles are still measured in multiples of years (even 10s of years), a well-conceived, comprising, and extensible interface has to be specified. A high-level solution regarding communication and data semantics, which is detached from the low-level communication systems of vehicles, is highly preferable. There should be no need to interface directly with specific (and changing) in-car bus systems, such as CAN or media oriented systems transport (MOST). Kranz et al. [204] proposed an open-access vehicular data interface for in-car context inference and adaptive automotive HMIs. An advantage of the system is that one can easily read out the current car state without the burden of acquiring a CAN matrix. The CODAR viewer [203] is an example of a situation-aware driver assistance system based on V2X communication. It demonstrates how V2X data can be provided efficiently to a visualization system. Slegers [362] shows an integration approach for personal navigation devices (PNDs) in the car systems. He also introduces the *Reflection Interface Definition* language that allows a simple description of changing interfaces. Those data interfaces are mainly focused on the context exchange part of the integration.

For interacting with natural user interfaces using gestures on a touch display or speech interaction in vehicles, another set of interfaces is necessary. Human interface device (HID) classes are, for

---

[2] http://www.paragon-online.de/en/2011/06/07/artikelblock-2/, accessed May 4, 2019

Interaction scenario	Role of IVI system	Role of integrated PMD
PMD as head unit	Provides vehicle parameters, gateway to different input and output systems (e.g., audio).	Provides all applications. Touch display used for input and output.
Head unit as PMD remote display/ control	Provides a display and can forward inputs to the mobile device. Only basic applications are running on the system.	Provides most of the applications. Sends output to the built-in head unit. Accepts inputs from IVI.
PMD as partial user interface provider	Provides the main interface. Allows integrating external UI in selected views.	Provides UI content for the IVI.
PMD as content provider (portable cloud)	Built-in head unit can request information from the PMD. Provides all applications.	Provides access to, for example, available multi-media content, calendar, or contacts.
PMD as context provider	Runs applications. Handles context itself.	Provides context such as language settings or saved seat adjustments.
PMD as input device	Has own display. Runs applications.	Sends inputs, such as detected touch gestures or evaluated speech input, to IVI.
PMD as connectivity provider	Runs applications, uses telephony and Internet connection of mobile device.	Mobile device provides telephony and Internet connection to IVI.

Table 6.1: The roles of the PMD and the IVI for different interaction scenarios.

example, available for USB and Bluetooth. These base classes can be used or adapted for many input and output devices. Depending on the role of the mobile device, it can act as the *host* or as a *device*. When it is used as a head unit replacement, it can work as a *host* and receive and interpret inputs from other car input devices, such as buttons, sliders, or knobs. When the device is acting as an input device, it can register itself as a *device* and provide inputs for the car system. 2D Camera or depth camera images that can be used for gesture recognition, or audio input for interactive voice response systems, such as Apple's Siri or Amazon's Alexa, can be transferred using available multimedia protocols for USB or Bluetooth. When an IP network connection is used, streaming protocols, such as real time streaming protocol (RTSP), can be used.

6.2.3 Interaction with Integrated Mobile Devices

There are various ways how an interaction between the integrated mobile device and the car's system could look like. For a simpler overview, we have summarized some typical cases in Table 6.1. A combination of several scenarios will be used in many cases. A clear distinction is not always possible.

Looking at the different scenarios, one can derive benefits for a natural user interface from every single scenario. Even when the mobile device only acts as a content provider, it can be beneficial for a natural user interface. As an example, the content on the phone likely describes the user's preferences. The content can even be used for deriving contextual information (as another example for beneficial information for natural user interfaces), such as the preferred music genre, by scanning the collection on the phone. The connectivity provider scenario can be considered as a support technique. It allows, for instance, connecting to social networks and cloud services using the user's private credentials that are stored on their mobile device.

6.2.4 Current Approaches and Available Systems

Carmakers and suppliers have already developed several interfaces for integrating mobile devices in the IVI systems. *MirrorLink* (formerly called *Terminal Mode*) [41] is the open industry standards solution of the Car Connectivity Consortium[3]. This protocol is an example for the *head unit as a mobile device remote display/control* scenario of Table 6.1. It uses IP technologies over USB and WLAN. Virtual network computing (VNC) is used for replicating the phones display on the head unit and to send key and touch events back to the mobile device. Audio can be streamed via real-time protocol (RTP) or via the Bluetooth audio profile. This system allows using the natural user interfaces of the mobile device (e.g., hand gesture interaction) directly on the vehicle's HMI. Since the mobile device is used as the primary system, the state is preserved on entering and leaving a vehicle.

Apple CarPlay[4], developed by *Apple* together with car manufacturers, is an example for the *PMD as a partial user interface provider* and *PMD as content provider (portable cloud)* scenarios. A TCP/IP connection via USB or wireless via a WLAN and Bluetooth combination is used for transferring rendered images of the media gallery from a connected *Apple iPhone* or *iPod* to the HMI, which displays the received content in a reserved view area. That allows the user a fast recognition of the displayed content since the content is presented in the same way as it would be displayed on the mobile device itself. The system can also be controlled via the HMI of the car. Since it has the same layout and follows the same interaction paradigms, the user can benefit partially from the mobile device's natural user interface [374]. The car audio system is used for playing the selected content.

6.3 Architecture for Mobile Device Integration in Vehicle-to-X Communication

For our research on a versatile and future-proof PMD integration solution for the automotive domain, we have chosen the area of V2X communication. We have selected this area since there is undeniable a big potential of using real-time spatial data for informing the driver about the current

---

[3] http://www.terminalmode.org/en/agenda/consortium

[4] https://www.apple.com/de/ios/carplay/, accessed June 20, 2019

surrounding beyond the sensory of the own vehicle. However, questions on the visualization and the communication of environmental information to the vehicle's driver and potential passengers are still open. We believe that the PMD integration can allow for (1) natural interaction with V2X information in the vehicle, and (2) simplify prototyping on the topic V2X data presentation for the research community.

V2X communication allows exchanging spatially-relevant data between vehicles and road-side units. The information can either be sent out periodically or in an event-based manner. Several different, standardized message types exist for the communication of different events or incidents. For example, the periodically distributed cooperative awareness messages (CAMs) [115] indicate the position and traffic-relevant properties (e.g., emergency vehicle on duty) of moving vehicles. The event-driven decentralized environmental notification messages (DENMs) [116] inform about stationary incidents, such as slippery road conditions, the end of a traffic jam, or construction sites.

By combining time-critical, low-delay V2X communication data with high-delay (e.g., several hundred milliseconds) data from Internet services via the mobile data link of the portable device (3G, 4G or 5G network), enriched and contextualized information can be provided to the driver and passengers. For example, when the V2X system reports a blocked road or traffic jam on the route, the application on the mobile device could automatically calculate an alternative route by querying the public transportation schedules.

We have investigated such a setup and will report on the details in the following. It consists of a vehicle-integrated V2X communication platform linked to an Android-based tablet PC. In this setup, it is essential to have an appropriate V2X message processing system that allows supplying the PMD with the required data in a fast and reliable manner. Our key objective is to achieve the required performance and reliability while keeping the system flexible and extensible. We provide quantitative results from our measurements that allow us to compare the performance of the different approaches.

6.3.1 System Overview for the V2X Integration Research

Figure 6.2 depicts an overview of the developed and implemented system setup. The setup consists of a V2X communication on-board unit (OBU) responsible for the communication with other V2X units, and an Android-based tablet PC as PMD.

Connectivity Between on-board unit and personal mobile device

To be able to forward all incoming V2X messages to the PMD, the connection between the OBU and the PMD has to support at least a transmission rate of $27\,\mathrm{Mbit/s}$ which is the maximum

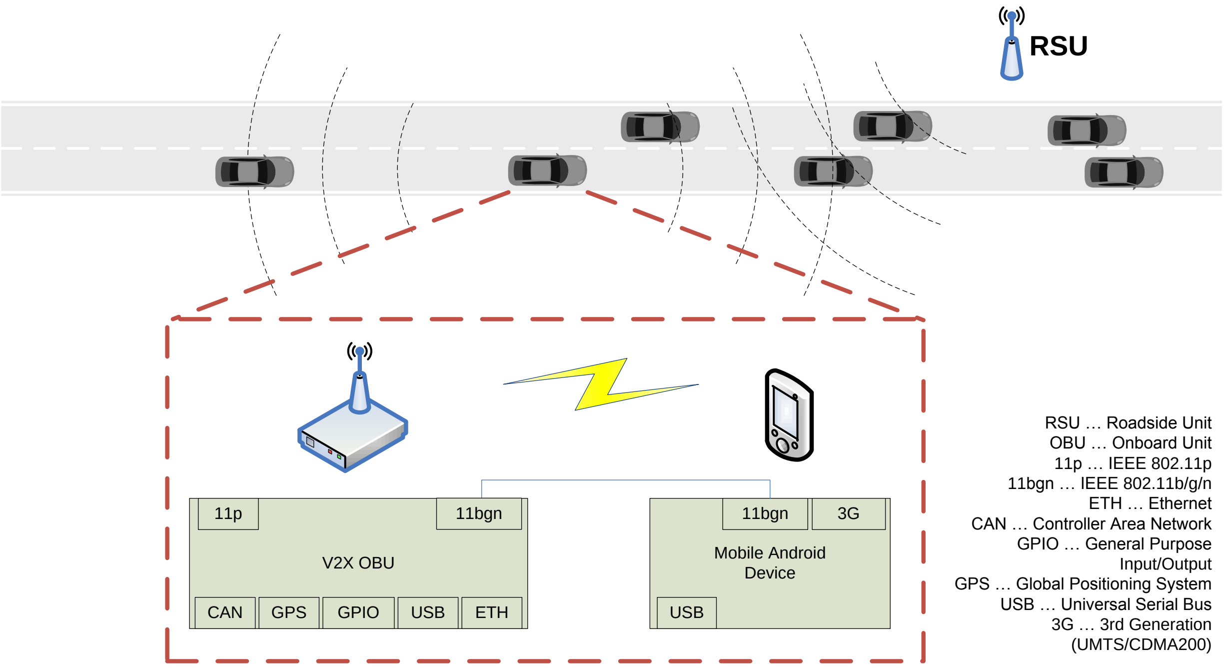


Figure 6.2: System overview including a detailed view of our in-vehicle setup. The connection between the OBU and the PMD is based on WLAN.

specified transmission rate for IEEE 802.11p [173]. For slower connections, such as USB 1.1, which only supports up to 12 Mbit/s, filtering would have to be applied at the OBU.

In order to combine data from Internet sources with V2X information coming from the OBU (e.g., as in the case of 5G-based V2X communication or navigation/routing using external traffic information systems), the PMD has to be connected to the OBU and at the same time to the Internet. However, current mobile devices usually only allow using either mobile data or WLAN. A possible workaround is putting the PMD in the so-called Wi-Fi tethering mode. In this mode, the PMD acts as a modem and WLAN access point. That could, in the future, also be implemented by an in-car WLAN hotspot with a security system shielding sensitive vehicle systems. That way, the WLAN module of the OBU could connect to the PMD, which then would be connected to both the Internet and the OBU.

For our evaluation of work splits between mobile devices and automotive systems, we have chosen WLAN for their connection. The access point is running in access point (AP) mode, and the PMD is connected to it via IEEE 802.11g. The connection allows a maximum transmission rate of 54 Mbit/s.

Hardware Elements

For reasons of simplicity that do not affect the core of our research, our prototype OBU consists of two physical devices, the DENSO Wireless Safety Unit (WSU) and a commercial, off-the-shelf

IEEE 802.11b/g/n WLAN access point. The WSU features a PowerPC central processing unit (CPU) running at 400 MHz and has 128 MB random access memory (RAM). It runs an embedded Linux system with a small footprint and supports IEEE 802.11p [173] for V2X communication. The utilized WLAN access point can either be run in AP mode, which allows connecting WLAN clients to it, or in Ethernet adapter mode, which allows a transparent connection of Ethernet devices to any other defined WLAN access point. We use a 7-inch Samsung Galaxy Tab GT-P1000 running Android 2.3.3., which was the most widely used Android-based operation system at the time of conducting the described research. It is equipped with a 1 GHz single-core Advanced RISC Machine (ARM) architecture CPU and has 512 MB RAM.

6.3.2 Evaluation of Work Splits

In a two-component system, work can be split in different ways. The split should consider the weaknesses and strengths of the individual components and the options for interlinking the components. In our scenario, we divide the typical architecture of a V2X-based driver assistance application into four major blocks. The *access technology* bundles the physical wireless interface with the device driver, the media access control, and the link-layer protocol. The *networking and transport* block includes GeoNetworking (GN) mechanisms and the basic transport protocol (BTP). The protocol handling and data structures for exchanging actual V2X information is summarized in the block *Facilities*. It covers, among others, the V2X messages CAM, DENM, signal phase and timing (SPaT), and topology (TOPO).

As shown in the system overview in Section 6.3.1, the distributed system under investigation consists of two autonomous computing nodes [398], the PMD and the V2X OBU. In order to reach the goal of presenting V2X real-time information to the user in the form of a driver assistance system, the V2X messages need to be received, processed, interpreted and displayed. Besides the access technology that is linked to the IEEE 802.11p interface, which is only available on the OBU and the user interface that can only be provided by the actuators and sensors of PMD, all other elements could be split freely between the two nodes. It is even possible to split elements within the architecture blocks between the computing devices. However, due to reasons of flexibility and computing performance, we limited the scope of the more detailed investigated two-tier architecture configurations to the following three work splits:

- PMD as HMI and V2X Message Processing Unit
- OBU as Facility Services Provider and PMD as HMI Provider
- Hybrid Approach for Handling Facility Services

The three work split configurations are depicted in Figure 6.3. Since mobile devices are not equipped with the V2X access technology IEEE 802.11p (or a potential 5th Generation Mobile Telecommunications (5G) network access), this functionality is for all cases provided by the OBU. In order to maximize the overall system stability and the interoperability with other V2X

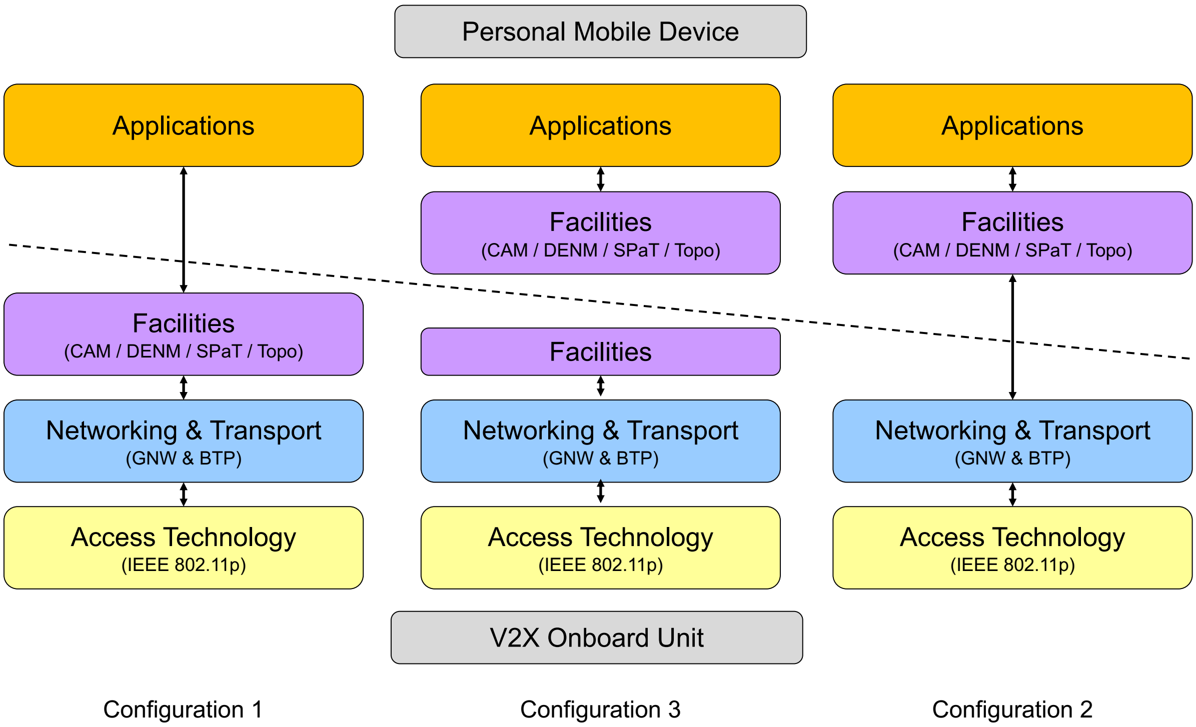


Figure 6.3: Overview of the three investigated two-tier architecture configurations. According to the distributed systems theory, further work splits would be possible by doing the split within or between each of the depicted blocks.

communication devices, we have chosen to implement the essential networking and transport functionalities in the V2X stack of the OBU. Both, the BTP [114] and GN [113] are at the time of conducting this research going through the final revision process at the European Telecommunications Standards Institute (ETSI). As soon as the revisions are completed, it can be expected that the protocols will not be changed for years, as it is common for automotive systems. Keeping these functions in the OBU means that we do not have to test the interoperability and the long-term stability for every new functionality we add to the PMD. Besides, this design decision ensures that the basic V2X functionalities, such as message forwarding, can also be provided by the OBU when no PMD is coupled to it.

We compare the three work splits with respect to the following criteria:

- Performance: messages per second
- Flexibility: the effort required to add/update message formats and types
- Battery usage: load on PMD

For benchmarking the work splits, we have chosen the decoding process of CAMs [115] that often contain information directly relevant for the driver. The CAM format is defined in Abstract Syntax Notation One (ASN.1). CAMs are repeatedly broadcast by all vehicles within the V2X network,

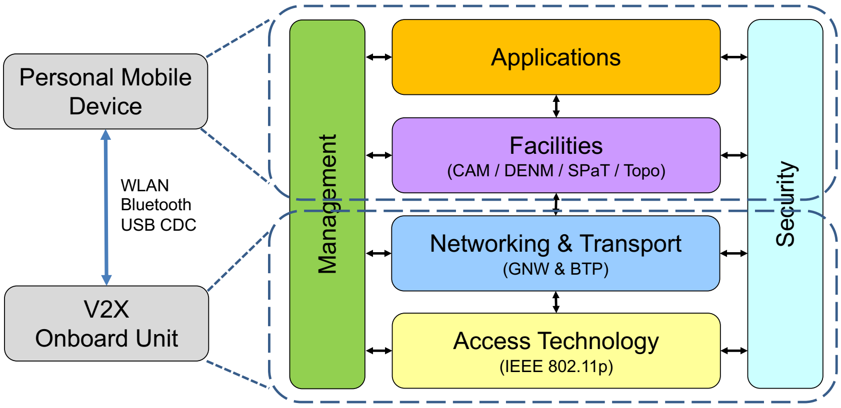


Figure 6.4: The OBU can be seen as a message gateway in this configuration. It forwards the incoming raw data directly to the PMD without further processing or interpretation.

usually at the frequency of 10 Hz. They provide information about the presence, position, vehicle type, and other basic information. Vehicles that receive the CAMs are aware of their neighbors and can use the information to evaluate their situation. Therefore, it is fair to assume that they will constitute the major load on V2X systems in non-emergency situations, i.e., in regular use.

Configuration 1: Personal mobile device as Human–machine interface and Vehicle-to-X Message Processing Unit

Figure 6.4 depicts the first investigated work split. The OBU acts mainly as a V2X message gateway. All incoming data that is intended for the intelligent transportation system (ITS) station is directly passed to the PMD. Forwarding the raw message directly to the PMD is the most flexible and future-proof solution. Instead of upgrading the software of the OBU at a garage when new message types are introduced, it is sufficient to supply a software update for the PMD, which can be installed by the end-user over the air.

For the first configuration, we have used the open-source ASN.1 Java framework *BinaryNotes*[5] for decoding incoming messages directly on the PPD. The first benchmark has been conducted under low a CPU load. $1,000$ decodes last, on average, about $9500\,\mathrm{ms}$, which leads to an average decode rate of $105\,\mathrm{Hz}$. Measurements during active map rendering with *mapsforge*[6] and distance calculations between the position received in the CAMs and a given point, lead to an average achievable CAM decode rate of $41\,\mathrm{Hz}$. Considering a CAM transmission rate of $10\,\mathrm{Hz}$ per vehicle, only four stations could be supported by this solution. When thinking of dense highway traffic, this number is much too low for a viable traffic awareness system. Given the tendency of automotive manufacturers to always buy the cheapest devices (and thus slowest units) and the rising future demands in communication, this result paves the way for a different distribution of workload between the devices.

---

[5] http://bnotes.sourceforge.net/, accessed August 10, 2019
[6] https://github.com/mapsforge/mapsforge, accessed August 10, 2019

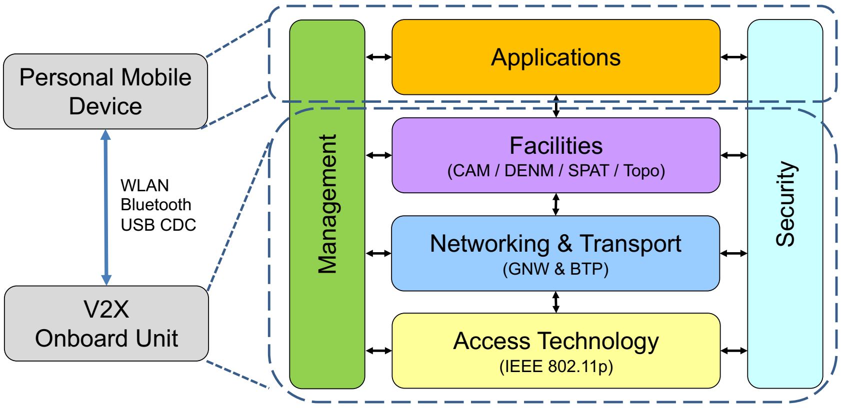


Figure 6.5: In this configuration, the PMD acts mainly as HMI. In this *thin-client* scenario, all processing and interpretation is done on the OBU.

For measuring the device's CPU load, CAMs arriving with a rate of 20 Hz have been used. The average CPU load for the decoding process has been between 32 % and 41 % on the Samsung Galaxy Tab P1000. Considering a short trip with the mobile device not connected to a power source, this would heavily drain the battery.

We expect from our experience that using a commercial ASN.1 decoding library, such as MARBEN's TCE-Java[7] or OSS Nokalva's ASN.1/Java[8], would lead to better results in terms of performance and battery usage. However, maximum flexibility through handling facilities and applications on the PMD would always lead to a massive battery drain. Besides, novel driver assistance systems or safety features integrated in the vehicle's system could also make use of the V2X data. For this setup, either the PMD would need to pass the encoded data back to these systems, or the new components would have to handle the message decoding themselves.

Configuration 2: On-board unit as Facility Services Provider and Personal mobile device as Human–machine interface Provider

In order to maximize the overall performance, we decided to evaluate a second work split, which is depicted in Figure 6.5. In contrast to Configuration 1, the PMD is only responsible for running the applications and for providing the HMI to the driver. The facilities, such as CAM and DENM services, have been completely shifted to the OBU. For decoding CAMs, the C/C++ ASN.1 library from Objective Systems[9] has been used. The CAM decoding benchmark on the OBU leads to an average CAM decoding rate of 41.500 Hz with a maximum CPU load of about 78 %. That is about 400 times faster than with *BinaryNotes* on the PMD.

---

[7] http://www.marben-products.com/asn.1/asn1-tools-java-api-compiler-runtime.html, accessed August 10, 2019
[8] http://www.oss.com/asn1/products/asn1-java/asn1-java.html, accessed August 10, 2019
[9] http://www.obj-sys.com/products/asn1c/index.php, accessed August 10, 2019

For forwarding the decoded V2X messages (together with management and statistical data) to the PMD, an efficient message format has to be chosen. Since lengthening the data many times over would cause a communication bottleneck between the PMD and the OBU, human-readable formats, such as extensible markup language (XML) or JavaScript object notation (JSON), are ineligible. However, several performance- and space-optimized binary serialization libraries are available that offer libraries for C/C++ and Java. Based on previous performance examinations[10] and availability of documentation, we have chosen protocol buffers (ProtoBuf)[11] for exchanging the data between the OBU and the PMD. ProtoBuf allows for a fast and flexible message creation that supports different scalar value types as well as lists and optional fields.

For evaluating the overall system performance, we have measured the average maximum combined ASN.1 decoding and ProtoBuf encoding on the OBU. The average encoding rate was about 15.900 Hz. That includes all integer-to-float conversions so that the PMD does not have to perform any pre-processing on the messages. On the PMD, the ProtoBuf decoding of the generated message has been benchmarked during map rendering. We have measured an average maximum achievable CAM processing rate of 3500 Hz on the Samsung Galaxy Tab, which is more than 80 times faster than Configuration 1. In another benchmark with additional position processing and data reasoning, we could handle data from more than 75 vehicles at the same time without influencing any other process on the OBU and the PMD.

The CPU load caused by the message handling on the PMD was again evaluated with CAMs at 20 Hz. On average, the ProtoBuf message decoding caused a CPU load of 2.3 % (averaged over 10 minutes). In contrast to the first configuration, the effect of message decoding on the battery drain is almost negligible.

However, the flexibility of this solution is very low. The introduction of new message types requires updating the OBU. The need to update both the OBU as well as the PMD can easily lead to compatibility issues when, for example, only one device's software is updated.

Configuration 3: Hybrid Approach for Handling Facility Services

In order to gain flexibility, we have developed a third configuration depicted in Figure 6.6 that combines the strengths of the previous configurations. That has been realized by enabling facility handling on the OBU and the PMD. The message decoding functionality remains on the OBU, with the difference that the PMD can also request messages on any BTP port in raw format. Additionally, the compatibility problem when having updated only the software of the PMD, or even just of the OBU, is addressed by this approach.

The elementary part of the configuration is an XML remote procedure call (RPC) server [398] running on the OBU. When the PMD is coupled to the OBU, it can send an XML-RPC request to

---

[10] https://github.com/eishay/jvm-serializers/wiki, accessed August 10, 2019

[11] https://github.com/google/protobuf, accessed August 10, 2019

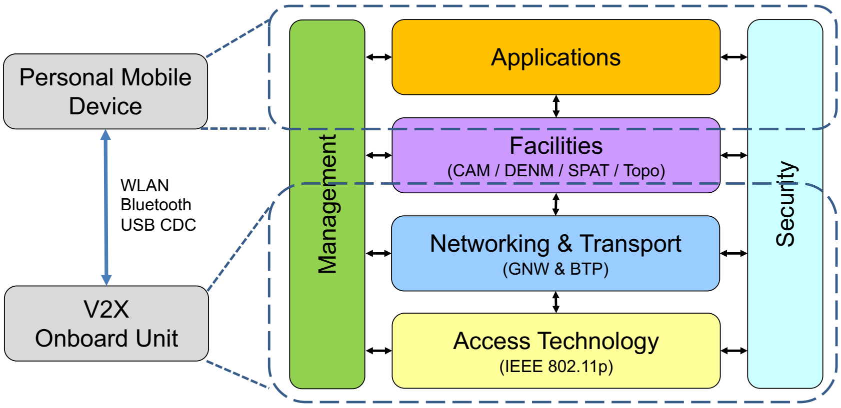


Figure 6.6: By splitting the facilities layer on the OBU and the PMD, flexibility and processing performance can be improved. Since the PMD can, in this case, also work with raw geo-networking messages, it is also a future-proof approach allowing the addition of new messages in the future.

this server, asking for the version and capabilities of the OBU's software. The OBU's response contains the software version of the OBU and a list of message types and versions that can be decoded on the OBU. Based on this information, the PMD can either request decoded messages or raw messages OBU that are received by the OBU on the desired BTP port.

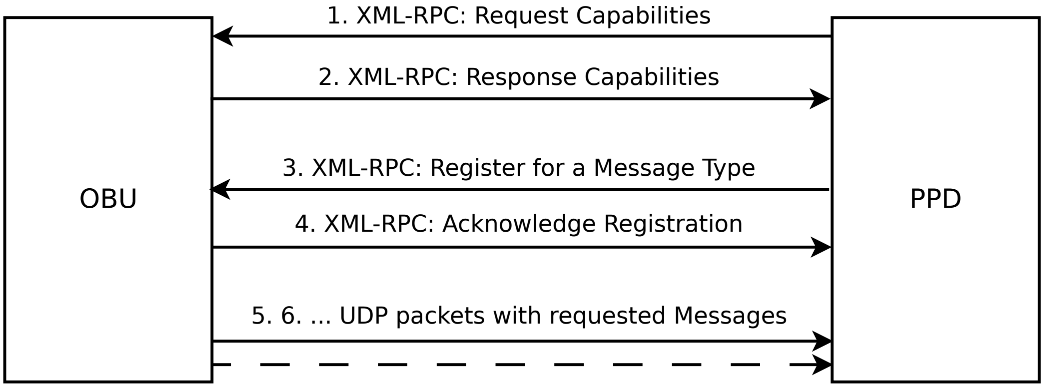
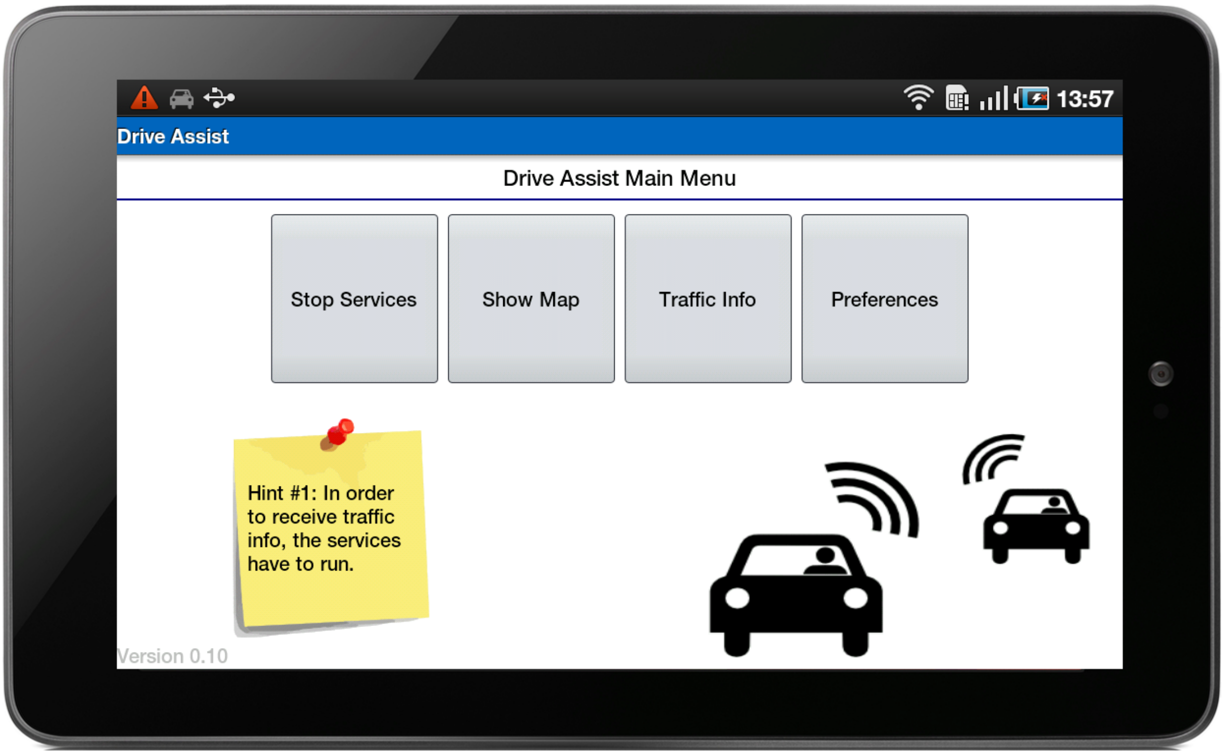


Figure 6.7: An XML-RPC server on the OBU allows registering for different message types. Besides already decoded messages, the PMD can also request raw messages on any BTP port.

A sample communication scenario between the OBU and the PMD is depicted in Figure 6.7. The PMD first requests the capabilities and then registers for a message type (for example, *raw*, *CAM*, or *DENM*) on a BTP port. When the OBU can fulfill the request, it acknowledges the PMD's request and starts sending either already decoded or raw messages to the PMD. In that way, multiple devices can register for multiple message types. In the case of raw message forwarding, performance and battery usage results from Configuration 1 are valid. When the OBU decodes the messages, performance and battery usage statistics from Configuration 2 apply.

6.4 DriveAssist – A Mobile Device-Based Advanced Driver Assistance Systems



Hint #1: In order to receive traffic info, the services have to run.

Figure 6.8: DriveAssist's main menu. The four big buttons in the top row are optimized for in-vehicle usage and allow controlling the central parts of the application. The yellow hint (bottom left) shows short pieces of usage information, when it is enabled in the preferences.

In this section, we describe our fully developed and implemented research prototype DriveAssist which we use as a research vehicle to investigate in more depth the distribution of functionalities across mobile devices and automobiles. It will allow us to use it for evaluation, gathering qualitative and quantitative data.

6.4.1 Description of the DriveAssist Prototype

DriveAssist is a framework for the rapid evaluation of visualization concepts of V2X data. Its main menu is depicted in Figure 6.8. The application offers an active map view (cf. Figure 6.9) for overseeing the vehicle's surrounding and a passive warning screen (cf. Figure 6.10a and Figure 6.10b) that is triggered by a service running in the background. Besides visual representations, DriveAssist also supports TTS output.

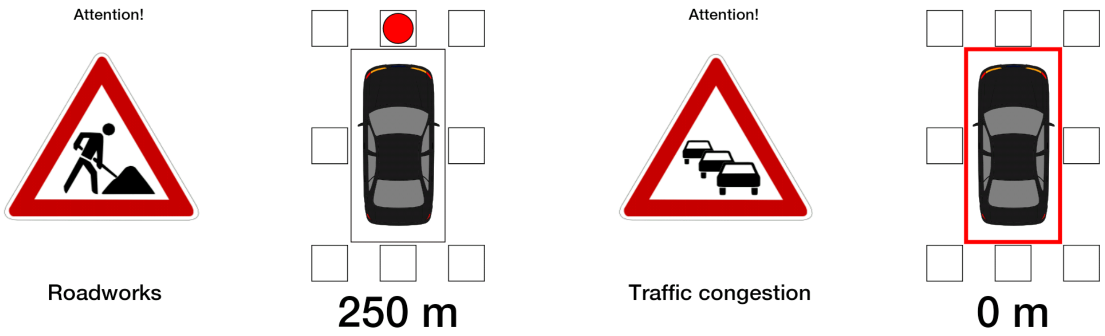
The map view presents an overview to inform the driver and other vehicle passengers. Figure 6.9 depicts a possible traffic scenario where the car is approaching a cross street with a stationary

Last TomTom HD Traffic update: 06.02.2012 15:56:33

Figure 6.9: DriveAssist's map view. The black car in the center represents the driver's vehicle. Newly received traffic events are indicated by the large traffic sign in the bottom left corner. The small traffic signs indicate the position as well as the type of the traffic event on the map.

vehicle warning and a roadwork warning. The warnings are displayed as they might become relevant for the driver when turning into this street. Additional information can be displayed by tapping on a warning icon. It contains the source of information, a more precise description of the event, and, when available, also the length and time-loss caused by the event. For acoustic notifications about new nearby incidents, a circle of interest around the car can be defined. Newly detected events are also indicated by a larger version of the warning symbol in the lower-left corner of the screen. Besides the map view, it is also possible to get a list view of all nearby incidents.

The warning screen is the passive warning module of DriveAssist. It is started and controlled by a service running in the background and can overlay any other application, such as a navigation application or the phone interface. Figure 6.10a depicts the warning screen indicating a working area warning (WAW) which refers to a construction site 250 meters ahead. The warning sign describing the event type is complemented by a textual description ("Roadworks"). The car top view on the right-hand side is used for visualizing the distance and the direction of the event relative to the car's long axis. The red dot indicates the direction of the incident by being displayed in one of the eight little squares around the car. When the distance to the incident gets too low, the direction cannot be calculated reliably due to the limited accuracy of the position data. In that case,



(a) The warning screen shows the type of the detected traffic incident through well-known and simple traffic symbols. The red dot indicates the direction of the event relative to the car. A text-to-speech generated audio warning accompanies the visual output.

(b) When the traffic event is nearby (e.g., less than 15 meters away), the GPS accuracy may not allow indicating the precise position of the event. For that reason, the red border around the car shall symbolize the user that the event can be anywhere around the car.

Figure 6.10: DriveAssist's warning screen shows the type of the detected traffic incident as well as the direction towards it.

the direction indicating dot is replaced by a red rectangle around the vehicle (cf. Figure 6.10b). Together with a TTS output, this shall inform the driver that the incident is nearby and can be anywhere around the car. When there are multiple traffic events nearby, the controlling background service applies prioritization. Approaching, moving traffic events, such as moving emergency vehicles or a sharp braking vehicle, get higher priority than static events. For static events, the prioritization is done by their distance to the vehicle.

Both warning modules offer TTS support. The speech cues allow informing the driver in a fast and reliable way even when the driver is distracted by a secondary or tertiary task [192] or has to focus on the primary driving task, as it could be the case for adverse or highly congested driving conditions.

The information from V2X communication is currently derived from CAMs [115] and DENMs [116]. DriveAssist supports the following day-1 use-cases [309]:

- Approaching emergency vehicle warning (AEVW) from CAM
- Electronic emergency brake light (EEBL) from DENM
- Stationery vehicle warning / post-crash warning (PCW) from DENM
- Traffic jam ahead warning (TJAW) from DENM
- Working area warning (WAW) from DENM
- Hazardous location notification (HLN) from DENM

An obstacle to V2X communication currently is the penetration rate required for realizing an efficient warning system [352]. Early adopters have no real benefit when the penetration rate is still low. A broad roll-out in the market has not yet begun. The questions researched in this thesis, therefore, contribute to state of the art and provide novel insights.

In order to provide functionality even at low V2X equipment proliferation rates, DriveAssist combines V2X data with data received via the mobile data connection of the PMD. The Internet-based central traffic services (CTSs) are usually provided by service providers that collect and aggregate data from different sources. Common sources are the police, road maintainers, private persons, mobile operators, or automobile clubs.

6.4.2 User Study on DriveAssist

Participants

The application has been evaluated in a laboratory user test with 12 participants between 22 and 30 years (average age: 27 years, $\sigma = 2.2$ years) using the application for about 45 minutes. Most of them were students or research assistants. All participants were male. Since V2X is a new technology and, thus, typical end-user do not have experience with such systems, an expert-based evaluation was chosen. They were recruited among acquaintances of the researchers. None were related to the research project.

The within-subjects study was performed for answering the following research questions (RQs):

- **RQ1**: Is the chosen user interface (UI) easy to understand and to learn?
- **RQ2**: Is text-to-speech (TTS) an appropriate way of supporting the visual warnings?
- **RQ3**: Would users prefer the map view, the warning screen, or a combination of both in order to get informed about a traffic incident?
- **RQ4**: What information is considered useful, and what information is still missing?

Method

The data for the study scenario was created with the c2xMessageTester (cf. Section 6.7). The data includes, amongst other data, according to the standard, the position of the subject's car, other traffic participants, and predefined traffic events. The Wizard of Oz technique [73] was used for triggering the defined events at the correct time. Four traffic scenarios with different levels of complexity were presented to the subjects. The most complicated scenario is depicted in Figure 6.11. The subject's simulated vehicle first approaches traffic congestion. While the vehicle is passing by, a hazardous location warning is triggered. Directly after the hazardous location, a stationary vehicle warning is set off.

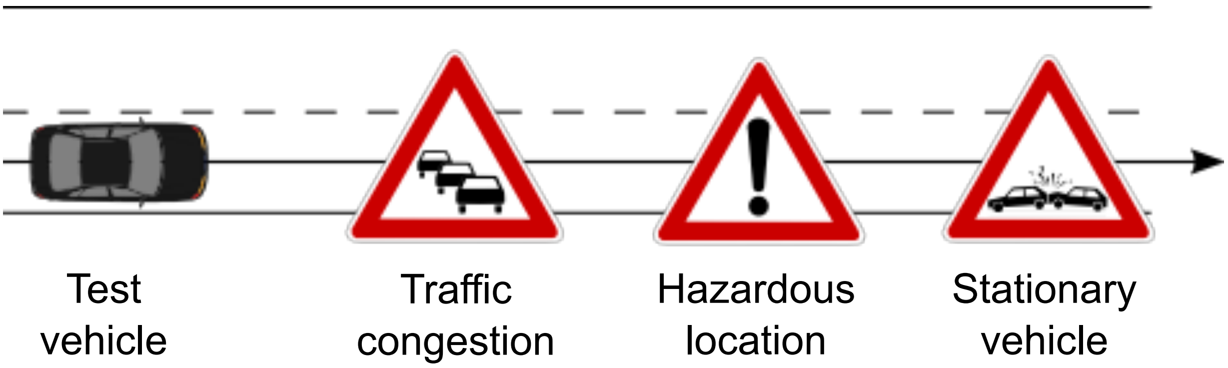


Figure 6.11: A simplified diagram of the fourth scenario that was shown to the subjects. The test vehicle corresponds to the subjects' vehicle. The traffic incidents were arranged on a curvy road and spaced $150\,\mathrm{m}$ to $300\,\mathrm{m}$ apart.

Task

A semi-structured questionnaire with open and closed questions was used for collecting the test data. Open questions invited the subjects to answer questions in their own words. The closed question set contained yes/no questions, questions with given answer options, and questions in which statements had to be rated on a Likert scale as a summative scale ranging from 1 (totally disagree) to 5 (totally agree).

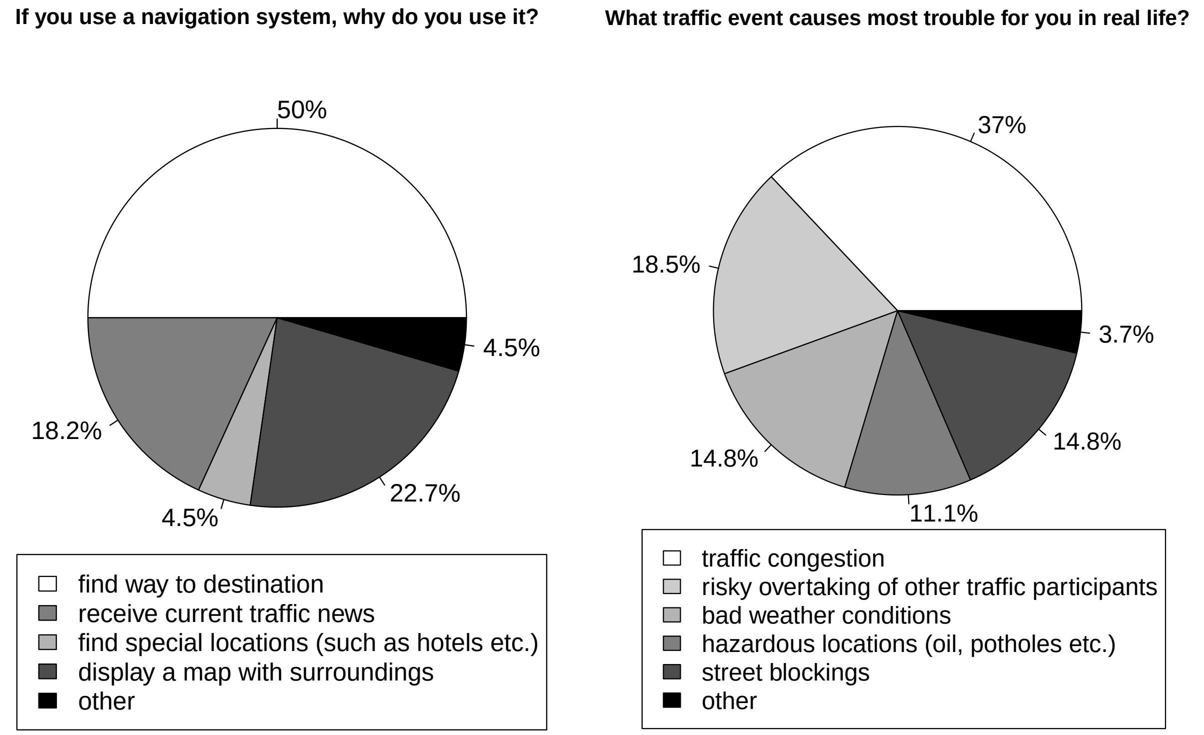
First, as part of the briefing and for assuring common minimal information for all participants, the subjects had to read an introduction and to answer some introductory questions concerning their knowledge about similar systems to learn about the baseline for later comparability. In the next part, DriveAssist's main menu was presented to them. After having examined the main menu for some adequate time, questions regarding their first impression had to be answered. We thus used the think-aloud method to collect the feedback. In the following part, the four different traffic scenarios were used. While playing *Superball*[12], warning messages according to the scenarios were displayed by using the passive warning screen. Afterward, the subjects were asked whether they had understood the situation. Specific questions about the warning screen followed those open questions. For testing the map view, two scenarios were played by the user study supervisor and followed by the user. This time, the subjects entirely concentrated on the map without playing the game. For collecting their opinion about the map view, several statements had to be rated afterward as part of a structured evaluation.

6.4.3 Results of User Study on DriveAssist

In order to be able to interpret the results, previous knowledge, expectations, and current usage of smartphones and navigation systems were elicited. From the 12 subjects, 10 subjects regularly

---

[12] The freeware game *Superball* can be obtained from http://christoph.stoepel.net/ViewSoftware.aspx?id=0103, accessed August 19, 2019



(a) The subjects use navigation systems mainly to find their way to (unknown) destinations. However, they also use them to display a map with their surroundings and to receive current traffic news. ($n = 12$, multiple items could be ticked)

(b) For the subjects, traffic congestion causes the most trouble in daily traffic. Except for risky overtaking and bad weather conditions, all chosen cases are supported by DriveAssist. ($n = 12$, multiple items could be ticked)

Figure 6.12: Previous knowledge, experiences, and expectations were elicited to have a better context for interpreting the results of the study.

use a smartphone and thus are familiar with the usage of mobile applications. 11 subjects use a navigation system on a regular basis. The main reason for using the navigation system is for finding a route to unknown destinations.

However, the subjects also use the navigation system to display a map of the surrounding area and to be informed about the current nearby traffic situation (cf. Figure 6.12a), such as traffic jams. In Figure 6.12b, the traffic events causing the most trouble for the subjects are summarized. Except for the causes 'risky overtaking' and 'bad weather conditions,' all other cases are supported by DriveAssist.

The results for the evaluation of the main menu are summarized in Table 6.2. **A1** and **A3** verify the clear and simple structure of DriveAssist. However, it is not as graphical appealing to the subjects as it could be (**A2**). For eight subjects, the main reason why DriveAssist does not remind them of their navigation system (**A4**) was the 'lack of icons and graphics.'

Table 6.3 summarizes the results for the warning screen that pops up when a traffic incident is nearby. All but one subject could quickly understand the warnings (**B1**). The subjects explained

#	Statement	TD (1)	D (2)	N (3)	A (4)	TA (5)	M	σ
A1	The application seems to be complex.	3	7	1	1	0	2.00	0.85
A2	The application is graphically appealing to me.	0	3	2	7	0	3.33	0.88
A3	The menu seems to be well usable in a car.	0	2	1	3	6	4.08	1.16
A4	The menu reminds me of my navigation system.	1	7	4	0	0	2.25	0.62

Table 6.2: Absolute frequencies of respondents' opinion on the first impression of DriveAssist. The statements are rated from *I totally disagree* (TD), *I disagree* (D), *neutral* (N), *I agree* (A), to *I totally agree* (TA). M stands for average value and σ for standard deviation.

#	Statement	TD (1)	D (2)	N (3)	A (4)	TA (5)	M	σ
B1	I have quickly understood the presented warnings.	0	1	0	4	7	4.42	0.90
B2	The indication of the direction was useful.	1	2	5	3	1	3.08	1.08
B3	Sometimes the red dot was "bouncing". That irritated me.	6	2	1	1	2	2.25	1.60
B4	The warning screen interrupted my attention violently.	1	8	3	0	0	2.17	0.58
B5	The voice output is a useful way of supporting the warning.	0	0	0	3	9	4.75	0.45

Table 6.3: Absolute frequencies of respondents' opinion on the warning screen. The statements are rated from *I totally disagree* (TD), *I disagree* (D), *neutral* (N), *I agree* (A), to *I totally agree* (TA). M stands for average value and σ for standard deviation.

that this was supported by the fact that standardized German traffic signs for indicating the traffic incidents' types have been used. Statements **B2** and **B3** refer to the red dot indicating the direction. Six subjects noted that for them, the red dot was a bit too small, which made it poorly visible. However, when the subjects recapitulated the scenarios, all subjects had determined the depicted direction of the traffic incidents correctly. Three subjects suggested the use of a continuous indication of the direction angle, and one subject would omit the direction indication completely.

In Table 6.4, the results concerning the map view are shown. In general, the subjects agreed that the map view is useful (**C2**). However, all but three subjects explained that displayed incidents should be limited to the planned route (**C4**). Similar to the warning screen (**B1**), the used symbols were clear to the participants (**C3**). In comparison to the warning screen (**B4**), the map view needs more attention, "especially when multiple traffic incidents are displayed" (**C5**).

The voice output (**B5** and **C7**) received excellent ratings in the users' perception. 10 subjects emphasized that it is a good extension to the visual display. One subject explained that he "just shortly glanced at the warning screen to identify the direction [of the event]." For the map view, the subjects further demanded that the position and the type of the newly announced traffic event should also be mentioned via TTS, and its position should be highlighted on the map (**C1**).

#	Statement	TD (1)	D (2)	N (3)	A (4)	TA (5)	M	σ
C1	When a new warning is announced by the voice output, its position should be highlighted on the map.	0	0	3	3	6	4.25	0.87
C2	The overview provided by the map is useful.	0	3	0	6	3	3.75	1.14
C3	The meaning of the symbols is easy to understand.	0	1	1	6	4	4.08	0.90
C4	Only traffic events on my itinerary should be displayed.	0	3	0	3	6	4.00	1.28
C5	The map view requires a lot of attention.	2	1	5	4	0	2.91	1.08
C6	The map view reminds me of my navigation system.	0	1	0	3	8	4.50	0.90
C7	The voice output is a useful support for the map view.	0	0	1	3	8	4.58	0.67

Table 6.4: Absolute frequencies of respondents' opinion on the map view. The statements are rated from *I totally disagree* (TD), *I disagree* (D), *neutral* (N), *I agree* (A), to *I totally agree* (TA). M stands for average value and σ for standard deviation.

#	Statement	TD (1)	D (2)	N (3)	A (4)	TA (5)	M	σ
D1	The navigation functionality is missing.	0	0	1	7	4	4.25	0.62
D2	I would only use the map view and omit the warning screen.	4	2	1	3	2	2.75	1.60
D3	Central traffic services provide useful additional information.	0	0	1	3	8	4.58	0.67

Table 6.5: Absolute frequencies of respondents' opinion on the overall impression of DriveAssist. The statements are rated from *I totally disagree* (TD), *I disagree* (D), *neutral* (N), *I agree* (A), to *I totally agree* (TA). M stands for average value and σ for standard deviation.

The results of statements on the overall impression of the DriveAssist system are given in Table 6.5. The combination of V2X data for real-time, nearby traffic information, and data from Internet services for long-term, distant traffic events was seen as one of the significant strengths of DriveAssist (**D3**). The map view reminds the subjects of a navigation system (**C6**). For that reason, the subjects miss navigation functionality (**D1**). That also corresponds to the ratings of statement **C4** that only traffic incidents on the current route should be displayed. Statement **D2** shows that the subjects had different preferences; for some, the map view would be enough. Three subjects mentioned that they would prefer to have both the warning screen and the map view at the same time with the warning screen displaying the warning with the highest priority.

6.4.4 Discussion of the Results

In the following, we provide answers to the formulated research questions **RQ1** to **RQ3** in Section 6.4.2. Based on our findings from the conducted study, we give recommendations for the functional design and technical implementation of a V2X communication-based visualization solution.

RQ1: Suitability of UI

In general, the user interface has been rated as good, except for the missing icons on the buttons of the main menu. For the warning screen, our novel concept of direction indication was seen controversial. Two subjects suggested that a huge arrow continuously showing the direction to the event could replace the current way of indication. We suppose this could be related to the acquaintance with conventional navigation systems. This idea came up due to the reason that the red dot sometimes quickly jumped between two directions. For that reason, we recommend implementing a debouncing mechanism, for example, by introducing a hysteresis. Contrary to the demand for continuous direction indication, two other subjects stated that the rough direction (front, left, right, back) indicated by a large bar or box next to the car's top view would be enough. Since the warning is normally displayed in cases when the driver should focus on the street, we recommend to set on a simple version that allows for fast direction recognition. Besides, the size of the font should be as large as possible since six participants complained about its readability.

In order that the map view can provide a good overview and situation awareness (visualizing CAM messages), only events on or nearby the planned route should be displayed. That requires the integration of navigation functionality into the warning system, which has been realized in a second prototype (see Section 6.5). When a traffic event relevant to the ego-vehicle is received that would be outside of the currently visible map region, it should be displayed at the map's border for indicating its direction, or not displayed at all. When a new event is added to the map view, it should be announced via TTS and highlighted on the map in order to be distinguishable and recognizable as a new event.

The choice of warning symbols for visualization is also an important concern. In our application, we have used standardized German traffic signs as the basis. The subject that disagreed with statement **B1** was from outside the European Union and had never driven a vehicle in Germany. For that reason, he had difficulties with interpreting the shown symbols. The chosen symbols should be matched with the target country. Here, modern ADAS could show local and symbols from the driver's origin side by side.

Another point of importance is the adaption of the screen to the brightness of the environment. When it is dark, the white background of the warning screen would be very exhausting for the driver, even when the display is automatically dimmed. The same holds for the map view. The bright colors should be replaced with darker ones in that case. An approach that has proven useful is the use of inverted contrasts (black on white during the day, white on black at night) as the overall luminance is lower, the driver's eye thus being less irritated when switching the view from the road to the console and back [200].

RQ2: Benefits through TTS Support

The subjects rated the speech output as very important. In their feedback, several subjects highlighted that they only had to take a short look at the warning sign and the direction, but did "not have to look at the written warning text as TTS provided it." Since the speech cues contain the information shown on the screen, less attention has to be paid to the visual representation for information polling. Thus, it reduces the overall time drivers need to take their eyes away from the road. When the warning pops up first, the spoken message began with the word "attention." Three subjects found this could be removed since it only delays the output of the crucial or time-critical information. However, two of them wanted some auditory icon at the beginning in order to direct their attention to the following speech output. That could be implemented by a special auditory icon or dedicated sound. The content of the spoken message should comprise the type of the traffic event, the distance, and the direction (only when a moving object causes a warning, all others should only be relevant when they are ahead on the route).

For optimizing the audibility, the volume of the speech output has to be context-aware adjusted based on the environmental noise. For the TTS setup (e.g., gender or mode of expression), cultural differences should be taken into account to create a positive listening experience.

RQ3: Mode of Warning Display

The subjects prefer a combination of the fast to understand warning screen for immediate incidents and the map view as an overview of surrounding incidents. One subject said that he would prefer the active warning screen for severe and urgent warnings. Other warnings could be presented using the map view. That could, for example, be realized by using severity classes [271]. Another subject suggested indicating the priority of an event by changing the background of the warning screen or by flashing the warning symbol. However, both measures would direct the driver's attention to the screen, which could negatively influence the driver's reaction time.

When the display is large enough, both views could be combined side-by-side, or the warning screen could partly overlay the map view as three subjects have demanded. In that case, the warning screen would just be displayed when necessary. The map view would be visible all the same time. We performed a few experiments with that approach. However, pre-tests showed that the 7-inch screen is too small for the simultaneous display of both screens. A list with all received incidents was also tested. However, the subjects rated the list as not entirely useful if the events cannot be displayed on a map next to the entries.

RQ4: Useful and Missing Information

The user test showed that users expect such a warning system to be coupled with navigation functionality. The received traffic events should be included in the (then updated) route calculation, e.g., for finding alternative routes to the current target. Besides, the route information should be used to avoid the presentation of warnings that are irrelevant for the driver.

The subjects further pointed out that the available information and real-time communication channels should be used for improving driving efficiency and comfort. For example, the vehicles could form an extensive network [87] that could optimize the overall, local, and individual traffic efficiency by suggesting to change the mode of transportation or to switch to routes with less traffic.

Other important aspects of the subjects were information security and privacy. They were afraid that wrong or forged V2X messages could be generated by attackers [224], which could lead to dangerous situations (e.g., warning of sharp braking vehicle in front). Since the position of their vehicles is also broadcast, the participants were afraid that their driving could be tracked. Approaches in the literature have already investigated privacy concepts with regular changing pseudonyms to counter these concerns [127, 223].

Other concerns refer to mobile application management. It should be distributed via a trusted channel and updated regularly, in an app store-like manner. For example, it could be installed and updated at garages, gas stations, or car dealerships. The currently available mobile application markets are seen as problematic since anyone can upload imitations of regular applications, and users are responsible for updating their installed applications themselves [273]. One subject mentioned that certificates from independent test institutions and guaranteed update mechanisms could create confidence.

6.5 DriveAssist 2.0 – Combination with Route Guidance

DriveAssist 2.0 is the result of continued development and improvement of DriveAssist that adds route context to the functionality of DriveAssist, which was one of the primary outcomes of the previous study.

6.5.1 Concept Enhancements in DriveAssist 2.0

The navigation functionality was be added by including the open-source navigation project OsmAnd[13]. Besides the routing mechanism, we also took over the main menu screen from OsmAnd. Figure 6.14a shows the main menu of DriveAssist 2.0. Compared to DriveAssist, it has two additional buttons for accessing the routing functionality: The *Search* and the *Favorites* button. As the names suggest, the first one opens a dialog that allows searching for locations, and the second one provides access to a list of favorite locations.

Figure 6.13 gives an overview of the features included in DriveAssist 2.0.

---

[13] https://osmand.net/, accessed February 3, 2020

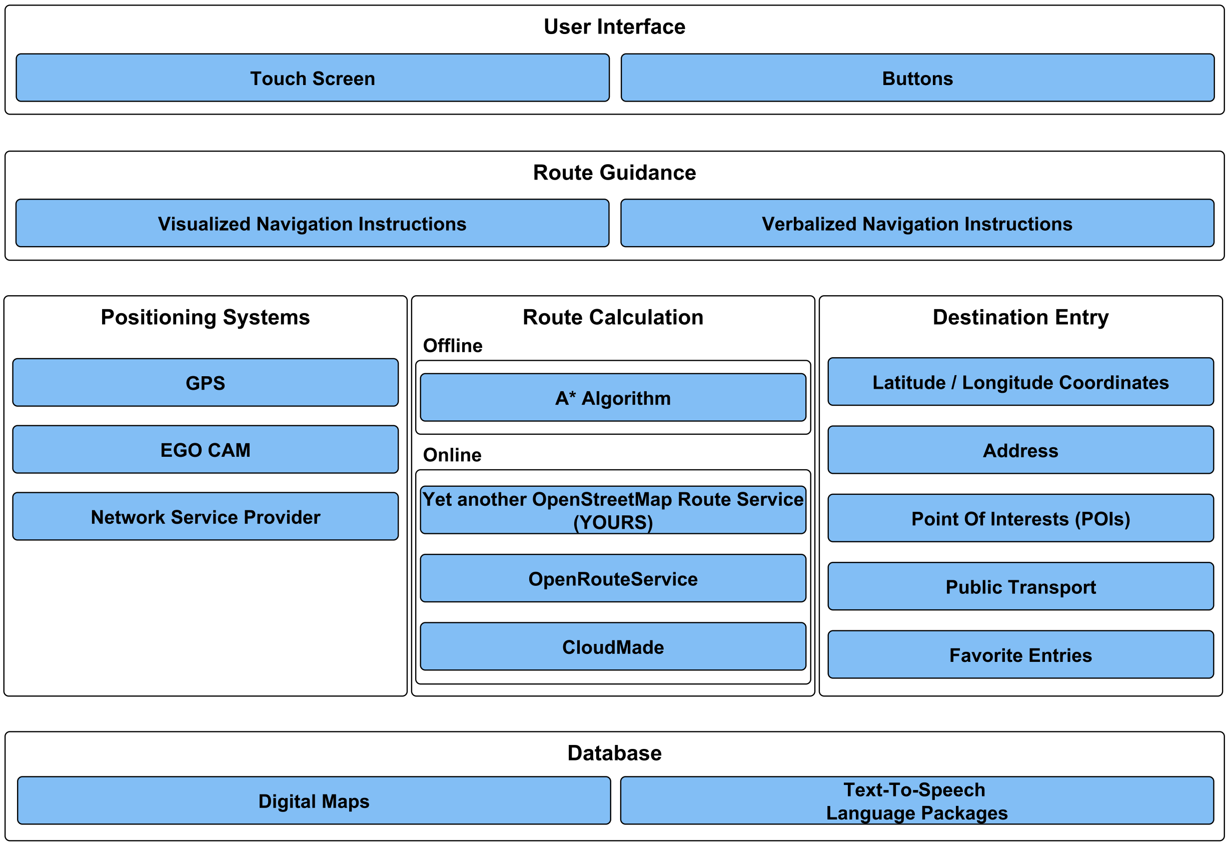
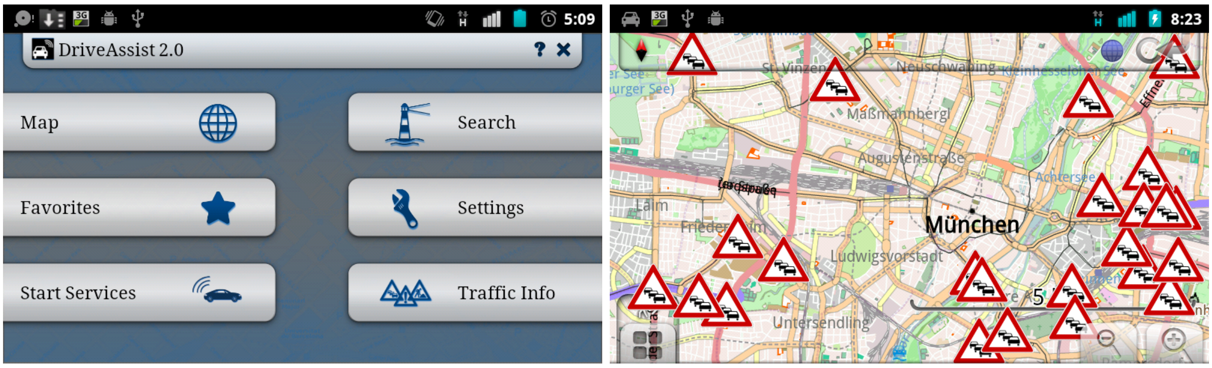


Figure 6.13: Overview of DriveAssist 2.0 functions split into its modular parts. We used the open source routing app OsmAnd as basis and added the functions from DriveAssist. The offline routing algorithm has been modified to include the traffic incidents that should be avoided.

The mechanisms for obtaining the position of the ego-vehicle and receiving the V2X data were taken over from DriveAssist. From the visualization, the warning screen and the overview of traffic incidents were adopted. For visualizing the incident on the map view showing the routing information, we introduced a new overlay. Figure 6.14b shows an example of the map view with active incidents.

In Figure 6.13, we provide an overview of the central elements of DriveAssist 2.0. We extended the offline routing algorithm so that it can avoid street segments with traffic incidents on it. This has been done by adding additional *weight* to the respective segments, depending on the traffic incident severity and — if available — the caused delay.



(a) The main menu of DriveAssist 2.0.

(b) Visualization of traffic information on top of the map.
Map data: © OSM contributors

Figure 6.14: Screenshots of DriveAssist 2.0. The application is based on OsmAnd and was developed in the course of this research.

6.5.2 User Study on DriveAssist 2.0

Participants

Similar to the user study of DriveAssist in Section 6.4.2, DriveAssist 2.0 has been evaluated by 11 participants between 22 and 32 years (average age: 26 years, $\sigma = 2.8$ years). Most of them were students or research assistants. We can assume that this is valid as they all were vehicle drivers. 2 participants were female, 9 were male. None of them had participated in the experiment with the first prototype of DriveAssist.

Method and Objective

The within-subjects study lasted for about 30 minutes per participant. It was performed for answering the following research questions (RQs) (numbering continued from Section 6.4.2):

1. RQ5: Is the adapted user interface (UI) easy to understand and to learn?
2. RQ6: Are users satisfied only to get notified about incidents on planned routes?
3. RQ7: How do users react on automatic route recalculations in case of detected incidents on routes?

Task and Data Collection

The study setup and procedure were identical with the DriveAssist study (cf. Section 6.4.2) except for the warning screen part that was not repeated in this study. Users rated questions regarding their previous knowledge, followed incident scenarios on the map view, and rated statements

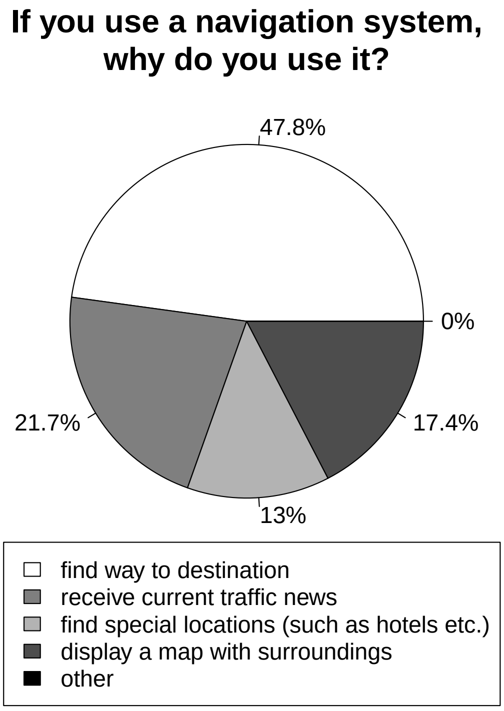


Figure 6.15: The subjects use navigation systems mainly to find their way to (unknown) destinations. However, they also use them to display a map with their surroundings and to receive current traffic news. The results correspond to those of the previous study results depicted in Figure 6.12a. ($n = 11$, multiple items could be ticked)

afterward. Since the *route* context was the focus here, also the recalculation of the current route was evaluated in two of the presented four scenarios.

6.5.3 Results of User Study on DriveAssist 2.0

All 11 subjects regularly use a smartphone and thus are familiar with the usage of mobile applications. 9 subjects use a navigation system regularly. 2 of them use only smartphone-based navigation applications. The main reason for using the navigation system for all participants is finding a route to unknown destinations. In Figure 6.15, a summary of the reasons is depicted.

The results for the evaluation of the main menu (cf. Figure 6.14a) are summarized in Table 6.6. Similar to DriveAssist, **E1** and **E3** confirm the clear and simple structure of DriveAssist 2.0. The 'use of icons and appropriate graphics' makes the main menu graphical appealing to the subjects (**E2**).

#	Statement	TD (1)	D (2)	N (3)	A (4)	TA (5)	M	σ
E1	The application seems to be complex.	2	4	3	1	1	2.55	1.21
E2	The application is graphically appealing to me.	0	2	2	4	3	3.72	1.10
E3	The menu seems to be well usable in a car.	0	3	2	3	3	3.55	1.21
E4	The menu reminds me of my navigation system.	2	1	1	6	1	3.27	1.35

Table 6.6: Absolute frequencies of respondents' opinion on the first impression of DriveAssist 2.0. The statements are rated from *I totally disagree* (TD), *I disagree* (D), *neutral* (N), *I agree* (A), to *I totally agree* (TA). M stands for average value and σ for standard deviation.

In Table 6.7, the results concerning the display of warning messages and the inclusion of the route context in the route planning are shown. In general, the subjects agreed that the map view is useful (**F2**). All but two subjects support that only incidents are displayed that affect the planned route (**F4**). The used symbols were clear to the participants (**F3**). The voice output (**F10**) got very good ratings. All subjects emphasized that it is a useful extension to the visual display.

The most interesting ratings are those concerning the route context. All but one subject appreciated that an alternative route is automatically calculated when an incident affects the current route (**F5**), even if it is not yet in close proximity (as data from online services can be incorporated). The disagreeing subject would prefer that the system notifies the user about the changed traffic situation and that the user can then actively decide which route should be chosen. This behavior is currently implemented in his current navigation system. That is also related to statements **F6** and **F7** that cope with the display of the previous route suggestion and the incidents that caused the route recalculation. The subjects were discordant whether this information should still be displayed after the recalculation. All subjects agreed that the system should incorporate the current driving situation to lower the demand when announcing a new traffic incident (**F8**). Subjects noted that new information should mainly be presented when they are driving straight and do not have to look for the next turn. However, two subjects also added that this also depends on the estimated duration that is available to act. One subject made the example that she still wants to be informed about an incident in the next route segment, although she is already about to turn into that segment.

6.5.4 Discussion and Comparison to DriveAssist Study Results

In the following, the results are discussed with regard to the RQs 5 to 7.

RQ5: Suitability of UI

Similar to the results for DriveAssist, the DriveAssist 2.0 prototype's user interface has been rated as good for utility and usability. It received even better ratings for the graphical representation (**E2**

#	Statement	TD (1)	D (2)	N (3)	A (4)	TA (5)	M	σ
F1	When a new warning is announced by the voice output, its position should be highlighted on the map.	0	0	0	4	7	4.64	0.50
F2	The overview provided by the map is useful.	0	0	3	3	5	4.18	0.87
F3	The meaning of the symbols is easy to understand.	0	0	1	5	5	4.36	0.67
F4	Only traffic events on my itinerary should be displayed.	1	1	0	3	6	4.09	1.38
F5	The automatic recalculation of the route is beneficial.	0	1	0	6	4	4.18	0.87
F6	The original route before the recalculation should remain visible.	1	1	5	3	1	3.18	1.08
F7	The display of incidents that led to the recalculation is useful.	1	0	4	3	3	3.64	1.21
F8	The system should only announce new traffic incidents in less demanding driving situations.	0	0	2	1	8	4.55	0.82
F9	The map view reminds me of my navigation system.	1	0	0	4	6	4.27	0.19
F10	The voice output is a useful support for the map view.	0	0	0	2	9	4.82	0.40

Table 6.7: Absolute frequencies of respondents' opinion on the map view. The statements are rated from *I totally disagree* (TD), *I disagree* (D), *neutral* (N), *I agree* (A), to *I totally agree* (TA). M stands for average value and σ for standard deviation.

compared to **A2**), which might be due to the symbols used in the main menu. Simultaneously, the complexity (**E1**) has been rated a bit higher than for the former prototype. The evaluation of the menu's suitability for in-vehicle use is similar to that of DriveAssist. Mann-Whitney U tests [250] have been performed to compare **A1** to **A4** with **E1** to **E4** respectively. No significant difference could be discovered for the first three statements. However, subjects indicated that the main menu of DriveAssist 2.0 bears resemblance with their navigation system (**E4**, $\mathrm{Mdn} = 4$, $\sigma = 1.35$); for DriveAssist the subjects mostly disagreed (**A4**, $\mathrm{Mdn} = 2$, $\sigma = 0.62$). That is a significant difference, according to a Mann-Whitney U test ($W = 32.5$, $Z = -2.03$, $p < 0.05$). Several subjects stated that the menu points 'Search,' 'Map,' and 'Traffic Info' were the decisive factors for them.

Some subjects also mentioned possible improvements for the interface. Two of them suggested utilizing the whole space for the buttons. Another subject asked for colored graphics.

RQ6: Notification only for Incidents on Route

In the DriveAssist experiment, all subjects stated that the navigation functionality is central for such an ADAS (**D1**) since they only wanted to be informed about incidents when it affects the currently planned route (**C4**, $\mathrm{Mdn} = 4.5$). That was rated similarly important in the second experiment (**F4**, $\mathrm{Mdn} = 5$). However, some subjects also mentioned that they would prefer to be able to see all nearby received incidents, which could be realized by making the configurable in the application's settings. The effects of recognition and processing times would be subject to a future study as it can be assumed that the perception of more objects takes more time and increases the cognitive load. One subject further stated that the presentation of incidents could be extended to neighboring streets. By evaluating the surrounding map data, incidents on nearby parallel streets or places that can be reached without significant deviation from the planned route could be included.

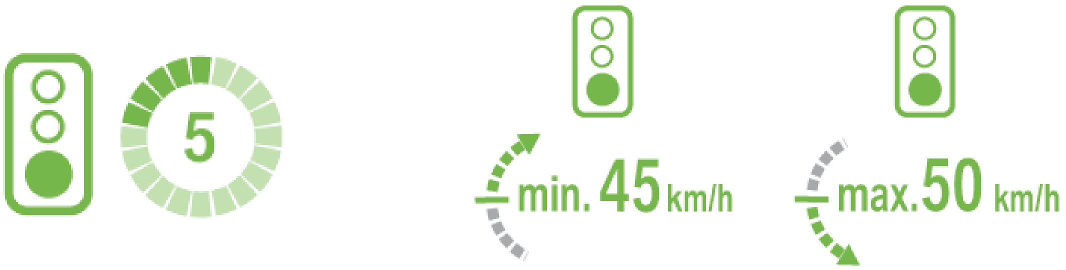
Inspired by the driving situation awareness statement (**F8**) in the survey, one subject said that he would extend this approach so that also nearby incidents are shown when the current driving situation is not very demanding. That would require calculating a score of how demanding the driving situation is at the moment [297, 307]. An implementation could, for example, be based on the evaluation of the course of the currently traversed and ahead route segments. For instance, when the driver has to drive straight for the next few seconds, this time could be used to present surrounding incidents.

RQ7: Automatic Route Recalculation

Besides showing incidents that affect the current route, the automatic recalculation of the suggested route was also evaluated positively (**F5**, $\mathrm{Mdn} = 4$). Only one subject did not want to give the control about the route choice completely away and suggested that manual confirmation of route changes should be included. The feeling of being in control is an interesting topic in view of future highly-automated or self-driving vehicles. For the research presented, this is beyond the scope of our work. It is thinkable that three incident bypass strategies could be implemented and activated in the settings: automatic route recalculation without confirmation, presentation of an alternative route suggestion that needs to be confirmed, and no incident bypass.

Due to the many comments on the automatic recalculation during the pre-test of the study, questions regarding the transparency of the recalculation process have been included. Mixed answers have been received whether in case of automatic route recalculation the previous route suggestion should remain visible (**F6**, $\mathrm{Mdn} = 3$). In contrast, the agreement for showing the cause for the recalculation was slightly higher (**F7**, $\mathrm{Mdn} = 4$). One subject commented that displaying the previously planned route together with the warning sign would make the recalculation more comprehensible and inspire confidence in the system. One subject also mentioned that the user then could still choose to drive the first suggestion. One subject raised concerns about overloading the screen with too much information. He suggested reducing the presented information to the absolute minimum required to reach the destination and to be warned of potentially dangerous incidents.

Overall, the integration of the navigation functionality based on V2X data was appreciated by all subjects. As for DriveAssist, all subjects understood the warnings. 7 subjects took further the possibility to compare the map view of DriveAssist with DriveAssist 2.0. They agreed that the 'first-person view' with rotating surrounding is much better than the turning car symbol in DriveAssist. One subject also mentioned that having a personal navigation assistant (PNA) and a



(a) The countdown HMI indicates the remaining seconds in the green phase.

(b) A minimum/maximum speed recommendation is given to indicate the speed required for passing the traffic light in the green phase.

Figure 6.16: Two green light optimized speed advisory (GLOSA) visualization examples by Thoma et al. [384]. The indications have been shown in the instrument cluster of a vehicle. Images from Thoma et al. [384].

PMD with DriveAssist would be too overwhelming, and thus he endorses the integration of the navigation functionality.

By integrating the warning functionality of DriveAssist in the established functionality 'navigation,' the acceptance could be increased. At the same time, having a new information source at hand allowed enhancing the navigation application. For that reason, a good approach for future PMD-based traffic assistance systems could be integrating them in applications that are already used on PMDs in the in-vehicle context.

6.6 Mobile Device-Based Green Light Optimized Speed Assistant

As a second exemplary AMAS running on a driver's PMD, the green light optimized speed advisory (GLOSA) use case was chosen. The use case was selected as this information is also available via infrastructure-to-vehicle V2X service and can be set up on our flexible mobile device integration architecture for V2X communication. We give a short overview of related work on GLOSA visualization before we present our concept and study results on the design choice.

6.6.1 Related Work on Green Light Optimal Speed Advisory

Thoma et al. [384] evaluated three visualization concepts for informing the driver about the traffic light phase and the corresponding GLOSA in a driving simulator experiment. The evaluated visualization concepts were a countdown indicating the residual time of the current phase (Figure 6.16a), a minimum or maximum speed advisory for reaching the green phase (Figure 6.16b), and an augmented speedometer showing the phase that will be reached when driving with a certain speed (Figure 6.17).

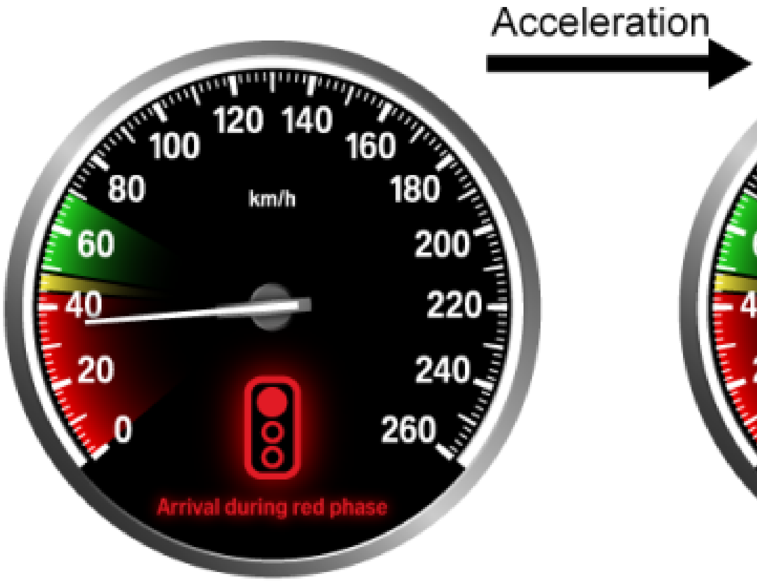


Figure 6.17: The colored overlay on the speedometer corresponds to the traffic light phase that will be reached when driving in the respectively covered speed interval. Image source: Thoma et al. [384].

The study compared the visual effectiveness of the three approaches by using gaze tracking and analyzing the driving behavior. Besides, the acceptance of the visualization was evaluated with a questionnaire. In most scenarios, the augmented speedometer led to significantly more efficient driving behavior at traffic lights than the other two visualizations and a baseline drive without assistance. The glance times were similar for all three visualizations. Regarding the acceptance, the speedometer visualization was preferred by most subjects.

All these visualizations were designed and tested as elements in the vehicle's dashboard. As the speedometer is a central element in most dashboards, the results cannot be directly transferred for the use case of visualizing GLOSA information on PMDs.

Within the *Kolibri* project[14], a similar study has been conducted with the GLOSA information being shown on a mobile device [208]. The study results indicate that the size of the displayed content influences the gaze duration. Larger content led to shorter gaze duration; however, statements of subjects revealed that too big content also leads to irritations. Besides the gaze duration, the gaze frequency is another critical factor as users have to take their eyes off the road. However, in the study, no relationship between the size of the content and the gaze frequency could be found. Auditory hints, indicating when new and relevant information is displayed, did not influence the gaze frequency.

---

[14] http://www.kolibri-projekt.de/, accessed October 17, 2019

(a) The main screen of *Ampelmeter* displays an advisory by augmenting a virtual speedometer with the traffic light phase to be reached at a certain speed. In addition, it displays the time left of the current phase in the center.

(b) *SignalGuru* uses the camera to detect the current phase of traffic lights. The three advisory values on the left indicate from top to bottom: the residual amount of time till the green phase, the time till the red phase, and the recommended GLOSA speed. Image source: http://www.gadgetreview.com/2011/08/smartphones-app-signalguru-improves-fuel-efficiency-20

Figure 6.18: Screens of the mobile application *Ampelmeter*.

Mobile Applications

Ampelmeter[15] is a mobile application for the Android platform that can display speed advisory for traffic lights with fixed phase and switching times. The application shows the information on the next traffic light's phase and timing about 2 km in front of it. In order to present the current phase and an advisory, the switching plan needs to be stored in the application. Schedules can be added directly within the application. Figure 6.18a shows the main screen of the application. A virtual speedometer indicates the current speed. The traffic light phase to be reached with a certain speed is displayed as a colored overlay on the speedometer. The remaining seconds of the current phase are displayed in the center. The color of the remaining time corresponds to the current phase.

In comparison to *Ampelmeter*, *SignalGuru* [201] does not need the manual entry of traffic light switching schedules. The mobile application uses the rear camera of mobile devices mounted to the windshield to detect the traffic light's current status. By combining traffic light status and phase reports of different mobile users over time, traffic signal schedules are automatically calculated and are used to predict the future schedule. The application has been evaluated in real traffic scenarios. The average measured prediction error for pre-timed traffic signals was about 0.66 s. For traffic-adaptive signals, the average prediction had a cumulative error of 2.45 s.

Figure 6.18b shows the main screen of *SignalGuru*. The red frame in the live camera image indicates the detection window. The current phase is represented by the color of the text box frame in the bottom left. The value in this text box indicates the confidence about the traffic

---

[15] http://www.ampelmeter.com, accessed October 17, 2019

Figure 6.19: For running the online study, a base design with exchangeable elements has been created. Essential elements are ① information bars, ② speed carpets for indicating the speed range to cross the traffic light in the green phase, ③ current speed visualizations, ④ traffic light representations with remaining time, and ⑤ warning for violations of the speed limit.

signal detection. The shown advisories indicate the time left until the traffic signal turns green, the amount of time until the traffic signal turns red, and the recommended GLOSA speed. The HMI of the application is not optimized for being used while driving. The interpretation of the shown absolute values in the small text fields needs too much attention [319].

6.6.2 GLOSA App Concept

Similar to DriveAssist, the concept was developed to run on a 7-inch Android-based tablet PC. The tablet PC was chosen as it has been shown that larger content leads to shorter glance durations [208]. Figure 6.19 depicts an example draft for explaining the different elements. The elements are explained in the following. The research was concerned with the design of a GLOSA application, both from the technological perspective and the HCI perspective. We contribute to the state of research by a methodological investigation of the design space and by providing insights from our online study.

① **Information bars** provide additional contextual information to the drivers. This information could be beneficial when the GLOSA information is not shown within the context of a running navigation application. The top bar displays the distance to the traffic light, for which the GLOSA prediction is currently shown, as well as the name of the intersecting street at the traffic light. The bar at the bottom lists the current speed as well as the name of the current street.

② The **speed carpet** is used to visualize the traffic light phase that can be reached by driving a certain speed from the current distance to the traffic light. Green color means that the traffic light can be crossed in the green phase while the red color stands for reaching the traffic light in a red phase. When different traffic lights are used for different directions, different lanes with arrows indicating the direction are presented. The maximum speed visualized by the carpet corresponds to the speed limit. Labels at the border of the carpet show the speed values.

③ The *current speed* is visualized in two different shapes. It is depicted as text in the lower information bar ① and directly on the speed carpet. The overlay on the carpet allows for a relative comparison of the current speed and the speed necessary for crossing the traffic light in a green phase. Several different overlays have been tested in the user study.

④ A *traffic light* phase visualization that displays the current phase's remaining time helps to interpret the speed carpet. Three different visualizations have been evaluated in the online study. The first visualization (see Figure 6.20a) corresponds to a default traffic light that distinguished between the red, yellow, and green phases. The second visualization (see Figure 6.20b) is an inverse progress circle. Its color corresponds to the current phase, and the circular filling decreases with advancing phase duration. The last visualization is a Marshalite signal (see Figure 6.20c). This rotary traffic signal visualizes the duration of the current and future phases in one graphic.

⑤ The *speed limit* sign is shown when the speed limit is exceeded by a defined threshold (can be deactivated). Using the well-known standard speed limit sign allows for faster recognition. In that case, the German regulation sign 274, defined by the road traffic regulations (German: *Straßenverkehrsordnung*), is used.

For indicating the current speed, three different drafts have been created (see Figure 6.21). Besides, different lane spacings and backgrounds have been used for the concept images presented in the online study.

6.6.3 User Study on Green Light Optimized Speed Advisory Assistant

Study Objective

Since the application shall be used while driving, the objective of the user study was to find the elements needed to create a clear and comprehensible design. The design shall provide space for all necessary information and, at the same time, limit the distraction from the primary task of driving.

(a) A standard traffic light with remaining seconds in the current phase.

(b) The color of the diminishing progress circle indicates the current phase.

(c) The Marshalite traffic signal uses a uniformly rotating arrow to mark the current phase.

Figure 6.20: Design alternatives for the traffic light of the GLOSA prototype.

(a) The position of the car icon on the carpet indicates the current speed.

(b) Current speed is displayed directly on top of a black line.

(c) Current speed is displayed directly on top of a white line.

Figure 6.21: Design alternatives for different speed markings on the speed carpet.

The goal of the application is to support the driver to reach and cross a traffic light in its green phase without stopping. This information is mainly conveyed via the speed carpet. The current phase and the remaining duration should also be visualized. For finding a suitable representation, three designs with the different selected traffic light phase and timing visualizations (see Figure 6.20) have been created. Additional variations have been designed in order to retrieve feedback on:

- the different speed markings (see Figure 6.21),
- additional information shown in the information bars,
- and, lane visualization alternatives.

Method and Data Collection

An online user study has been conducted to choose appropriate elements for the visualization of the current traffic light phase and the speed advisory. The survey was conducted with the online survey tool *SoSci Survey*[16]. The survey was open for 10 days, and the link to the survey has been spread via online social platforms.

A short video sequence was shown to the participants in the beginning. That should put them in the position of a driver using the GLOSA software. The video sequence showed a car approaching a traffic light, and next to it, the draft of the application that updated according to the depicted scenery.

In the central part of the evaluation, the participants had to rate their agreement to statements. A 7-step Likert scale was used to gather the agreement level where -3 corresponds to "strongly disagree" and 3 to "strongly agree." The scales in the questionnaire were not numbered; the numbers are only used for result presentation. Besides, subjects had to rank different drafts. The order of the presented drafts was random.

Participants

69 people between 22 and 51 years (average age: 29 years, $\sigma = 4.5$ years) participated in the survey. 19 were female, and 50 were male. 66 of the participants stated to have a valid driver's license. Half of the subjects (49 %) stated to drive regularly (almost daily), and another 13 % are driving two to three times per week. 61 % drive mainly in cities and 16 % on rural roads (*Bundesstraßen*, *Landesstraßen/Staatsstraßen*, and *Kreisstraßen*) with at least one traffic light on their way.

6.6.4 Results of the Online Study

An important point was the added distraction caused by different visual elements. In the first part of the study, the perception of the traffic light visualization was determined. The presented drafts are depicted in Figure 6.22. It is important to state that untrained users exploring the device for the first time have increased perception times compared to experienced users after some time of exposition to the system.

The main question regarding the added distraction was whether the shown elements are overwhelming the subjects. The focus was purposely not directed on the presentation of the current traffic light state, although only this element was different between the layouts. Figure 6.23 shows the results for the comparison of the three drafts. There was a statistically significant difference in perceived added distraction depending on the traffic light presentation (Friedman $\chi^2(2) = 35.40$, $p = 2.05 \times 10^{-8}$ [129]). For that reason, post hoc analysis with Wilcoxon signed-rank (paired, exact distribution, Pratt zero handling) tests [414] was conducted. To avoid type I errors ("false positive"), Bonferroni correction was applied [104]. That led to a new significance level of $0.05/3 = 0.017$. There are no significant differences between the standard traffic light

---

[16] https://www.soscisurvey.de/, accessed October 17, 2019

(a) Standard three-color traffic light.

(b) Circular progress of remaining time.

(c) Marshalite traffic signal with all phases at once.

Figure 6.22: The different traffic light visualizations were presented in the same design draft. Different statements regarding the understandability of the visualization and the amount of presented information had to be rated.

and the circular progress visualizations ($Z = -0.32$, $p = 0.74$). However, there were statistically significant differences between the standard traffic light and the Marshalite ($Z = -5.07$, $p = 5.96 \times 10^{-8}$) as well as between the circular progress and the Marshalite visualizations ($Z = -5.05$, $p = 7.90 \times 10^{-8}$).

This result was confirmed by a second question on the ability to understand the traffic light visualization. While the standard traffic light ($\mathrm{M}_{\text{standard}} = 1.57$, $\sigma = 1.55$) and the circular progress visualization ($\mathrm{M}_{\text{circular progress}} = 1.35$, $\sigma = 1,75$) are rated to be rather comprehensible, the Marshalite ($M_{\text{Marshalite}} = -0.09$, $\sigma = 1.82$) got negative results that were significantly worse compared to the other two visualizations.

That limits the choice to the standard traffic light and the circular progress visualization. Both have similar ratings. However, subjects also had to select their preferred visualization out of the three drafts. When limiting the answers to the two left visualizations, the standard traffic light was preferred (77.27 %) over the circular progress visualization (22.73 %). Some subjects commented that they would prefer the well-known traffic light visualization, as no additional learning is required. That is an effect that we assume to not be present after ensuring some prior training with the application. One subject further added that using a standard three-color traffic light would simplify the situation for people with defective color vision. Two subjects supported their preference for the circular progress visualization with the fact that the elements included an arrow for indicating the turning direction.

In order to limit the added distraction potential, users were also asked which information would be beneficial for them to allow for a better assessment of the situation. Checked elements were the current speed, the name of the current street, the distance to the traffic light, and the name of the cross street at the traffic light. Subjects rated the importance on a Likert scale from -3 (unimportant) to +3 (very important). The most important information was the current speed ($\mathrm{M} = 1.64$, $\sigma = 1.61$) followed by the distance to the traffic light ($\mathrm{M} = 1.45$, $\sigma = 1.66$). The street names were rated statistically significantly less important (exact Wilcoxon signed-rank test, $ps < 0.05$). The current street name got an average importance rating of $\mathrm{M} = 1.07$ ($\sigma = 1.36$),

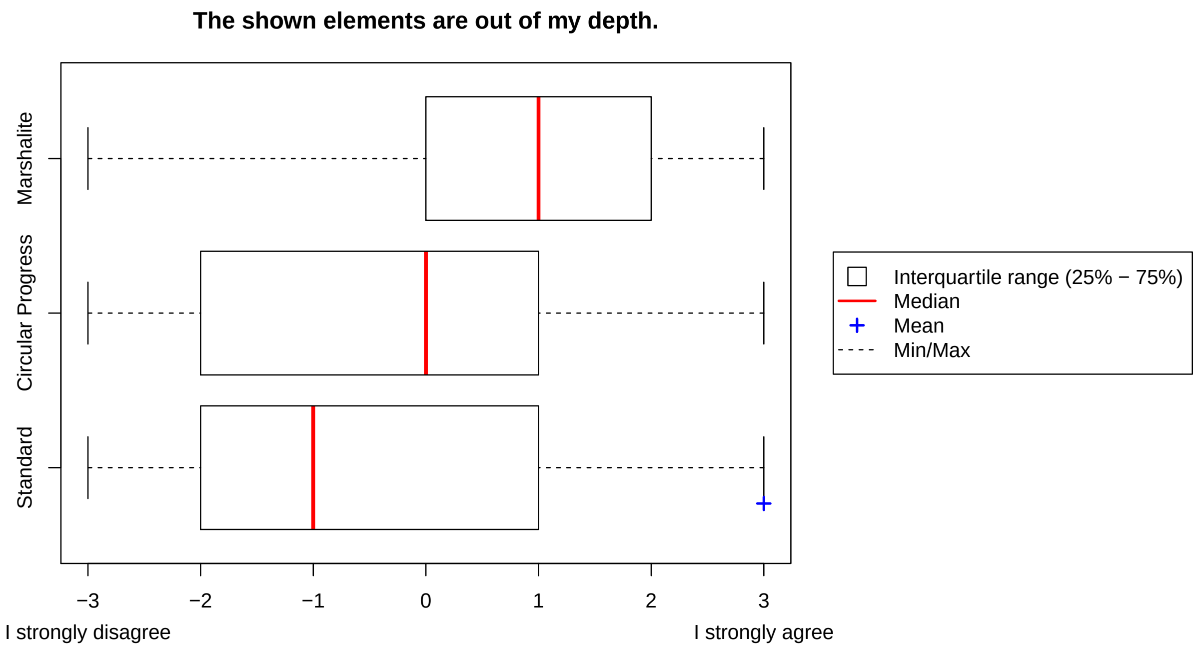


Figure 6.23: Subjects' feedback on the understandability of the designs with different traffic light visualizations. Answers were given on a 7-step Likert scale, ranging from -3 *strongly disagree* to 3 *strongly agree*.

the importance of the cross street's name was rated with $\mathrm{M} = 0.68$ ($\sigma = 1.64$). However, three-quarters of the subjects (75.36 %) stated that the information bars should be off by default and should be configurable via the app's setting dialog.

The display of a speed limit warning was approved by 78.26 % of the participants. However, as for the information bars, the subjects commented that the speed warning should have a switch-off option. A configurable threshold for triggering the speed limit warning was also mentioned. Several participants noted that the speed carpet should not visualize speed segments above the prevailing speed limit.

The design and layout of the speed carpet was another part of the online study. The first questions were on the depiction of the lanes. The subjects agreed that the lanes should be represented in the app as they are in the real world ($\mathrm{M} = 1.62$, $\sigma = 1.65$). That means, for example, when a turning lane is summarized with the straight lane, the app should visualize summarized lanes. In addition, subjects would prefer when the design and layout of the roads at the crossings are visualized ($\mathrm{M} = 1.75$, $\sigma = 1.17$) corresponding to their real counterparts. Overall, the integration of the GLOSA functionality into a navigation system would be ideal for most subjects ($\mathrm{M} = 1.71$, $\sigma = 1.61$). Some subjects mentioned that having a second device for GLOSA next to their PNA would not be acceptable.

In the drafts that were presented for measuring the added distraction (see Figure 6.22), the car symbol was used as a rather vague speed indicator (compare Figure 6.21a). The subjects rated the effectiveness of this visualization to determine the current relative speed on the carpet with $\mathrm{M} = 0.73$ ($\sigma = 1.87$). Comments were that the car symbol might suggest that the lane in the center must be taken or that the application assumes that the car is driving on this lane. One subject commented that he was unsure which part of the symbol had to be in the green carpet. Another subject noted that he could not reliably read the traffic light phase of the outer lanes with the speed indication in the center. Besides the car symbol as speed indicator, also the two other speed indicator drafts were presented to the subjects (see Figure 6.21). The majority (66.67 %) chose the black line with the speed value as their preferred speed indication. The car symbol was chosen by 18.84 % and the white line with speed value by 14.49 % of the subjects.

An important aspect of a GLOSA application is the correctness of the depicted information, which can be affected negatively by delay. For 37.68 % of the subjects, a noticeable delay is not acceptable. Another third (34.78 %) could image a maximum deviation of up to $1\,\mathrm{s}$. For counteracting the effect of deviation, subjects suggested treating the yellow phase as the red phase so that the chance of going through a red light is minimized when the synchronization is inaccurate.

6.6.5 Concept Refinement

The findings of the online study have been used to refine the concept of the GLOSA application. The adapted concept design is depicted in Figure 6.24. For visualizing the current phase of the traffic light, the standard traffic light was chosen. The information bar is per default only displaying the current speed and the distance to the traffic light in meters. A black line with the current speed value is utilized to visualize the current speed on the carpet.

The redundant display of the speed value in the information bar and on the black current speed indication is on purpose, as the speed indication is only shown when an active traffic light is approached.

6.7 Simulation and Verification Environment for Mobile Device-Complemented Advanced Driver Assistance Systems

In order to simulate V2X scenarios, we developed the PC application c2xMessageTester. It allows for mixed-reality V2X message simulations in which simulated vehicles and incidents can interact with real vehicles by sending and receiving V2X messages via a real V2X on-board unit (OBU) with an installed proxy application. The tool was developed as a research and verification tool, and was employed in several of the systems and studies presented in this thesis.

The tool supports the V2X message types decentralized environmental notification message (DENM) for simulating stationary incidents, and cooperative awareness message (CAM) for simulating other moving vehicles of different types (e.g., also emergency vehicles). Besides, it

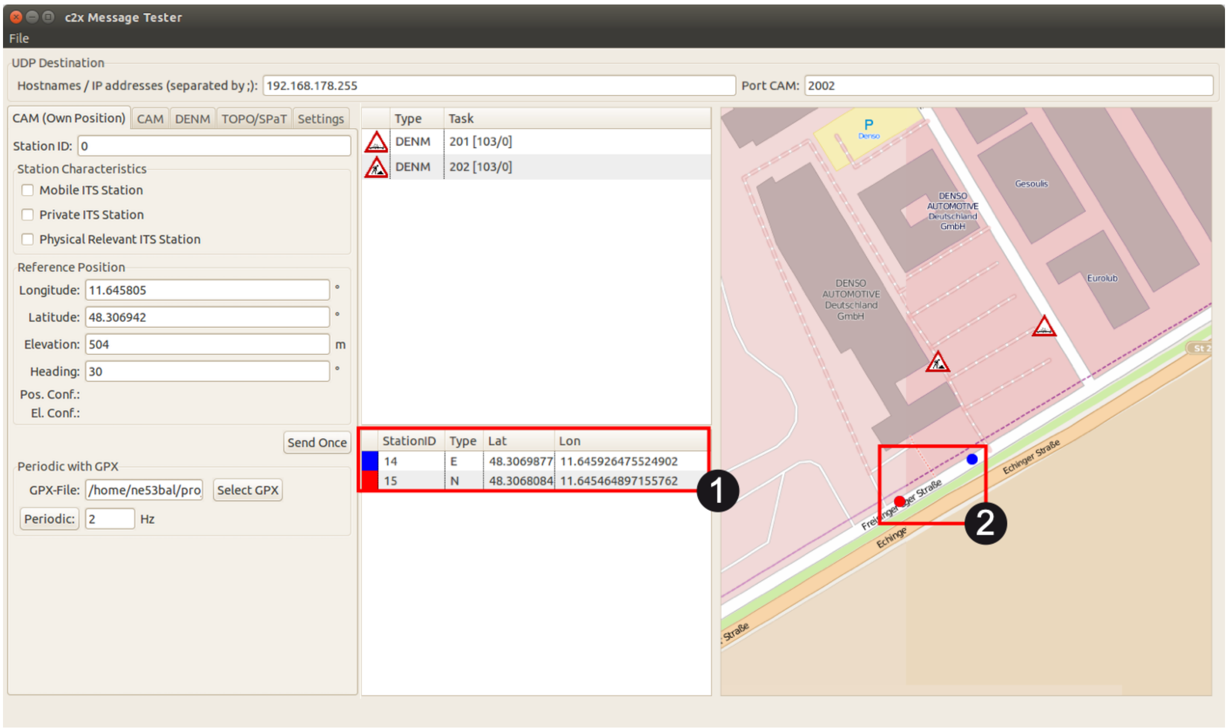
Figure 6.24: The final design includes the findings from the online study. The standard traffic light visualization is used to indicate the traffic lights' current phases. Arrows on the lanes support the user with identifying the relevant lane.

allows the simulation of topology (TOPO) and signal phase and timing (SPaT) messages for GLOSA scenarios. The relevant parameters and the message sending rate can be set individually for each message instance. The map view can be used to position traffic incidents on the map and track moving vehicles in real time. Its GUI is depicted in Figure 6.25. For simulated vehicles, it is possible to use prerecorded GPS eXchange format (GPX) files or to plan a route based on the shown map data. Besides one instance of an ego vehicle (ego CAM sender with vehicle identifier 0), unlimited other vehicles (CAM) and incidents (DENM) can be simulated.

Having tools like the c2xMessageTester allows for reproducible research of defined scenarios and bringing simulations into real life. Its capabilities of creating messages at a very high rate and the support of a very high number of concurrent stationery and moving events were also used to measure the performance of the mobile applications DriveAssist and GLOSA.

6.8 Summary of Contributions

In this chapter, we have reported on the integration of PMDs with automotive IVISs. Today's mobile platforms allow for rapid application development with various user interaction possibilities that can make use of the latest sensor technology. Prototypes for visualization can, thus, be created with minimal effort in comparison to automotive-grade embedded systems with proprietary platform software. Moreover, owing to the increased processing power, the PMDs can take over computing tasks that are not integral to the vehicle's safety.



UDP Destination

Hostnames / IP addresses (separated by ;): 192.168.178.255

Port CAM: 2002

Station ID: 0

Station Characteristics

☐ Mobile ITS Station

☐ Private ITS Station

☐ Physical Relevant ITS Station

Reference Position

Longitude: 11.645805 °

Latitude: 48.306942 °

Elevation: 504 m

Heading: 30 °

Pos. Conf.:

El. Conf.:

Periodic with GPX

GPX-File: /home/ne53bal/pro

Periodic: 2 Hz

	Type	Task
⚠	DENM	201 [103/0]
⚠	DENM	202 [103/0]

	StationID	Type	Lat	Lon
🟦	14	E	48.3069877	11.645926475524902
🟥	15	N	48.3068084	11.645464897155762

Figure 6.25: The c2xMessageTester is our research enabler for simulating and observing V2X scenarios. It allows for the combination of real messages with simulated ones. The screenshot shows the main screen of the tool. The positions of received CAMs information (ID, type of vehicle, and geo-position) for vehicles are presented in a table ①. The color of the first field in the table matches with a dot indicating the vehicle's positions on the map ②.

We investigated three different work splits for the integration, with the one setting the split at the facility layer being the best trade-off between performance for the day-1 use case and for providing flexibility for a future extension at the message layer. With the example of our implemented V2X solutions, we have shown the potential of this work split. With the c2xMessageTester, we created a research vehicle that allowed for the evaluation of mixed-reality V2X scenarios.

Our key contributions to the topic of PMD integration with IVISs of mobility means are the following:

- The user's PMD is a proper context provider for the IVISs of other mobility means. It can further take over HMI parts or processing tasks.
- When designing a work split for an integrated PMD–IVIS system, one can balance among flexibility, reliability, and performance. By exposing lower levels of systems, forward compatibility can be maximized.
- The architecture shall provide interfaces and mechanisms to allow for testing.

- Our implementation of V2X use cases and integration with standard navigation shows the potential of using mobile platforms as the basis for in-vehicle HMI. The smart devices combine the latest HCI modalities with high computing power, and the mobile platforms are designed for developing appealing applications with low effort.

The three created prototypes have not only been used for the evaluation of the architecture approach but also represent one of the first implementations of V2X use cases. From the studies with our prototypes, we contribute the following findings on usability topics:

- The actual and planned routes of the user are an important context for extended mobility-related information. For example, showing traffic warnings for *nearby* incidents causes distraction, although they do not influence the user's route.
- Consistency of real-world traffic objects and virtual displayed content is important. For instance, our online study on visualizing red light phase duration showed that users prefer the well-known red light presentation, although, for example, a Marshalite signal would combine more information in a single graphic.
- Subjects preferred the mixed-modality output for incident warnings. In particular, the TTS support helped them grasp the content of the warning screen more correctly.

Chapter 7

Expert Evaluation in the Context of General Mobility Assistance

In the previous chapters, the evaluations were performed on singular parts of the developed AMAS. This chapter summarizes the holistic concept evaluation that has been performed via a heuristic approach.

7.1 Choice of Evaluation Method

Since working prototypes were available (e.g., *Seamless Mobile* – our route planning app prototype with fitness route concept (Section 4.4.2), the *Rollator Training* app (Section 5.4), the *Automotive User Interface Training* app (Section 5.2), or DriveAssist 2.0 – our V2X app prototype with navigation support (Section 6.5)), a prototype evaluation of the developed mobility assistance chain (from trip planning over support during the journey to exercising during and between trips for maintaining mobility) could be performed. However, the different solutions were not all seamlessly integrated into each other. Although the fidelity of the prototypes was quite high, the reliability and the stability of the offered solutions were only appropriate for our research in controlled environments. For that reason, a long-term user study would have required additional effort, and the probability of suffering from bias due to limitations of the research applications was very high.

Besides, the user-based evaluation of the whole assistance chain turned out to be challenging since not all users require assistance at every stage of mobility. For example, a user who needs support for training the usage of a mobility aid might not drive unknown vehicles. That would lead to non-comparable results on the large-scale, requiring a much higher user number for statistically valid and significant results. Long-term studies would be of high interest, since there is little reported in the literature, too. However, due to time and money constraints in the scope of this thesis, the long-term study had to be deferred to future work.

For those reasons, we decided to work with experts from different domains whose expertise and experience cover the whole mobility process. An important factor for selecting the experts was

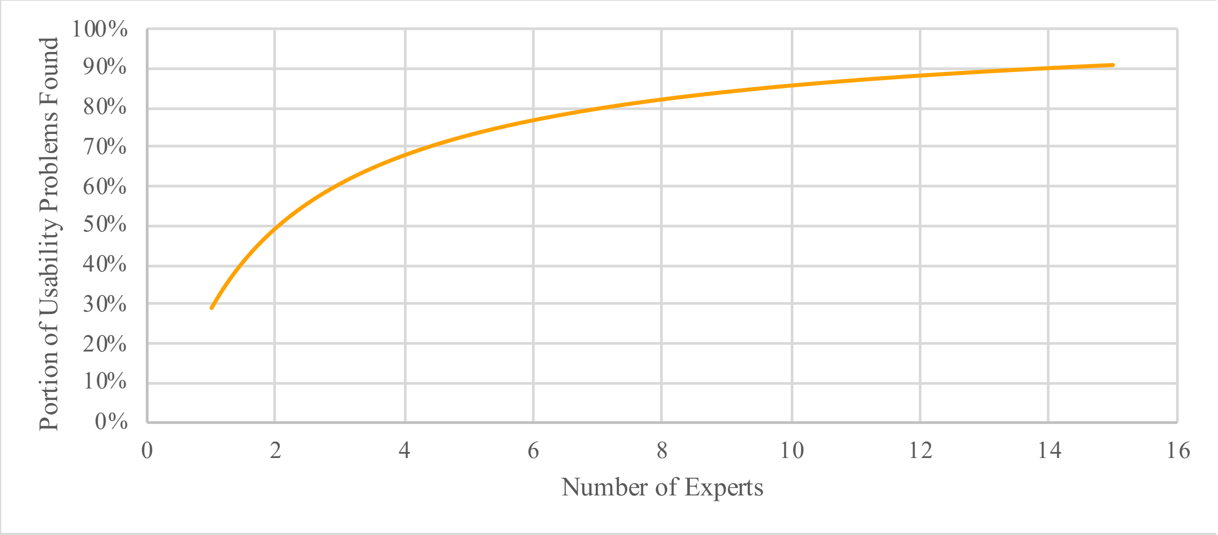


Figure 7.1: Already a small number of experts with specialized knowledge and experiences on the field of usability (this knowledge is referred to as *the heuristics*) can identify a large portion of usability problems. This diagram shows a sample curve with average values on issue detection probability.
Diagram adapted from data presented by Nielsen and Landauer [282].

that they regularly work with users benefiting from assistance in mobility. Expert reviews have proven to be able to evaluate systems in many stages of the research and implementation process as they assess the systems with their expert insights. That can partially decrease the number of end user-based evaluations, especially for not yet finished systems and for systems for which users with prior expertise do not exist, like for the research presented in this thesis.

By evaluating the number of found issues in six expert evaluation case-studies, Nielsen and Landauer [282] derived a model that provides a relation between the proportion of found usability issues a system has and the number of experts involved in an expert evaluation. Figure 7.1 depicts a sample result. The example is based on the average value of problem detection probability. The exact shape of the curve is dependent on the overall number of issues and the time experts spend on the evaluation. However, this usually has only an impact on the initial inclination of the curve. That means, for common systems, there is usually no more significant gain when more than 10 to 12 experts are involved [142]. The best benefit to cost ratio is usually achieved when 2 to 5 experts are involved [282]. For non-expert evaluators, 9 people are required to at least identify 90 % of the major usability issues (cf. Section 2.5.2).

7.2 Evaluation Participants and Setting

The recruitment of the experts was done via letter. Over 50 letters have been written to acknowledged experts in southern Germany. The considered areas of expertise covered the fields of elderly care, mobility planning, interior design, exercising, health insurance, and ICT. The focus was on experts having experiences with the mobility of older people or regularly work with older people. The experts were selected through personal networks of researches participating in the project PASSAge as well as via contacts provided from the committees for the interests of senior citizens in Munich[1] and Bad Tölz[2].

11 experts could be recruited this way. 9 experts were from the fields of interior design, mobility, and geriatric care. One expert was from the committee for the mobility interests of senior citizens in Munich. One expert was an ICT expert that regularly gave ICT-related courses for older adults. All experts are actively involved in the topic of *mobility*, with 7 regularly having to do with the *mobility of elderly and disabled people*. The experts did not receive any monetary compensation, but a small present with chocolate. Beverages and snacks have been provided for free during the review.

In two half-day workshops, the 11 experts evaluated the developed mobility assistance solution. The workshops were conducted in large meeting rooms with a large table for the discussions. Central points were kept on flipcharts and whiteboards, and a backlog was maintained during the review. The prototypes were exhibited in a secondary room. The tablet PCs were also taken into the room, where the discussion took place. That way, the experts could follow the discussed issues and steps directly in the respective mobile applications.

In the beginning, the research prototypes were introduced. Afterward, the experts could try out all developed research prototypes themselves on provided test devices. The V2X and GLOSA system was a simulation with the c2xMessageTester (cf. Section 6.7). The in-vehicle training was only presented in the introduction. According to our findings that there are no significant differences between the in-vehicle training and the mobile app-based training, we referred to the mobile training app as the selected implementation for this evaluation.

The scope of the workshop was broader than the research prototypes presented in this thesis. Partners in the project PASSAge also presented developed mobility assistance solutions, e.g., a retro-fitted electric-driven vehicle with the support of loading a wheelchair, and business aspects and models for marketing the developed solutions. The full expert review documentation of the project can be found in the particular project reports[3].

7.3 Evaluation Procedure and Focus

After the introduction and the possibility to try out the prototypes, a guided discussion was started. The feedback was recorded in the form of a summary. The guided discussion lasted around 1,5

---

[1] https://www.muenchen.de/rathaus/Stadtverwaltung/Sozialreferat/Sozialamt/Alter-und-Behinderung/Seniorenbeirat.html, accessed March 14, 2019.

[2] http://www.engagementkompass.net/Seniorenvertretung-des-Landkreises.n1125.html, accessed March 14, 2019.

[3] https://www.tib.eu/suchen/id/TIBKAT%3A862235359/, accessed March 6, 2019.

hours. Afterward, the persona *Anna* and the associated scenario *Anna travels to the mountains* described in Section 3.3.2 were presented. The scenario was used to allow putting the experts into the situation of a potential user, which is the basis for expert-based evaluation methods in human-computer interaction. That was the basis for a cognitive walkthrough [247].

The focus points of the evaluation were:

- Meaningfulness and appropriateness of functionalities for supporting the planning, the actual trip, and the wrap-up.
- Suitability of the developed HMI for mobility assistance.
- General potentials for improving the solutions in the presented chain of assistance.

7.4 Limiting the Scope of the Evaluation

The discussion of the experts came several times to the business aspects and *monetarization* of the proposed assistance solution. This aspect is excluded in this research-based dissertation as these aspects are based on many specific implementation choices that, at this time, cannot be made with reliability. We acknowledge the need for sustaining a business, but the focus was on exploring the research design space.

Another often mentioned feedback was that support beyond pure technical support was not provided or sufficient. We acknowledge that extended support in mobility and assistance concerns is necessary, and this support needs to be directly accessible in the particular situation the support is required. Our proposed and evaluated digital assistance systems cannot solely provide all the assistance a user may need. However, as for the business model, this was not the focus of our research.

Data protection and *privacy* were other valid points that have been named when applications made use of sensitive personal data. In the research prototypes, we respected basic requirements of data protection [403] (e.g., transparency, the principle of the data economy, avoiding data transmission to servers when data could be processed on the users' devices). However, we did not go into detail about this topic. We acknowledge the need for comprehensive data protection handling. Especially when users are skeptical of digital systems, this is an essential confidence-building requirement.

7.5 Expert Evaluation Results

In this section, we report the distilled results from the expert evaluation.

7.5.1 Evaluation Results on Functionalities, User Interface and User Experience of the Developed Prototypes

The summary is clustered in the three categories *planning*, *training*, and *assistance* that have been used in the thesis. Since we gave the experts much room to discuss and come up with new ideas, several topics have been discussed that go beyond the thesis' scope. For that reason, we filtered the topics and only summarized the results that are directly related to the systems and solutions presented in the thesis.

Support for Travel Planning

Fitness Route

The first reviewed solution was the *fitness route*, which we presented in Section 4.3. The experts planned several routes themselves with our mobile application prototype Seamless Mobile and inspected several walking offers (the so-called *fitness routes*). They concluded that this feature should be made "available in all modern trip planning systems." However, the availability of many established trip planning systems "with a lot of data and manpower" was also the biggest concern of the experts. They stated that they see the likelihood of using another platform as very low. Since this is a general topic of research prototypes, we do not go into detail here.

The possibility to define preferred areas for walking was rated as very important. The experts supported our hypothesis that users are more motivated when the train at a place they enjoy. Besides, the proposed algorithm[4] to provide more variation in walking segments when a user often travels the same way was rated good. However, the experts were missing an option to select more or less demanding routes of different lengths. The adaption and suggestion of the walking segment length based on the daily taken steps was interesting for the experts. On the one hand, an expert stated that this feature should always be active (not coupled to the taken steps), and, on the other hand, the experts found it extremely attractive to make the daily movement transparent to the users. That way, it can motivate the user to take extra steps.

Some experts had concerns when the *fitness route* option is offered for users of walking aids. They stated that, in their experience, the (map) data on accessibility is very limited and, thus, there is always the possibility of bringing the user into a problematic situation. The rather low reliability of accessibility information, especially outside inner-cities, is also supported by data evaluation of Neis [280]. Bringing the users into a difficult situation can lead to "a loss of trust in the application," as one expert put it, and that users avoid the feature afterward. In general, the experts had the opinion that this is rather a feature for people that have no impairments and are good walkers.

---

[4] The feature of dynamic adaption based on the latest chosen routes was not implemented in the research prototype. The prototype worked with a static pre-computed attractiveness map based on the chosen preferred area of the user.

Mobile Trip Planning Application

The route planning application prototype Seamless Mobile (cf. Section 4.4) was used by the experts to evaluate the fitness route concept. In their feedback, the experts highlighted the reduced function set. The ICT expert said that he often gets presented "apps with useful functions that have such an enormous function set, [the useful functions] are not visible anymore." In general, the experts believed apps should concentrate on one core function. That also corresponds to the findings of studies of mobile application popularity [60, 194, 232]: after visual design aspects, users look up at the complexity of the application and the focus on the functionality they get the app for. The experts also gave positive feedback on the correct visualization of transportation line colors, the use of known symbols, and the display of the direction that is written on the track or vehicle. They summarized that this allows for fast navigation due to the recognition of color-coding and symbols and that it reduces uncertainty when one needs to navigate in an unknown environment.

Looking at the possibility of showing a map and get route instructions through Google Maps' pedestrian navigation, the experts asked for more support during guidance on the walking segments. The experts highlighted that insecurities could be supported by an appropriate multimodal navigation system that uses, for example, vibration, audio, or AR. That has also been explored within the scope of the project PASSAge. More details on the AR-based pedestrian navigation prototype can be found in the final project report of the project partner Metaio GmbH[49].

A point of criticism was "hidden" options that have a significant impact on the actual route planning. The options were not hidden by intention but had to be accessed via the menu button in the top right (cf. Figure 4.3 on the main screen). Among other things, the need for barrier-free access, the preferred fitness route environment, and the step length could be configured here. That corresponds to the feedback we gathered in the simultaneously conducted two-week study (cf. Section 4.4.6). Only 5 of the 13 subjects changed settings, although the menu was shown to the subjects in the introduction of the study. As suggested in Section 4.4.7, an initial setup wizard with reasonable defaults could help to overcome this problem. Also, context from the mobile phone itself, for example, through fitness or health data, could help to adjust settings automatically.

The nudging approach for increasing trust in the shown data was also introduced. The experts shortly discussed the ethical evaluation of nudging. On the one hand, they assessed it as "manipulation." On the other hand, they understood the idea of taking away doubts, and, thus, increasing the probability of allowing precariously users (e.g., due to accessibility needs) to perform trips to unknown or farther destinations. The ethical dimension of behavioral economics and persuasive technologies is broadly covered in the research [26, 32, 148, 243, 302]. For example, Berdichevsky and Neuenschwander [26] compiled a flow chart and a list of eight ethical principles that shall help to identify whether a persuasive approach could be unethical. According to these, our approach complies with the ethical requirements. However, in a final version, it should be clarified that a human did not create the route, but, for example, humans regularly control the data for its quality. The experts were convinced that showing a real reachable operator that could be directly reached without the apposition of having compiled the trip suggestions. In their vision, the contact button could also transmit the shown route details and the settings on accessibility requirements to the operator so that there is no need to explain the data. However, also the weather forecast was appealing to the experts. In their opinion, weather warnings for the traveled area and the rain probability should always be displayed.

Training to Preserve Individual Mobility

The focus of this category is on our solutions for physical mobility training presented in Chapter 5.

Rollator Training

Most feedback was given on the Rollator training solution Section 5.4. The experts found the approach very valuable since it (1) provides short and straightforward training units that everyone can safely reproduce, and (2) it "communicates the need of moving to the user." Two experts together performed a complete training unit and screened the other exercises. They concluded that the exercises are "understandable," "effective," and "diverse."

One expert brought up the idea to create exercise sets with special focus on a field (e.g., standing up) that is explicitly named as exercise category. That way, he argued, users could be "better motivated, because they understand what the exercises are good for." Another idea was the free creation of exercise sets. However, since this adds much complexity and consumes a lot of time that "should be better used for actual training," most experts did not support the necessity of this function.

However, since the exercises are meant for daily rollator users, some experts asked for initial correct adjustment assistance. In their eyes, this could be done by some kind of step-by-step instructional video that explains the critical factors for adjusting the height of the grips, which is the most common misuse [238]. Some experts, however, were against such an instruction. Instead, they recommended informing the user that a rollator needs to be initially adjusted together with a professional, and – in case this has not been done yet – that users should be able to find a nearby service partner that could help with the adjustment. Altogether, the experts agreed that the topics *adjustment* and *maintenance* should be part of the application.

Another topic that was mentioned several times is the support of daily activities. One expert mentioned the initiative "rollator training license"[5] that organizes training for rollator users. Their focus is on situations of daily living, such as getting on and off the bus or overcoming physical

---

[5] The actual trade name of the initiative is "Rollatorführerschein." More information can be found on https://www.60plus-sicher-mobil.de/rollatortraining/rollatortraining.htm, accessed June 20, 2019.

barriers. The expert suggested providing videos on particular daily challenges with rollators and how these could be handled safely.

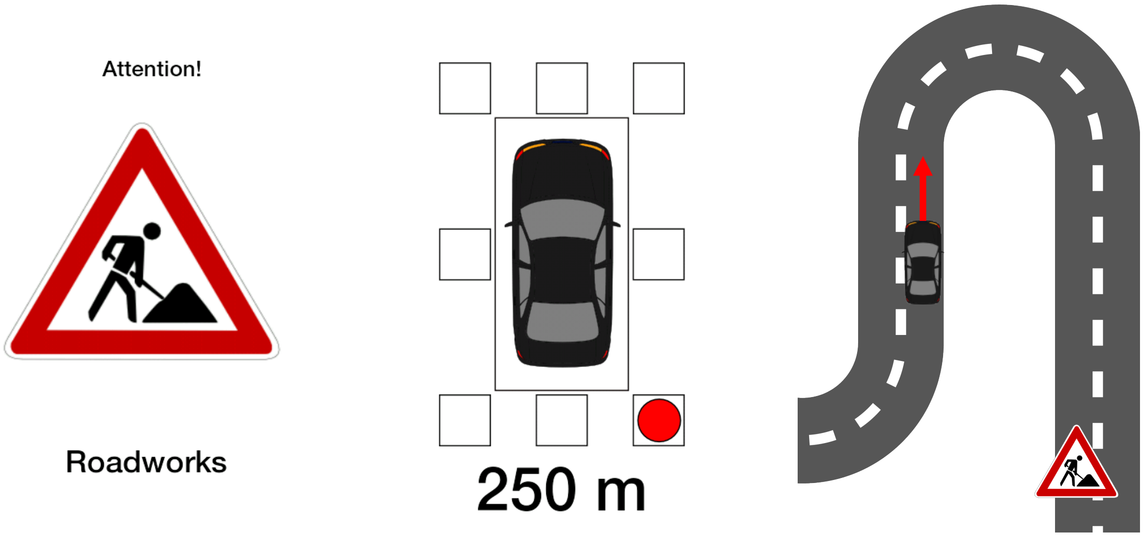
We also presented some results of the performed training study. The experts were not surprised that only a few users trained on their own. However, they did not see this as a fundamental problem, but highlighted the positive effect of communicating the need for training and daily movement to the users and inspiring how “simple this can be integrated into the daily living.”

Vehicle User Interface Training

The experts could try the mobile application-based automotive user interface training presented in Section 5.2 on the provided tablet PCs. Already during this phase, we noticed that the experts regarded the application rather a game than a training assistant. That corresponds to the initial predominate feedback that the training app feels like a “game for in between.” For that reason, the experts were unsure whether older people would accept this approach. Afterward, we also presented some images of the in-vehicle training concept (cf. Section 5.3). The experts rated this as more appropriate for elderly people but would leave out the game elements. Especially with the rise of sharing concepts (e.g., car-sharing), they find it very important that users get to know the means of mobility before they use them. Doing this in a “guided manner in the real vehicle” can be an effective method for content mediation.

Although the game elements were rated as unnecessary by the experts at first, they later gave the feedback that they discussed their progress in finding the elements with their peers in a break. They noticed the *effect of engagement* [150] that was our hypothesis when creating the concept. For that reason, some experts revised their initial feedback, and argued that a minimal gamified approach could be a good discussion starter for communicating about the learning system. It was also mentioned that the game character could be beneficial in certain situations where a vehicle owner wants the user to be informed about the vehicle functions. Since the application feels more like a game, the users may not feel to be in some kind of exam situation.

We also guided the discussion on the topics and functions that should be covered in the eyes of the experts. Similar to our findings in Section 5.2.1, the experts first named “safety-relevant functions.” For the experts, these were mainly the correct adjustment of the seat and the mirrors. One expert mentioned that the driver should also be aware of the driving assistance functions that are built-in and can warn the driver. He named here the collision warning and the blind spot assist. As the next vital functions, the experts named things that can be categorized as secondary driving tasks [385], e.g., the usage of the headlights, the turn indicators, or the wiper. Last mentioned were tertiary tasks, such as the operation of the radio and the navigation system. Our in-vehicle training application could support the adjustment of seats and mirrors when the car is equipped with an electronic adjustment that is connected via a bus system to a central OBU.



(a) The warning screen was rated to be useful as the display of the warning sign allows for fast recognition of the imminent danger point. However, it was unclear why one should care about roadworks that are located behind the vehicle.

(b) In this scenario, the direction of the roadworks would be shown temporarily behind the vehicle.

Figure 7.2: In certain situations, it can happen that stationary events are displayed as lying behind the vehicle during the approach. The experts recommended to change this screen for stationary events, but leave it when the incident causing object is moving. An example for this is the approaching emergency vehicle warning (AEVW).

Assistance During Driving

Vehicle-to-X Information Visualization

The last evaluated solution was the mobile-device based V2X assistance system presented in Chapter 6. The application was also installed on the tablet PC. The experts became a short demonstration of an incident scenario (cf. Section 6.4.2) and a GLOSA scenario (cf. Section 6.6).

The experts found DriveAssist 2.0 very useful. One expert highlighted that bringing a known application on a known device in different vehicles can be very beneficial since the interaction and the warning system is then known to the user. He added that in dangerous situations, “this can be the decisive time between an accident or a good outcome.” Especially the use of well-known warning signs was rated as very good since that allows for fast recognition of the imminent danger. A point of criticisms was the active warning screen’s direction indication that was evaluated as a bit confusing. One expert asked the question of why one should care about roadworks behind the vehicle (cf. Figure 7.2a). Although stationary events, such as roadworks or the end of traffic congestion, will only be shown when they lie ahead in the route, an incident may be shown as lying behind during the approach. That can be the case for curvy routes, such as winding roads on hills, or in situations with one-way streets. We agree that for stationary events, the warning screen should only show that an event will occur at a certain distance.

The experts found the choice of supported warnings (approaching emergency vehicle warning, electronic emergency brake light, stationery vehicle warning/post-crash warning, traffic jam ahead warning, working area warning, and hazardous location notification) suitable and sufficient for the start. Some experts highlighted the usefulness of the approaching emergency vehicle warning since they know how “stressful it can be in traffic to find out where an emergency vehicle is when [one] hears the siren.”

The experts saw it problematic that an extra V2X OBU is necessary in order to use the functionality, and, when manufacturers build in such a system, the manufacturers will also build in a system to present the data. The first point is valid: in order to get V2X data at all, vehicles and infrastructure need a certain equipment rate. That can, for example, be accelerated by politics demanding connected use-cases [393]. A possibility would be to add these to the individual New Car Assessment Programme (NCAP). The second point is also valid in case a car manufacturer wants to create a full-extent application that warns the user. However, when specific use-cases, such as the electronic emergency brake light for avoiding rear-end collisions, are demanded by New Car Assessment Programme (NCAP) or similar, low- and mid-prized vehicles may be equipped with a V2X OBU that only evaluates the data for this single use-case. In that case, the forwarding to a user’s PMD can be a reasonable alternative. Since car-sharing programs are usually not based on high-prized vehicles, we see potential in our suggested solution.

Another hardware topic that was mentioned by the experts was the need to fix one’s PMD in the vehicle securely. The experts further demanded that universal fixtures also would need a universal charging solution so that the devices can be charged. We acknowledge that solutions for fixing and charging are essential. As the experts also highlighted, adding “another screen” offers additional distraction potential. The experts suggested that at least the “normal applications are blocked during the driving” and that only the assistance system is available until the drive ends. There are already solutions for blocking apps that require much interaction during driving [294]. As shown in Section 6.2.2, there are also alternative ways of integrating the mobile device directly with the vehicle’s infotainment system. Solutions such as *Apple CarPlay*[6] or *Android Auto*[7] allow showing the content directly on the vehicle’s screen. At the same time, the device is charging via an in the vehicle integrated wireless charging system. Especially the popularity[8] of these two mobile device integration systems support the assumption that users do not want to go without their mobile device environment during driving.

---

[6] https://www.apple.com/de/ios/carplay/, accessed June 20, 2019.

[7] https://www.android.com/intl/de_de/auto/, accessed June 20, 2019.

[8] https://www.strategyanalytics.com/strategy-analytics/news/strategy-analytics-press-releases/strategy-analytics-press-release/2018/04/12/apple-carplay-and-android-auto-will-impact-future-vehicle-purchase-decision-finds-strategy-analytics, accessed June 20, 2019.

Green Light Optimized Speed Advisory

The green light optimized speed advisory (GLOSA) application (cf. Section 6.6) has been demonstrated together with DriveAssist 2.0 since it also relies on V2X technology and runs on a mobile device affixed in the vehicle. The hardware concerns on the vehicle-side and for the V2X infrastructure are also valid for this solution and are not repeated here. However, the transition phase of such a V2X-based GLOSA system might be more challenging. During that phase, the red lights will be equipped gradually with V2X communication technology. That would lead to situations where a driver would have support only for those red lights. One expert had the opinion that the system would then not be used or at least be ignored since "one cannot rely on getting the assistance" and, thus, "one has to monitor each red light anyway." Research on trust on automation show that *missing alarms* can be as severe as *false alarms* [222]: the effect is not only that the trust is lost, but also that delayed reactions may occur when there are only a few "missing alarms" [2]. A possibility to solve this situation could be using red light positions in map data to show that there is a red light in a certain distance, but no assistance can be offered yet. That way, the trust in the assistance system could be maintained [296], and the driver would be aware that there is a red light ahead.

Similar to DriveAssist, the experts found it useful to have a familiar interface for the assistance function. One expert suggested that the red light assistant should be part of DriveAssist and pop-up similar to the warning screen. That led to the question of prioritization: what should be shown when a vehicle approaches a red light and, at the same time, an incident that would trigger a warning screen. A solution could be a split-screen view. However, this may lead to situations where too much visual attention is required since twice the amount of information would be shown [337, 366]. Instead of just showing both, logic could be implemented that, for example, displays directly upcoming red lights or incidents, but only shows the detailed information for the event or incident that will be passed next.

For the display of the GLOSA (cf. Figure 7.3), the experts rated the presentation of the *speed carpet* at first as very complicated. However, after a simulation of a red light approach with the c2xMessageTester (cf. Section 6.7), the idea of the visualization was understood. One expert summarized that the "[speed] carpet makes it easy since I only have to drive at a speed that [the black line] keeps in the green area." The fact that the shown current velocity may be different from the vehicle's tachometer was not considered as a problem for the experts. That behavior is also known from PNDs. Moreover, since the application does not just write, for example, "you need to drive between $30\,\mathrm{km/h}$ and $40\,\mathrm{km/h}$", the actual velocity does not matter but is just a rough indication of the necessary velocity range.

The experts also discussed whether GLOSA at all, and this application could promote speeding. In order to reach the red lights within the green phase, people could be animated to drive faster than allowed. When looking at existing GLOSA implementations [106, 354], they are implemented in a way that the regulations of the individual countries are met. As presented in Section 6.6.2,

Figure 7.3: The experts initially rated the “color carpet” as not comprehensible. However, after a live demonstration in a simulated driving situation, they understood the approach. One expert summarized that the “[speed] carpet makes it easy since I only have to drive at a speed that [the black line] keeps in the green area.”

our GLOSA prototype was also designed according to the road traffic regulations. Its speed carpet ends at the current speed limit, and when a velocity above the current limit is detected, it can warn the driver visually, when the feature is not disabled.

7.5.2 General Feedback and Improvement Potentials

Besides potential usability issues of the presented solutions, the expert evaluation also came across several general topics and suggested multiple improvement ideas. The most relevant ones are summarized in this section.

A central, recurring point in the discussions was the appropriateness of functionality allocation between humans and technical systems. The experts warned of replacing social cooperation with technology. They argued that the incorporation of humans in the assistance solutions would increase the acceptance of the digital systems.

Crucial factors for the acceptance of digital assistance are creating and maintaining trust in the digital assistance system[219]. Lee and See [218] derived principles that allow people to manage imperfect automation through actively managing factors that influence trust. Examples are *revealing intermediate results*, *showing the reliability to expect*, and *showing the relation of the assistance system to the goal of the user by evaluating context*. When a digital system cannot provide the necessary reliability, for example, due to high uncertainty or complexity, it can be better to have

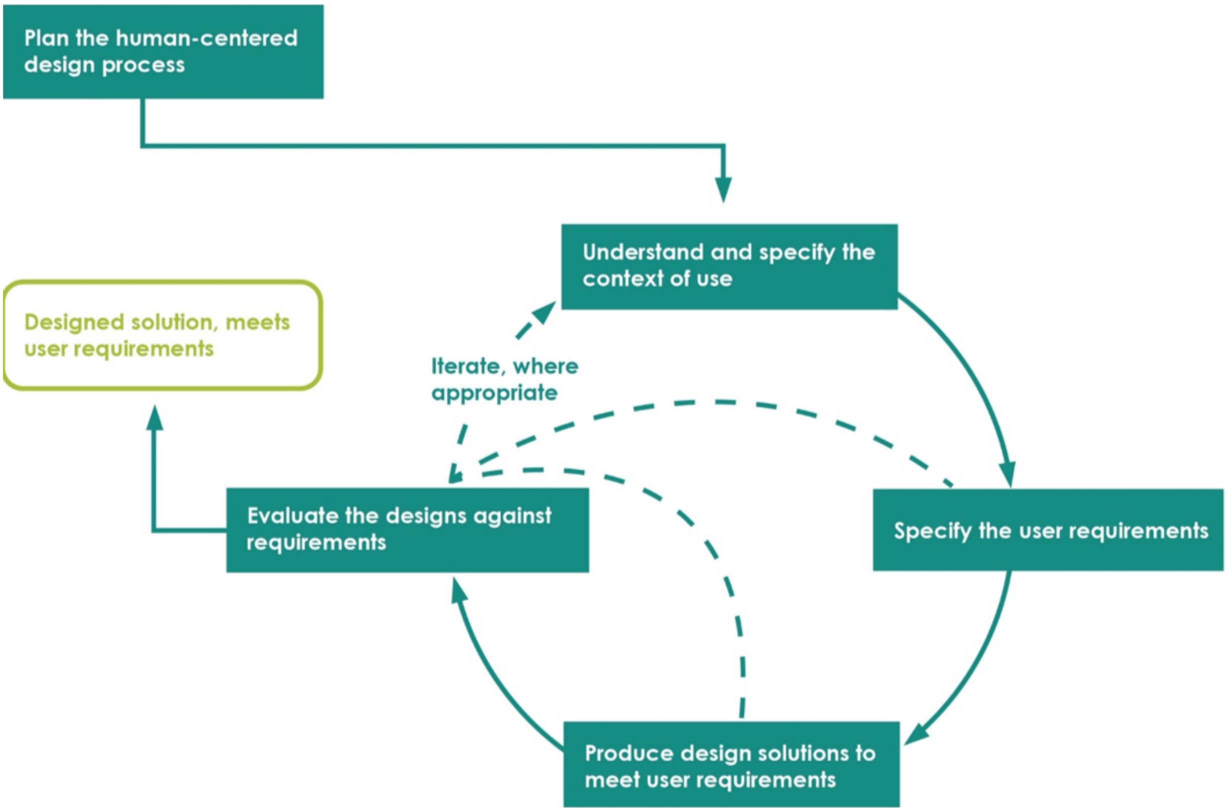


Figure 7.4: All prototypes have been implemented following the human-centered design process, as defined in ISO 9241-210 [176]. That ensures that basic usability and acceptance factors are respected in the implementation.
Image source: ISO 9241-210 [176].

humans handling this part. These principles have been respected in our prototype implementations by following the human-centered design process as defined by ISO 9241-210 [176].

Figure 7.4 depicts the human-centered design process. The points *understanding and specifying the context of use* and *specifying the usage requirements* are mainly covered in Chapter 3, where we identified the central needs and research gaps, and analyzed the individual tasks of mobility processes. The design evaluation happened in individual user studies and, finally, also by this expert evaluation. Following the human-centered design process ensures that basic usability and acceptance factors are respected. Since this also includes the analysis of individual tasks to be solved, we also covered the question of whether a task can be realized reliable by a digital assistance system.

Positive reactions from the experts came about the usage of standard off-the-shelf smartphones and tablet PCs for the studies, even when they have been performed with older adults that are not acquainted with the use of this kind of device. Instead of provoking “stigmatization in the family [and the social community], that may attract the attention [of peers].” That makes it also easier to receive peer support when questions on or problems with the usage of the devices arise. In

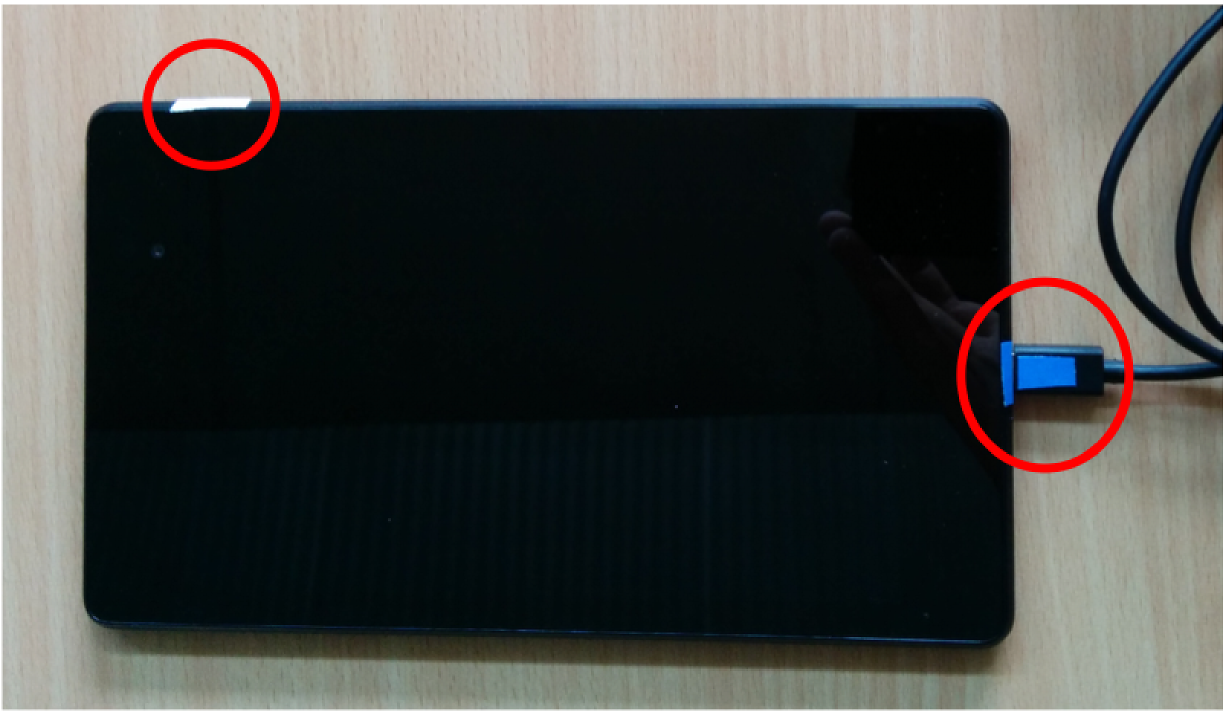


Figure 7.5: Even for the studies with elderly users (above 70 years), standard off-the-shelf tablet PCs have been used. The white adhesive marking helped the users to find the on/off switch. The blue marking on the device and the USB connector gave orientation where and in which direction the charging cable has to be plugged in. These markings were explained during the introduction of our studies. Besides, printed short manuals were distributed.

order to simply the usage of the hardware, we prepared printed manuals and attached markings on the devices to show where the device can be switched on or where and in which direction the charging plug needs to be connected (cf. Section 5.4.5 and Figure 7.5).

This positive feedback on having a product that fits "for young and old" also affected the UIs in general. The ICT expert said that providing interfaces that "look like to be targeted at almost-blind persons with no fine motor skills left, are doomed to fail" since they compromise the limitations of the users. We achieved this by applying the principles of universal design [373] (cf. Sections 4.4 and 5.4). A central principle is an *equitable use* without stigmatizing any of the potential users. For example, in our implementations, we either support swipe gestures but also display buttons to get from one content page to the next (e.g., in the Rollator Training in Section 5.4).

Including *more humans* in the whole mobility process does not necessarily mean that this has to be service personnel. Providing networking possibilities to find peers or to form support groups can also avoid social isolation and simplify the mobility process for individuals. Studies on physical activity and fitness have shown that training with peers can create high motivation and lead to long-term exercising [318]. Traveling in groups also has a positive effect on individual mobility [128].

A concrete idea of the experts was the inclusion of help buttons in the assistance applications to get immediate support when the user is stuck. The support "shall not be pure technical support, but provide help for any questions concerning the mobility," as one expert put it. We think that this would be beneficial. However, as stated in the limitations in Section 7.4, this can only be realized when the assistance system is operated by a larger service provided and is distributed with a business model or public funding in the background.

From the usability perspective, improvements for the design have been suggested. We acknowledge that there is a vast potential for the design of the applications. In particular, since studies on the effect of the design on usability have revealed that appealing applications are not only subjectively rated to be more usable, but also lead to better performance [346], e.g., in terms of task completion times [368]. In order to make full use of providing assistance solutions on the known mobile interface to the users, the applications should also have a standard styling and follow the design guidelines of the mobile platform [70].

7.6 Overall Summary of Evaluation Results

These points summarize the key evaluation results:

1. Getting started was simplified by reducing features to essential functions and options. However, for some applications that cannot derive the necessary context themselves, a first-run wizard, a guided setup, or hints on user settings during usage are necessary to deliver the appropriate assistance.
2. The used off-the-shelf hardware and the developed UIs that combine modern design and interaction with support functions (e.g., swiping gestures and buttons to switch between contents) do not trigger stigmatization of the elderly.
3. Adaptations to individual needs and barriers (e.g., limited hearing, seeing, or haptic capabilities) are well integrated and not intrusive. For example, concerning the UI, reading out the exercise description and offering larger buttons are also prevalent functions in standard fitness apps. In the case of hardware, small marks on the device's edges that help with finding small buttons or the place to plug in the charger are not only beneficial for inexperienced users but may also support practiced users in everyday life.
4. Considering individual needs (e.g., fostering of movement) and anxieties (e.g., handling of unknown means of mobility) of users at the same time increases the probability that the developed assistance solutions are accepted and used by the targeted users. In the case of the fitness route, the solution not only encourages physical activity but also takes personal limitations into account. Furthermore, the vehicular user interface training with its game character can hide the severity of the actual driving task and allow exploration without negative consequences.

Although the developed solutions received overall positive feedback, the experts noted that users could only benefit from the solutions when the anxiety over using the assistance systems and the different means of mobility can be removed. Future research will, therefore, need to investigate how this can be achieved with respect to employed technology. Proposed solutions were the inclusion of individualized training in the business model and providing contact points for emerging questions and problems with the assistance system or the mobility processes in general.

Part III

Conclusion

Chapter 8

Conclusion

8.1 Summary of the Contributions

At the end of the dissertation, we summarize the answers to the high-level research questions (HRQs) we formulated in Section 1.2.1 to highlight the main contributions of our research.

RQ1: What are the typical steps of intermodal mobility scenarios?

We first established a common language and understanding of mobility with our background view and definitions in Chapter 2. In Section 3.1, we introduced a process definition that was derived from literature and extended by our research. The division into the phases *before the trip*, *during the trip*, and *after the trip* provided the structure for our mobility assistance research. This structure was the basis for the scenarios defined in Section 3.3.2 and for the profound requirements analysis in Section 3.4.

The elaborated structure provides a foundation for the systematic inspection of (intermodal) mobility processes and is compatible with approaches found in the literature [97, 160, 162, 388]. An advantage of the defined process is the inclusion of the first and last mile, which are as important as the main trip itself. The current trend of electric micro-mobility (cf. Section 3.1.3) underlines the importance of bridging short distances for travelers. Our user study on the contextual trip planning application in Section 4.4 confirms this.

RQ2: What are the main requirements for information and digital services of mobility users?

The main contributions to **HRQ2** can be found in Section 3.4. The requirements have been derived from extensive literature research complemented by results from our mobility process analysis and the conducted user studies. Our work with older people broadened the scope in comparison to available literature because we also included possible visual, auditory, and physical impairments of users. Furthermore, this helped us compile a comprehensive overview of mobility barriers in Section 3.2.1.

On the one hand, the requirements were used to identify research gaps where users can benefit from assistance and no solutions are available. On the other hand, the applicable requirements on information and digital services were the basis for our concepts and developed prototypes in Chapters 4–6, which then led to the development, evaluation, and verification of mobility system prototypes.

The underlying basic requirement is the reduction of physical and cognitive effort required for users' mobility. To fulfill this adequately, the users request that the provided information is of high quality (complete, concise, and up to date) and provided in real time.

Some concepts and results from user studies of the developed research prototypes have been published in peer-reviewed conference contributions [86, 90, 94–96].

RQ3: What steps in intermodal mobility scenarios can benefit from digital assistance through users' personal mobile devices (PMDs)?

In Section 3.8, the areas and steps that can benefit from digital assistance are summarized. For this work, we selected the areas of *contextual trip planning* with a focus on physical health and data credibility (Chapter 4), *supportive mobility training* for maintaining self-determined mobility and enhancing travel comfort (Chapter 5), and *real-time assistance* on the users' PMDs in the automotive context (Chapter 6). The exact placements of the identified and investigated research gaps in the mobility chain scenarios are given in the introductory problem statements of Chapters 4–6 that tackle the mentioned areas.

Our selection of the areas was grounded in extensive related research. The distilled summary of this research can be found in Chapter 2, and especially in Section 2.3, in which we summarized the existing digital mobility assistance concepts and systems. For the selection, we concentrated on areas and mobility steps that had been neglected in the literature and current products.

The scientific outcome of the literature review is the distilled structured and concise summary of requirements. It can serve researchers in the field of mobility assistance systems and intermodal transportation as the starting point for future research. For example, when looking at the requirements users may have when a transfer is necessary, our overview provides the central factors of *duration until transfer station is reached*, *station name where transfer shall happen*, *time necessary for transfer*, *time available for transfer availability of barrier-free transfer option*, and *name and direction of next line* (cf. Section 3.4, Figure 3.8).

Parts of the answer to this research question have been published in a peer-reviewed conference article [87].

RQ4: How can the complexity of operating mobility services and assistance systems be reduced for users?

The central point of reducing the complexity of a mobility assistance system is to focus on the essential information and support that matches the user's current context and phase of travel (cf. Section 3.4). In our vision in Section 3.6, we describe a fully-integrated mobility assistance solution that could accomplish this by interconnecting the mobility-relevant elements with the users' data and PMDs.

Answers to this research question are also our concretions of the principles of universal design [359, 373] in the context of mobility assistance systems given in Sections 4.4, 5.4, and 7.6. Examples are advisedly chosen default values or the derivation of mobility context via sensors instead of explicit user input. These, in turn, can be used by engineers of mobility assistance systems as well as computer scientists to implement intermodal transportation systems. We conducted several studies with older people that had only partial or minimal experience with digital systems (cf. Sections 4.4 and 5.4). Especially in these cases, we could identify the tasks (e.g., textual input of addresses) and functions (e.g., an unnecessary extra step to start the stopwatch for the physical training) that caused challenges in the digital mobility assistance systems.

We demonstrated the successful integration of supportive functions in the trip planning application Seamless Mobile (Section 4.4) and our vehicle-to-X (V2X) prototype DriveAssist 2.0 (Section 6.5). Inter-vehicle communication is about to enter the market, and can further leverage mobility assistance systems. In both prototypes, we enriched mobility assistance functions with additional supportive functionalities and information that were only relevant for certain phases and, thus, were only presented to the user in these cases. At the same time, we limited the integrated functions to those that are regularly used to prevent overloading. Overall, we reduced the cognitive effort for the users by using their acquainted human–machine interface (HMI) environment on their PMDs (Section 6.2).

Parts of the user study results from the individual underlying research prototypes have been published in peer-reviewed articles [86, 94–96].

RQ5: How can users be supported in accessing and using mobility services and means of mobility?

Though the answers to **HRQ4** help to develop an advanced mobility assistance system (AMAS) with reduced complexity, this research question is aimed at simplifying the access to and usage of mobility services. A central point in our presented vision of connected mobility in Section 3.6 is the seamless integration of digital mobility services into systems supporting mobility. Because mobility assistance systems on PMDs possess user and route context, they can support users by choosing a suitable service and providing necessary data without explicit user actions such as entering data or changing applications. Examples are checking for sharing vehicle availability at transfer stations on the route or purchasing a bus ticket for a leg of a journey without having the user enter the details again in the application of the bus operator or even at a ticket vending machine. Requirements for this are standardized and open application programming interfaces (APIs) (see Section 3.5 on possible data sources).

Besides the available context on the PMD, users are usually well acquainted with its operation and the usage of the apps. For that reason, the integration of the PMD with in-vehicle systems can be beneficial (Section 6.2). With our investigation of possible two-tier architectures for the integration of PMD with V2X communication in vehicles (Section 6.3), we have shown how a trade-off between flexibility (for future additions and changes) and processing performance can be achieved.

In cases where it is inevitable to operate other mobility-related HMIs — for example, when operating a vehicle on one's own — explicit instruction or training can support the user. With our automotive user interface (UI) training on the users' PMDs (Section 5.2), we created a novel concept that can reduce the stress for users who regularly change vehicles. Because our research has shown no significant difference between performing the training in the real vehicle and working through it on the mobile device, such training can be offered in advance of trips to reduce the stress further. Though our rollator training concept (Section 5.4) does not focus on the usage of the mobility aid itself, exercising with it also helps users get a better feel for its operation.

Parts of the results have been published in peer-reviewed conference articles [84, 85, 89, 94].

RQ6: How can users be motivated to actively deal with their mobility and assistance systems that can improve their mobility situation?

In our research, we came several times across the topic of (the need of) motivating users to employ applications and services that could enhance their mobility situation. This is often a paradox: Users who could benefit the most, are often the least motivated [421]. The training of computer skills, while important, is no all-encompassing solution to this problem, for example in the context of older users with limited access to information systems. To overcome this situation, we looked into motivating people through employing game elements in two of our assistance prototypes (Sections 5.2, 5.3, and 5.4). Our study results have shown that gamification can be especially useful when rather young people are the target group. However, we have also highlighted that competitive game elements should not be chosen for motivating people when safety-critical tasks, such as driving a vehicle, are involved.

The second focus point was on enhancing the credibility (or better communication of existing credibility) of trip data to avoid reservations against created journeys and public transport in general. Although our framing approaches did not show a significant effect (cf. Section 4.4), we could demonstrate that making use of available context and, especially, showing what user context has been considered can significantly enhance the credibility.

Some of our research results on gamification and nudging approaches have been previously published in peer-reviewed conference articles [88, 90, 91, 93, 96].

8.2 Concluding Remarks

As concluding remarks, we want to touch on some aspects that should also be considered for future work on AMASs.

8.2.1 Possible Future Extensions

The individual exemplary implementations of mobility assistance systems can only cover small parts of the identified mobility assistance design space. For route planning, we see great potential in pro-active live assistance, such as when one needs to reschedule because of delays. For support during trip execution, technologies such as augmented reality (AR) can significantly reduce the effort for the user. Besides helping with navigation, AR could, for example, also give instructions on how to operate a means of mobility. In the field of training and exercising, the integration in tasks of daily living seems to be most promising. Besides, we see great potential in digital mobility assistance solutions for elderly users, given that the smart device adoption of seniors is increasing rapidly.

8.2.2 Sensitive Areas for Mobility Assistance Systems

During our research, we came across several areas of conflict that should be taken into account when developing an assistance system.

Seamless Integration Versus Closed Ecosystems

Our research has shown that users have the desire for seamlessly integrated assistance in solutions they are already used to. An example is the integration of V2X real-time information in navigation solutions, as we have done for DriveAssist 2.0 (Section 6.5). A potential problem is that closed ecosystems do not allow the seamless inclusion of meaningful assistance aspects (cf. remarks on “big platforms dominating the digital market” during the expert evaluation in Section 7.5.1). Possible solutions are open APIs and regulatory measures, such as the Second Payment Services Directive (PSD2) in the banking sector[1].

---

[1] https://www.bundesbank.de/en/tasks/payment-systems/psd2/psd2-775954, accessed December 12, 2019.

Extensive User Context Versus Data Protection

On the one hand, extensive user context data can help in automatically tailoring assistance solutions to the abilities and needs of individuals. On the other hand, however, especially for mobility, this often means the analysis of movement profiles and the inclusion of health data. The provider of the assistance systems can abuse these data. For example, when a health insurance company offers a physical exercising application that makes use of personal context and gathers exercising history and feedback, it may use these data to assess the user's health and willingness of training. That, in turn, may lead to adaptations of insurance conditions. To avoid these conflicts, data minimization and full transparency of how gathered data are used could be applied.

Motivation versus Manipulation

In our research, we examined gamification for building motivation and nudging for building trust. As already stated in Section 7.5.1, ethical aspects shall be respected when applying such measures. There is often only a small border between fostering beneficial behavior and actively manipulating the user. In the mobility context, this may, for example, be used to manipulate the perceived quality of different mobility services or to provoke dangerous driving maneuvers that are only performed to *earn some points*. We recommend a detailed situation and risk analysis when such measures shall be performed.

List of Figures

List of Tables

Bibliography

[1] E. Aarts, *The New Everyday: Views on Ambient Intelligence*. 010 Publishers, 2003, ch. Technological Issues in Ambient Intelligence, pp. 12–16. 18

[2] G. Abe and J. Richardson, “The Influence of Alarm Timing on Driver Response to Collision Warning Systems Following System Failure,” *Behaviour & Information Technology*, vol. 25, no. 5, pp. 443–452, Sep. 2006. 185

[3] H. Abraham, H. McAnulty, B. Mehler, and B. Reimer, “Case Study of Today’s Automotive Dealerships,” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2660, pp. 7–14, Jan. 2017. 96

[4] J. Ahn, J. Williamson, M. Gartrell, R. Han, Q. Lv, and S. Mishra, “Supporting Healthy Grocery Shopping via Mobile Augmented Reality,” *ACM Transactions on Multimedia Computing Communications and Applications*, vol. 12, no. 1, pp. 16:1–16:24, Oct. 2015. 22

[5] M. Akhavan and G. Vecchio, “Mobility and Accessibility of the Ageing Society. Defining Profiles of the Elderly Population and Neighbourhood,” *Journal of Land Use, Mobility and Environment*, vol. 2, pp. 9–22, Oct. 2018. 44, 45

[6] J. Allen, “Synthesis of Speech from Unrestricted Text,” *Proceedings of the IEEE*, vol. 64, no. 4, pp. 433–442, Apr. 1976. 19

[7] H. Almuhimedi, F. Schaub, N. Sadeh, I. Adjerid, A. Acquisti, J. Gluck, L. F. Cranor, and Y. Agarwal, “Your Location has been Shared 5,398 Times!” in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI ’15. ACM, Apr. 2015, pp. 787–796. 28

[8] R. Alsnih and D. A. Hensher, “The Mobility and Accessibility Expectations of Seniors in an Aging Population,” *Transportation Research Part A: Policy and Practice*, vol. 37, no. 10, pp. 903–916, Dec. 2003. 3

[9] J. Aron, “How Innovative is Apple’s New Voice Assistant, Siri?” *New Scientist*, vol. 212, no. 2836, p. 24, Oct. 2011. 17

[10] A. Asthana, M. Cravatts, and P. H. Krzyzanowski, “An Indoor Wireless System for Personalized Shopping Assistance,” in *Proceedings of the Workshop on Mobile Computing Systems and Applications*. IEEE, Dec. 1994, pp. 69–74. 22

[11] M. Auais, T. Ahmed, B. Alvarado, S. P. Phillips, N. Rosendaal, C.-L. Curcio, J. Fernandes, J. Guralnik, and M. V. Zunzunegui, “Gender Differences in Four-Year Incidence of Self-Reported and Performance-Based Functional Disability: The International Mobility in Aging Study,” *Archives of Gerontology and Geriatrics*, vol. 82, pp. 266–272, May 2019. 3

[12] J. C. Augusto, *Ambient Intelligence: The Confluence of Ubiquitous/Pervasive Computing and Artificial Intelligence*. Springer, 2007, pp. 213–234. 18

[13] J. Bakker, M. Pechenizkiy, and N. Sidorova, “What's Your Current Stress Level? Detection of Stress Patterns from GSR Sensor Data,” in *Workshop Proceedings of the 11th International Conference on Data Mining*. IEEE, Dec. 2011, pp. 573–580. 56

[14] R. K. Balan and N. Ramasubbu, "The Digital Wallet: Opportunities and Prototypes," *Computer*, vol. 42, no. 4, pp. 100–102, Apr. 2009. 56

[15] R. Ballagas, J. Borchers, M. Rohs, and J. G. Sheridan, "The Smart Phone: A Ubiquitous Input Device," *Pervasive Computing*, vol. 5, no. 1, pp. 70–77, Jan. 2006. 18, 21

[16] S. Bamberg, S. Fujii, M. Friman, and T. Gärling, "Behaviour Theory and Soft Transport Policy Measures," *Transport Policy*, vol. 18, no. 1, pp. 228–235, Jan. 2011. 44, 45

[17] J. A. Bargh, P. M. Gollwitzer, A. Lee-Chai, K. Barndollar, and R. Trötschel, "The Automated Will: Nonconscious Activation and Pursuit of Behavioral Goals," *Journal of Personality and Social Psychology*, vol. 81, no. 6, pp. 1014–1027, Dec. 2001. 28

[18] L. Barkhuus and A. K. Dey, "Location-Based Services for Mobile Telephony: A Study of Users' Privacy Concerns," in *Proceedings of the 9th IFIP International Conference on Human-Computer Interaction*, ser. INTERACT '03, vol. 3. IOS Press, Sep. 2003, pp. 702–712. 131

[19] Y. Bart, V. Shankar, F. Sultan, and G. L. Urban, "Are the Drivers and Role of Online Trust the Same for All Web Sites and Consumers? A Large-Scale Exploratory Empirical Study," *Journal of Marketing*, vol. 69, no. 4, pp. 133–152, Oct. 2005. 16

[20] P. Baudisch and G. Chu, "Back-of-Device Interaction Allows Creating Very Small Touch Devices," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '09. ACM, Apr. 2009, pp. 1923–1932. 19

[21] K. Baxter and C. Courage, *Understanding Your Users: A Practical Guide to User Requirements Methods, Tools, and Techniques*, ser. Interactive Technologies. Morgan Kaufmann, Jan. 2005. 32

[22] H. Becker, F. Ciari, and K. W. Axhausen, "Comparing Car-Sharing Schemes in Switzerland: User Groups and Usage Patterns," *Transportation Research Part A: Policy and Practice*, vol. 97, pp. 17–29, Mar. 2017. 52

[23] G. Beirão and J. A. S. Cabral, "Understanding Attitudes Towards Public Transport and Private Car: A Qualitative Study," *Transport Policy*, vol. 14, no. 6, pp. 478–489, Nov. 2007. 48

[24] R. Belk, "You Are What You Can Access: Sharing and Collaborative Consumption Online," *Journal of Business Research*, vol. 67, no. 8, pp. 1595–1600, 2014. 2

[25] E. Ben-Elia, R. D. Pace, G. N. Bifulco, and Y. Shiftan, "The Impact of Travel Information's Accuracy on Route-Choice," *Transportation Research Part C: Emerging Technologies*, vol. 26, pp. 146–159, 2013. 85

[26] D. Berdichevsky and E. Neuenschwander, "Toward an Ethics of Persuasive Technology," *Communications of the ACM*, vol. 42, no. 5, pp. 51–58, May 1999. 93, 180

[27] A. Berenguer, J. Goncalves, S. Hosio, D. Ferreira, T. Anagnostopoulos, and V. Kostakos, "Are Smartphones Ubiquitous?: An In-Depth Survey of Smartphone Adoption by Seniors," *IEEE Consumer Electronics Magazine*, vol. 6, no. 1, pp. 104–110, Jan. 2017. 75

[28] L. M. Bergasa, D. Almeria, J. Almazan, J. J. Yebes, and R. Arroyo, "DriveSafe: An App for Alerting Inattentive Drivers and Scoring Driving Behaviors," in *Proceedings of the IEEE Intelligent Vehicles Symposium*. IEEE, Jun. 2014, pp. 240–245. 26

[29] H. Bergman and J. Keene-Moore, "The Birth of a HELP System," in *Proceedings of the Annual Conference on The Range of Computing*, ser. ACM '85. ACM, Oct. 1985, pp. 289–295. 15

[30] S. Beul-Leusmann, E.-M. Jakobs, and M. Ziefle, “User-Centered Design of Passenger Information Systems,” in *IEEE International Professional Communication Conference*, ser. IPCC ’13. IEEE, Jul. 2013, pp. 1–8. 53

[31] S. Beyer and A. Müller, “Evaluation of Persona-Based User Scenarios in Vehicle Development,” in *Human Systems Engineering and Design*, ser. IHSED ’18. Springer International Publishing, Oct. 2018, pp. 750–756. 3

[32] J. S. Blumenthal-Barby and H. Burroughs, “Seeking Better Health Care Outcomes: The Ethics of Using the “Nudge”,” *The American Journal of Bioethics*, vol. 12, no. 2, pp. 1–10, Feb. 2012. 180

[33] J. Bobadilla, F. Ortega, A. Hernando, and A. Gutiérrez, “Recommender Systems Survey,” *Knowledge-Based Systems*, vol. 46, pp. 109–132, Jul. 2013. 15

[34] L. Böcker and T. Meelen, “Sharing for People, Planet or Profit? Analysing Motivations for Intended Sharing Economy Participation,” *Environmental Innovation and Societal Transitions*, vol. 23, pp. 28–39, Jun. 2017. 48

[35] E. A. I. Bogers, F. Viti, and S. P. Hoogendoorn, “Joint Modeling of Advanced Travel Information Service, Habit, and Learning Impacts on Route Choice by Laboratory Simulator Experiments,” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1926, no. 1, pp. 189–197, Jan. 2005. 57

[36] R. W. Bohannon, “Comfortable and Maximum Walking Speed of Adults Aged 20—79 Years: Reference Values and Determinants,” *Age and Ageing*, vol. 26, no. 1, pp. 15–19, Jan. 1997. 91

[37] D. Bohus and A. I. Rudnicky, “The RavenClaw Dialog Management Framework: Architecture and Systems,” *Computer Speech & Language*, vol. 23, no. 3, pp. 332–361, Jul. 2009. 17

[38] Y. Bontekoning and H. Priemus, “Breakthrough Innovations in Intermodal Freight Transport,” *Transportation Planning and Technology*, vol. 27, no. 5, pp. 335–345, Oct. 2004. 13

[39] H. R. Booher, “Relative Comprehensibility of Pictorial Information and Printed Words in Proceduralized Instructions,” *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 17, no. 3, pp. 266–277, Jun. 1975. 16

[40] P. Borkowski, “Towards an Optimal Multimodal Travel Planner – Lessons from the European Experience,” in *Advances in Intelligent Systems and Computing*. Springer International Publishing, Jul. 2016, pp. 163–174. 53

[41] R. Bose, J. Brakensiek, and K.-Y. Park, “Terminal Mode: Transforming Mobile Devices into Automotive Application Platforms,” in *Proceedings of the 2nd International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI ’10. ACM, Nov. 2010, pp. 148–155. 136

[42] S. M. Botden and J. J. Jakimowicz, “What is Going on in Augmented Reality Simulation in Laparoscopic Surgery?” *Surgical Endoscopy*, vol. 23, no. 8, pp. 1693–1700, Sep. 2008. 21

[43] M. Bradway, E. Årsand, and A. Grøttland, “Mobile Health: Empowering Patients and Driving Change,” *Trends in Endocrinology & Metabolism*, vol. 26, no. 3, pp. 114–117, Mar. 2015. 21

[44] G. L. Brase and J. Richmond, “The White–Coat Effect: Physician Attire and Perceived Authority, Friendliness, and Attractiveness,” *Journal of Applied Social Psychology*, vol. 34, no. 12, pp. 2469–2481, Dec. 2004. 29

[45] H. Breuer, M. Kettner, M. Wagler, N. Preuschen, and F. Steinhoff, “Love at First Encounter –

Start-Up of New Applications," in *Human-Computer Interaction. Ambient, Ubiquitous and Intelligent Interaction*. Springer Berlin Heidelberg, Jul. 2009, pp. 585–594. 93

[46] G. Broll, H. Palleis, H. Richter, and A. Wiethoff, "Exploring Multimodal Feedback for an NFC-Based Mobile Shopping Assistant," in *Proceedings of the 5th International Workshop on Near Field Communication*, ser. NFC '13, Feb. 2013, pp. 1–4. 22

[47] H. Brunner, M. Hirz, W. Hirschberg, and K. Fallast, "Evaluation of Various Means of Transport for Urban Areas," *Energy, Sustainability and Society*, vol. 8, no. 1, pp. 1–11, Mar. 2018. 52

[48] A. Bucchiarone, M. De Sanctis, and A. Marconi, *ATLAS: A World-Wide Travel Assistant Exploiting Service-Based Adaptive Technologies*. Springer International Publishing, 2017, pp. 561–570. 23

[49] K. Buckl and D. Kurz, "Personalisierte Mobilität, Assistenz und Service Systeme in einer alternden Gesellschaft : Teilvorhaben: AR unterstützte Dienste : Abschlussbericht für das Vorhaben PASSAGE : Berichtszeitraum: 01.08.2012 bis 31.07.2015," Metaio GmbH, Tech. Rep., 2016. 180

[50] L. Bunce, M. Harris, and M. Burgess, "Charge Up then Charge Out? Drivers' Perceptions and Experiences of Electric Vehicles in the UK," *Transportation Research Part A: Policy and Practice*, vol. 59, pp. 278–287, Jan. 2014. 39

[51] J. K. Burgoon, J. A. Bonito, B. Bengtsson, C. Cederberg, M. Lundeberg, and L. Allspach, "Interactivity in Human–Computer Interaction: A Study of Credibility, Understanding, and Influence," *Computers in Human Behavior*, vol. 16, no. 6, pp. 553–574, 2000. 86

[52] G. Burnett, "Turn right at the Traffic Lights: The Requirement for Landmarks in Vehicle Navigation Systems," *Journal of Navigation*, vol. 53, no. 3, pp. 499–510, 2000. 25

[53] G. E. Burnett, "Usable Vehicle Navigation Systems: Are We There Yet?" in *Proceedings of the European Conference and Exhibition on Vehicle Electronic Systems*, ser. VES '00, 2000, pp. 3.1.1–3.1.11. 24

[54] A. Butz, J. Baus, A. Krüger, and M. Lohse, "A Hybrid Indoor Navigation System," in *Proceedings of the 6th International Conference on Intelligent User Interfaces*, ser. IUI '01. ACM, Jan. 2001, pp. 25–32. 25

[55] N. Caceres, J. P. Wideberg, and F. G. Benitez, "Review of Traffic Data Estimations Extracted from Cellular Networks," *IET Intelligent Transport Systems*, vol. 2, no. 3, p. 179, Sep. 2008. 56

[56] J. A. Cafazzo, M. Casselman, N. Hamming, D. K. Katzman, and M. R. Palmert, "Design of an mHealth App for the Self-Management of Adolescent Type 1 Diabetes: A Pilot Study," *Journal of Medical Internet Research*, vol. 14, no. 3, pp. 1–10, May 2012. 21

[57] M. Caliskan, D. Graupner, and M. Mauve, "Decentralized Discovery of Free Parking Places," in *Proceedings of the 3rd International Workshop on Vehicular Ad Hoc Networks*, ser. VANET '06. ACM, 2006, pp. 30–39. 66

[58] J. Chai, V. Horvath, N. Nicolov, M. Stys, N. Kambhatla, W. Zadrozny, and P. Melville, "Natural Language Assistant: A Dialog System for Online Product Recommendation," *AI MAGAZINE*, vol. 23, no. 2, pp. 63–75, 2002. 17

[59] S. Chaiken and A. H. Eagly, "Communication Modality as a Determinant of Message Persuasiveness and Message Comprehensibility," *Journal of Personality and Social Psychology*, vol. 34, no. 4, pp. 605–614, Oct. 1976. 16

[60] T.-R. Chang, E. Kaasinen, and K. Kaipainen, “What Influences Users’ Decisions to Take Apps into Use?” in *Proceedings of the 11th International Conference on Mobile and Ubiquitous Multimedia*, ser. MUM ’12. ACM, Dec. 2012, pp. 2:1–2:10. 180

[61] G. Charness, U. Gneezy, and M. A. Kuhn, “Experimental Methods: Between-Subject and Within-Subject Design,” *Journal of Economic Behavior & Organization*, vol. 81, no. 1, pp. 1–8, Jan. 2012. 101

[62] C. L. P. Chen and C.-Y. Zhang, “Data-Intensive Applications, Challenges, Techniques and Technologies: A Survey on Big Data,” *Information Sciences*, vol. 275, pp. 314–347, Aug. 2014. 57

[63] Y. Chen, D. Lymberopoulos, J. Liu, and B. Priyantha, “FM-Based Indoor Localization,” in *Proceedings of the 10th International Conference on Mobile Systems, Applications, and Services*, ser. MobiSys ’12. ACM, Jun. 2012, pp. 169–182. 69

[64] A. Chinaei and F. Tompa, “User-Managed Access Control for Health Care Systems,” in *Secure Data Management*, ser. Lecture Notes in Computer Science. Springer, 2005, vol. 3674, pp. 63–72. 67

[65] J. H. Choi and H.-J. Lee, “Facets of Simplicity for the Smartphone Interface: A Structural Model,” *International Journal of Human-Computer Studies*, vol. 70, no. 2, pp. 129–142, Feb. 2012. 130

[66] D. J. Cook, J. C. Augusto, and V. R. Jakkula, “Ambient Intelligence: Technologies, Applications, and Opportunities,” *Pervasive and Mobile Computing*, vol. 5, no. 4, pp. 277–298, Aug. 2009. 18

[67] M. Cools and L. Creemers, “The Dual Role of Weather Forecasts on Changes in Activity-Travel Behavior,” *Journal of Transport Geography*, vol. 28, pp. 167–175, Apr. 2013. 93, 94

[68] A. Correa, M. R. Walter, L. Fletcher, J. Glass, S. Teller, and R. Davis, “Multimodal Interaction with an Autonomous Forklift,” in *Proceedings of the 5th International Conference on Human–Robot Interaction*, ser. HRI ’10. IEEE, 2010, pp. 243–250. 20

[69] T. G. Crainic and K. H. Kim, “Intermodal Transportation,” in *Transportation*, ser. Handbooks in Operations Research and Management Science, C. Barnhart and G. Laporte, Eds. Elsevier BV, 2007, vol. 14, ch. 8, pp. 467–537. 13

[70] F. Cuadrado and J. Dueñas, “Mobile Application Stores: Success Factors, Existing Approaches, and Future Developments,” *IEEE Communications Magazine*, vol. 50, no. 11, pp. 160–167, Nov. 2012. 189

[71] S. J. Czaja and C. C. Lee, “The Impact of Aging on Access to Technology,” *Universal Access in the Information Society*, vol. 5, no. 4, pp. 341–349, Mar. 2007. 120

[72] S. G. Dacko and C. Spalteholz, “Upgrading the City: Enabling Intermodal Travel Behaviour,” *Technological Forecasting and Social Change*, vol. 89, pp. 222–235, Nov. 2014. 41

[73] N. Dahlbäck, A. Jönsson, and L. Ahrenberg, “Wizard of Oz Studies – Why and How,” *Knowledge-Based Systems*, vol. 6, no. 4, pp. 258–266, 1993. 148

[74] M. J. Daley and W. L. Spinks, “Exercise, Mobility and Aging,” *Sports Medicine*, vol. 29, no. 1, pp. 1–12, Sep. 2012. 2

[75] T. C. Davies, S. D. Pinder, G. Dodd, and C. M. Burns, “Where Did That Sound Come From? Comparing the Ability to Localise Using Audification and Audition,” *Disability and Rehabilitation: Assistive Technology*, vol. 7, no. 2, pp. 130–138, 2012. 19

[76] C. de Fabritiis, R. Ragona, and G. Valenti, "Traffic Estimation and Prediction Based on Real Time Floating Car Data," in *Proceedings of the 11th International Conference on Intelligent Transportation Systems*, ser. ITS '08. IEEE, Oct. 2008, pp. 197–203. 24

[77] B. de Jonge and R. H. Teunter, "Optimizing Itineraries in Public Transportation with Walks between Rides," *Transportation Research Part B: Methodological*, vol. 55, pp. 212–226, Sep. 2013. 82

[78] S. Deterding, D. Dixon, R. Khaled, and L. Nacke, "From Game Design Elements to Gamefulness: Defining "Gamification"," in *Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments*, ser. MindTrek '11, Sep. 2011, pp. 9–15. 28

[79] F. F. Dias, P. S. Lavieri, V. M. Garikapati, S. Astroza, R. M. Pendyala, and C. R. Bhat, "A Behavioral Choice Model of the Use of Car-Sharing and Ride-Sourcing Services," *Transportation*, vol. 44, no. 6, pp. 1307–1323, Jul. 2017. 52

[80] O. Dib, M.-A. Manier, L. Moalic, and A. Caminada, "A Multimodal Transport Network Model and Efficient Algorithms for Building Advanced Traveler Information Systems," *Transportation Research Procedia*, vol. 22, pp. 134–143, 2017. 23

[81] J. Dibbelt, T. Pajor, and D. Wagner, "User-Constrained Multimodal Route Planning," *Journal of Experimental Algorithmics*, vol. 19, pp. 3.2:1–3.2:19, Apr. 2015. 24, 81

[82] B. E. Dicianno, B. Parmanto, A. D. Fairman, T. M. Crytzer, D. X. Yu, G. Pramana, D. Coughenour, and A. A. Petrazzi, "Perspectives on the Evolution of Mobile (mHealth) Technologies and Application to Rehabilitation," *Physical Therapy*, vol. 95, no. 3, pp. 397–405, Mar. 2015. 21

[83] J. E. Dickinson, K. Ghali, T. Cherrett, C. Speed, N. Davies, and S. Norgate, "Tourism and the Smartphone App: Capabilities, Emerging Practice and Scope in the Travel Domain," *Current Issues in Tourism*, vol. 17, no. 1, pp. 84–101, 2014. 23

[84] S. Diewald, A. Möller, L. Roalter, and M. Kranz, "Mobile Device Integration and Interaction in the Automotive Domain," in *AutoNUI: Automotive Natural User Interfaces Workshop at the 3rd International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI '11, Nov.–Dec. 2011. 130, 195

[85] S. Diewald, T. Leinmüller, B. Atanassow, L.-P. Breyer, and M. Kranz, "Mobile Device Integration and Interaction with V2X Communication," in *Proceedings of the 19th World Congress on Intelligent Transport Systems*, ser. ITS WC '12, Oct. 2012, pp. 411:1–411:8. 195

[86] S. Diewald, A. Möller, L. Roalter, and M. Kranz, "DriveAssist – A V2X-Based Driver Assistance System for Android," in *Mensch & Computer 2012 – Workshopband: interaktiv informiert – allgegenwärtig und allumfassend!? Konstanz, Germany,*. Oldenbourg Verlag, Sep. 2012, pp. 373–380. 130, 193, 194

[87] S. Diewald, A. Möller, L. Roalter, and M. Kranz, "MobiliNet: A Social Network for Optimized Mobility," in *Adjunct Proceedings of the 4th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI '12, Oct. 2012, pp. 145–150. 63, 155, 193

[88] ——, "Gamification-Supported Exploration of Natural User Interfaces," in *Adjunct Proceedings of the 4th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI '12, Oct. 2012, pp. 47–48. 97, 196

[89] S. Diewald, B. Atanassow, T. Leinmüller, L.-P. Breyer, and M. Kranz, "Key Findings from

the Development of a V2X Data Visualization Solution," in *Proceedings of the 20th World Congress on Intelligent Transport Systems*, ser. ITS WC '13, Oct. 2013, pp. 2069:1–2069:10. 130, 195

[90] S. Diewald, A. Möller, L. Roalter, T. Stockinger, and M. Kranz, "Gameful Design in the Automotive Domain: Review, Outlook and Challenges," in *Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI '13. ACM, Oct. 2013, pp. 262–265. 28, 97, 193, 196

[91] S. Diewald, P. Lindemann, A. Möller, T. Stockinger, M. Koelle, and M. Kranz, "Gamified Training for Vehicular User Interfaces - Effects on Drivers' Behavior," in *Proceedings of the 3rd International Conference on Connected Vehicles & Expo*, ser. ICCVE '14. IEEE, Nov. 2014, pp. 246–253. 97, 196

[92] S. Diewald, A. Möller, L. Roalter, and M. Kranz, "Today, you walk! – When Physical Fitness Influences Trip Planning," in *Mensch & Computer 2014 – Tagungsband*. De Gruyter Oldenbourg, Sep. 2014, pp. 383–386. 74, 121

[93] S. Diewald, A. Möller, T. Stockinger, L. Roalter, M. Koelle, P. Lindemann, and M. Kranz, "Gamification-Supported Exploration and Practicing for Automotive User Interfaces and Vehicle Functions," in *Gamification in Education and Business*, T. Reiners and L. C. Wood, Eds. Springer, Nov. 2014, pp. 637–661. 28, 97, 196

[94] S. Diewald, B. Geilhof, M. Siegrist, M. Kranz, M. Heuberger, A. Winkler, D. Kurz, K. Wessig, and M. Halle, "Körperliche Fitness im Alter: Mobile Anwendungen für regelmäßiges und eigenständiges Training im Alltag," in *8. AAL-Kongress: Zukunft Lebensräume*. VDE-Verlag, Apr. 2015, pp. 72–77. 74, 193, 194, 195

[95] S. Diewald, B. Geilhof, M. Siegrist, P. Lindemann, M. Koelle, M. Halle, and M. Kranz, "Mobile AgeCI: Potential Challenges in the Development and Evaluation of Mobile Applications for Elderly People," in *Computer Aided Systems Theory – EUROCAST 2015*. Springer International Publishing, Apr. 2015, pp. 723–730. 120

[96] S. Diewald, M. Koelle, T. Stockinger, P. Lindemann, and M. Kranz, "Mobile AgeCI: Insights from the Development of a Mobile Training Application for Elderly Users," in *Proceedings of the 15th International Conference on Computer Aided Systems Theory*, ser. Eurocast '15. Universidad de Las Palmas de Gran Canaria, Feb. 2015, pp. 233–234. 97, 120, 193, 194, 196

[97] C. Digmayer, S. Vogelsang, and E.-M. Jakobs, "Designing Mobility Apps to Support Intermodal Travel Chains," in *Proceedings of the 33rd Annual International Conference on the Design of Communication*, ser. SIGDOC '15. ACM, 2015, pp. 44:1–44:11. 36, 38, 192

[98] C. Dijksterhuis, K. A. Brookhuis, and D. D. Waard, "Effects of Steering Demand on Lane Keeping Behaviour, Self-Reports, and Physiology. A Simulator Study," *Accident Analysis & Prevention*, vol. 43, no. 3, pp. 1074–1081, May 2011. 25

[99] M. W. M. G. Dissanayake, P. Newman, S. Clark, H. F. Durrant-Whyte, and M. Csorba, "A Solution to the Simultaneous Localization and Map Building (SLAM) Problem," *IEEE Transactions on Robotics and Automation*, vol. 17, no. 3, pp. 229–241, Jun. 2001. 56

[100] A. Dix, *Human–Computer Interaction*. Pearson/Prentice-Hall, 2003. 30

[101] A. Domínguez, J. S. de Navarrete, L. de Marcos, L. Fernández-Sanz, C. Pagés, and J.-J. Martínez-Herráiz, "Gamifying Learning Experiences: Practical Implications and Outcomes," *Computers & Education*, vol. 63, no. 1, pp. 380–392, 2013. 100

[102] S. Dotenco, T. Götzelmann, and F. Gallwitz, *Smartphone Input Using Its Integrated Projector and Built-In Camera*. Springer International Publishing, 2014, pp. 124–133. 19

[103] F. Dressler, H. Hartenstein, O. Altintas, and O. Tonguz, “Inter-Vehicle Communication: Quo Vadis,” *IEEE Communications Magazine*, vol. 52, no. 6, pp. 170–177, Jun. 2014. 25

[104] O. J. Dunn, “Multiple Comparisons Among Means,” *Journal of the American Statistical Association*, vol. 56, no. 293, pp. 52–64, Mar. 1961. 168

[105] E. Duval, “Attention Please!: Learning Analytics for Visualization and Recommendation,” in *Proceedings of the 1st International Conference on Learning Analytics and Knowledge*, ser. LAK ’11. ACM, 2011, pp. 9–17. 23

[106] D. Eckhoff, B. Halmos, and R. German, “Potentials and Limitations of Green Light Optimal Speed Advisory Systems,” in *Proceedings of the IEEE Vehicular Networking Conference*, ser. VNC ’13. IEEE, Dec. 2013, pp. 103–110. 185

[107] J. F. Ehmke, D. C. Mattfeld, and L. Albrecht, “Combining Mobility Services by Customer-Induced Orchestration,” in *Proceedings of the ACM Workshop on Recommenders in Tourism*, ser. RecSys ’16, Sep. 2016, pp. 51–54. 24, 26, 70

[108] G. Elia, M. Bargis, M. P. Galante, N. P. Magnani, L. Santilli, G. Romano, and G. Zaffiro, “Connected Transports, V2X and 5G: Standard, Services and the TIM-Telecom Italia Experiences,” in *Proceedings of the AEIT International Conference of Electrical and Electronic Technologies for Automotive*, ser. AUTOMOTIVE ’19. IEEE, Jul. 2019, pp. 12–15. 129

[109] R. B. Ellison, A. B. Ellison, S. P. Greaves, and B. Sampaio, “Electronic Ticketing Systems as a Mechanism for Travel Behaviour Change? Evidence from Sydney’s Opal Card,” *Transportation Research Part A: Policy and Practice*, vol. 99, pp. 80–93, May 2017. 54

[110] M. Endlein, S. Trede, and P. Letzner-Friedlein, “DAT-Report 2014,” DAT Group, Tech. Rep. 40, Feb. 2014. 108

[111] T. Erickson, “From PIM to GIM: Personal Information Management in Group Contexts,” *Communications of the ACM*, vol. 49, no. 1, pp. 74–75, Jan. 2006. 22

[112] A. Esteva, B. Kuprel, R. A. Novoa, J. Ko, S. M. Swetter, H. M. Blau, and S. Thrun, “Dermatologist-Level Classification of Skin Cancer with Deep Neural Networks,” *Nature*, vol. 542, pp. 115–118, Feb. 2017. 21

[113] ETSI TS 102 636-4-1, “Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 4: Geographical Addressing and Forwarding for Point-to-Point and Point-to-Multipoint Communications; Sub-Part 1: Media-Independent Functionality,” European Telecommunications Standards Institute, Tech. Rep. V1.1.1, Jun. 2011. 140

[114] ETSI TS 102 636-5-1, “Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 5: Transport Protocols; Sub-Part 1: Basic Transport Protocol,” European Telecommunications Standards Institute, Tech. Rep. V1.1.1, Feb. 2011. 140

[115] ETSI TS 102 637-2, “Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service,” European Telecommunications Standards Institute, Tech. Rep. V1.2.1, Mar. 2011. 137, 140, 147

[116] ETSI TS 102 637-3, “Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service,” European Telecommunications Standards Institute, Tech. Rep. V1.1.1, Sep. 2010. 137, 147

[117] European Commission, “Intermodality and Intermodal Freight Transport in the European

Union," Communication from the Commission to the European Parliament and Council, Oct. 1997. 13

[118] J. R. Evans and A. Mathur, "The Value of Online Surveys," *Internet Research*, vol. 15, no. 2, pp. 195–219, Apr. 2005. 31

[119] M. C. Falvo, D. Sbordone, I. S. Bayram, and M. Devetsikiotis, "EV Charging Stations and Modes: International Standards," in *International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, ser. SPEEDAM '14. IEEE, Jun. 2014, pp. 1134–1139. 40

[120] R. S. Fenchel, "An Integral Approach to User Assistance," in *Proceedings of the Joint Conference on Easier and More Productive Use of Computer Systems. (Part - II): Human Interface and the User Interface - Volume 1981*, ser. CHI '81. ACM, 1981, pp. 98–104. 15

[121] J. Feng, S. Bangalore, and M. Rahim, "WebTalk: Mining Websites for Automatically Building Dialog Systems," in *Proceedings of the Workshop on Automatic Speech Recognition and Understanding*, ser. ASRU '03. IEEE, Nov. 2003, pp. 168–173. 17

[122] B. Ferris, K. Watkins, and A. Borning, "OneBusAway: Results from Providing Real-Time Arrival Information for Public Transit," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '10. ACM, Apr. 2010, pp. 1807–1816. 53, 54

[123] L. Fletcher, G. Loy, N. Barnes, and A. Zelinsky, "Correlating Driver Gaze with the Road Scene for Driver Assistance Systems," *Robotics and Autonomous Systems*, vol. 52, no. 1, pp. 71–84, 2005. 18

[124] D. Fodness and B. Murray, "A Model of Tourist Information Search Behavior," *Journal of Travel Research*, vol. 37, no. 3, pp. 220–230, Feb. 1999. 55

[125] B. J. Fogg, "Persuasive Technology," *Ubiquity*, vol. 2002, p. 2, Dec. 2002. 29

[126] B. J. Fogg and H. Tseng, "The Elements of Computer Credibility," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '99. ACM, May 1999, pp. 80–88. 29

[127] D. Förster, F. Kargl, and H. Löhr, "PUCA: A Pseudonym Scheme with Strong Privacy Guarantees for Vehicular Ad-Hoc Networks," *Ad-Hoc Networks*, vol. 37, pp. 122–132, Feb. 2016. 155

[128] L. Frändberg and B. Vilhelmson, "More or Less Travel: Personal Mobility Trends in the Swedish Population Focusing Gender and Cohort," *Journal of Transport Geography*, vol. 19, no. 6, pp. 1235–1244, Nov. 2011. 188

[129] M. Friedman, "The Use of Ranks to Avoid the Assumption of Normality Implicit in the Analysis of Variance," *Journal of the American Statistical Association*, vol. 32, no. 200, pp. 675–701, Dec. 1937. xv, 168

[130] J. L. Gabbard, D. Hix, and J. E. Swan, "User-Centered Design and Evaluation of Virtual Environments," *IEEE Computer Graphics and Applications*, vol. 19, no. 6, pp. 51–59, Nov. 1999. 31

[131] B. Gardner and C. Abraham, "What Drives Car Use? A Grounded Theory Analysis of Commuters' Reasons for Driving," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 10, no. 3, pp. 187–200, May 2007. 45, 52

[132] T. Gärling, R. Gillholm, and A. Gärling, "Reintroducing Attitude Theory in Travel Behavior Research: The Validity of an Interactive Interview Procedure to Predict Car Use," *Transportation*, vol. 25, no. 2, pp. 129–146, May 1998. 53

[133] P. Garrido, F. J. Martinez, and C. Guetl, "Adding Semantic Web Knowledge to Intelligent Personal Assistant Agents," in *Proceedings of the 9th International Semantic Web Conference*, ser. ISWC '10, P. Cudre-Mauroux and B. Parsia, Eds., Nov. 2010, pp. 1–12. 17

[134] S. Garzonis, S. Jones, T. Jay, and E. O'Neill, "Auditory Icon and Earcon Mobile Service Notifications: Intuitiveness, Learnability, Memorability and Preference," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '09. ACM, Apr. 2009, pp. 1513–1522. 19

[135] D. Gavalas, C. Konstantopoulos, K. Mastakas, and G. Pantziou, "Mobile Recommender Systems in Tourism," *Journal of Network and Computer Applications*, vol. 39, pp. 319–333, Mar. 2014. 16

[136] L. Gebhardt, D. Krajzewicz, R. Oostendorp, M. Goletz, K. Greger, M. Klötzke, P. Wagner, and D. Heinrichs, "Intermodal Urban Mobility: Users, Uses, and Use Cases," *Transportation Research Procedia*, vol. 14, pp. 1183–1192, Apr. 2016. 35, 37, 51

[137] G. Giannakakis, M. Pediaditis, D. Manousos, E. Kazantzaki, F. Chiarugi, P. G. Simos, K. Marias, and M. Tsiknakis, "Stress and Anxiety Detection Using Facial Cues from Videos," *Biomedical Signal Processing and Control*, vol. 31, pp. 89–101, Jan. 2017. 56

[138] J. Gish, B. Vrkljan, A. Grenier, and B. V. Miltenburg, "Driving with Advanced Vehicle Technology: A Qualitative Investigation of Older Drivers' Perceptions and Motivations for Use," *Accident Analysis & Prevention*, vol. 106, pp. 498–504, Sep. 2017. 53

[139] A. R. Goetz and T. M. Vowles, "Progress in Intermodal Passenger Transportation: Private Sector Initiatives," Department of Geography and Intermodal Transportation Institute, University of Denver, Project report, Sep. 2001. 13

[140] U. Gretzel, Y.-H. Hwang, and D. R. Fesenmaier, "Informing Destination Recommender Systems Design and Evaluation through Quantitative Research," *International Journal of Culture, Tourism and Hospitality Research*, vol. 6, no. 4, pp. 297–315, Oct. 2012. 55

[141] J.-W. Grotenhuis, B. W. Wiegmans, and P. Rietveld, "The Desired Quality of Integrated Multimodal Travel Information in Public Transport: Customer Needs for Time and Effort Savings," *Transport Policy*, vol. 14, no. 1, pp. 27–38, Jan. 2007. 53, 55

[142] G. Guest, A. Bunce, and L. Johnson, "How Many Interviews Are Enough?" *Field Methods*, vol. 18, no. 1, pp. 59–82, Feb. 2006. 176

[143] J. M. Guralnik, E. M. Simonsick, L. Ferrucci, R. J. Glynn, L. F. Berkman, D. G. Blazer, P. A. Scherr, and R. B. Wallace, "A Short Physical Performance Battery Assessing Lower Extremity Function," *Journal of Gerontology*, vol. 49, no. 2, pp. 85–94, Mar. 1994. 122

[144] T. A. Gurman, S. E. Rubin, and A. A. Roess, "Effectiveness of mHealth Behavior Change Communication Interventions in Developing Countries: A Systematic Review of the Literature," *Journal of Health Communication*, vol. 17, no. 1, pp. 82–104, May 2012. 21

[145] L. A. Guzman and D. Oviedo, "Accessibility, Affordability and Equity: Assessing 'Pro-Poor' Public Transport Subsidies in Bogotá," *Transport Policy*, vol. 68, pp. 37–51, Sep. 2018. 45

[146] C. L. Hafer, K. L. Reynolds, and M. A. Obertynski, "Message Comprehensibility and Persuasion: Effects of Complex Language in Counterattitudinal Appeals to Laypeople," *Social Cognition*, vol. 14, no. 4, pp. 317–337, Dec. 1996. 16

[147] M. Haklay and P. Weber, "OpenStreetMap: User-Generated Street Maps," *Pervasive Computing*, vol. 7, no. 4, pp. 12–18, Oct.–Nov. 2008. 81

[148] S. D. Halpern, P. A. Ubel, and D. A. Asch, "Harnessing the Power of Default Options to

Improve Health Care," *New England Journal of Medicine*, vol. 357, no. 13, pp. 1340–1344, Sep. 2007. 180

[149] S. Hamine, E. Gerth-Guyette, D. Faulx, B. B. Green, and A. S. Ginsburg, "Impact of mHealth Chronic Disease Management on Treatment Adherence and Patient Outcomes: A Systematic Review," *Journal of Medical Internet Research*, vol. 17, no. 2, pp. 1–10, Feb. 2015. 21

[150] M. D. Hanus and J. Fox, "Assessing the Effects of Gamification in the Classroom: A Longitudinal Study on Intrinsic Motivation, Social Comparison, Satisfaction, Effort, and Academic Performance," *Computers & Education*, vol. 80, pp. 152–161, Jan. 2015. 182

[151] J. L. Harbluk, P. C. Burns, M. Lochner, and P. L. Trbovich, "Using the Lane-Change Test (LCT) to Assess Distraction: Tests of Visual-Manual and Speech-Based operation of Navigation System Interfaces," in *Proceedings of the 4th International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*. University of Iowa, Jul. 2007, pp. 16–22. 102

[152] S. Harding, M. Kandlikar, and S. Gulati, "Taxi Apps, Regulation, and the Market for Taxi Journeys," *Transportation Research Part A: Policy and Practice*, vol. 88, pp. 15–25, Jun. 2016. 40

[153] S. G. Hart and L. E. Staveland, "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research," in *Advances in Psychology*. Elsevier BV, 1988, vol. 52, pp. 139–183. 103, 115

[154] G. Häubl and V. Trifts, "Consumer Decision Making in Online Shopping Environments: The Effects of Interactive Decision Aids," *Marketing Science*, vol. 19, no. 1, pp. 4–21, Feb. 2000. 16

[155] S. Haustein, "Mobility Behavior of the Elderly: An Attitude-Based Segmentation Approach for a Heterogeneous Target Group," *Transportation*, vol. 39, no. 6, pp. 1079–1103, Nov. 2011. 38, 39, 45

[156] S. Haustein and A. Siren, "Older People's Mobility: Segments, Factors, Trends," *Transport Reviews*, vol. 35, no. 4, pp. 466–487, Mar. 2015. 48

[157] G. Heidemann, I. Bax, and H. Bekel, "Multimodal Interaction in an Augmented Reality Scenario," in *Proceedings of the 6th International Conference on Multimodal Interfaces*, ser. ICMI '04. ACM, 2004, pp. 53–60. 20

[158] N. Henze, E. Rukzio, and S. Boll, "100,000,000 Taps," in *Proceedings of the 13th International Conference on Human–Computer Interaction with Mobile Devices and Services*, ser. MobileHCI '11. ACM, 2011, pp. 133–142. 124

[159] T. Hermann, "Taxonomy and Definitions for Sonification and Auditory Display," in *Proceedings of the 14th International Conference on Auditory Display*, ser. ICAD '08, P. Susini and O. Warusfel, Eds. IRCAM, 2008, pp. 8:1–8:8. 19

[160] P. Hertzog and M. Torrens, "Context-Aware Mobile Assistants for Optimal Interaction," in *Proceedings of the 9th International Conference on Intelligent User Interface*, ser. IUI '04. ACM, Jan. 2004, pp. 256–258. 192

[161] E. L. Hillsman and S. J. Barbeau, "Enabling Cost-Effective Multimodal Trip Planners through Open Transit Data," National Center for Transit Research, techreport, May 2011. 81

[162] A.-M. Hjalager and J. M. Jensen, "A Typology of Travelers Based on Their Propensity to Go Online Before, During and After the Trip," in *Information and Communication Technologies in Tourism*. Springer Vienna, 2012, pp. 96–107. 192

[163] C. Q. Ho, C. Mulley, and D. A. Hensher, "Public Preferences for Mobility as a Service: Insights from Stated Preference Surveys," *Transportation Research Part A: Policy and Practice*, pp. 1–16, Sep. 2019. 52

[164] L. Hobert, A. Festag, I. Llatser, L. Altomare, F. Visintainer, and A. Kovacs, "Enhancements of V2X Communication in Support of Cooperative Autonomous Driving," *IEEE Communications Magazine*, vol. 53, no. 12, pp. 64–70, Dec. 2015. 41

[165] B. Hofmann-Wellenhof, K. C. Legat, and M. Wieser, *Navigation – Principles of Positioning and Guidance*. Springer, 2003. 24

[166] E. Hoggan, S. A. Brewster, and J. Johnston, "Investigating the Effectiveness of Tactile Feedback for Mobile Touchscreens," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '08. ACM, Apr. 2008, pp. 1573–1582. 20

[167] E. Hoggan, A. Crossan, S. A. Brewster, and T. Kaaresoja, "Audio or Tactile Feedback: Which Modality When?" in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '09. ACM, Apr. 2009, pp. 2253–2256. 20

[168] J. H. Hollman, E. M. McDade, and R. C. Petersen, "Normative Spatiotemporal Gait Parameters in Older Adults," *Gait & Posture*, vol. 34, no. 1, pp. 111–118, May 2011. 84, 85

[169] R. C. Houghton, Jr., "Online Help Systems: A Conspectus," *Communications of the ACM*, vol. 27, no. 2, pp. 126–133, Feb. 1984. 15

[170] H. Huang, S. Klettner, M. Schmidt, G. Gartner, S. Leitinger, A. Wagner, and R. Steinmann, "AffectRoute – Considering People's Affective Responses to Environments for Enhancing Route-Planning Services," *International Journal of Geographical Information Science*, vol. 28, no. 12, pp. 2456–2473, Jun. 2014. 24

[171] S. Y. R. Hui and W. C. Ho, "A New Generation of Universal Contactless Battery Charging Platform for Portable Consumer Electronic Equipment," in *Proceedings of the 34th Annual Power Electronics Specialists Conference*, ser. PESC '04. IEEE, Jun. 2004, pp. 638–644. 133

[172] H. Hwangbo, S. H. Yoon, B. S. Jin, Y. S. Han, and Y. G. Ji, "A Study of Pointing Performance of Elderly Users on Smartphones," *International Journal of Human-Computer Interaction*, vol. 29, no. 9, pp. 604–618, Jun. 2013. 123

[173] IEEE 802.11p-2010, "Local and Metropolitan Area Networks – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) – Amendment 6: Wireless Access in Vehicular Environments," 2010. 138, 139

[174] W. Ijsselsteijn, H. H. Nap, Y. de Kort, and K. Poels, "Digital Game Design for Elderly Users," in *Proceedings of the Conference on Future Play*, ser. FuturePlay '07. ACM, Nov. 2007, pp. 17–22. 120

[175] ISO 6346, "Freight Containers – Coding, Identification and Marking," Nov. 1995. 13

[176] ISO 9241-210, "Ergonomics of Human-System Interaction – Part 210: Human-Centred Design for Interactive Systems," Jul. 2019. 187

[177] Y. Jansen, T. Karrer, and J. Borchers, "MudPad: Tactile Feedback and Haptic Texture Overlay for Touch Surfaces," in *Proceedings of the International Conference on Interactive Tabletops and Surfaces*, ser. ITS '10. ACM, 2010, pp. 11–14. 20

[178] Y. Jia, B. Xu, Y. Karanam, and S. Voida, "Personality-Targeted Gamification: A Survey Study on Personality Traits and Motivational Affordances," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '16. ACM, Apr. 2016, pp. 2001–2013.

118

[179] P. Jittrapirom, V. Caiati, A.-M. Feneri, S. Ebrahimigharehbaghi, M. J. A. González, and J. Narayan, “Mobility as a Service: A Critical Review of Definitions, Assessments of Schemes, and Key Challenges,” *Urban Planning*, vol. 2, no. 2, pp. 13–25, Jun. 2017. 63

[180] W. Jones, “Personal Information Management,” *Annual Review of Information Science and Technology*, vol. 41, no. 1, pp. 453–504, 2007. 21

[181] B. Jonsson, H. Stenlund, M. Y. Svensson, and U. Björnstig, “Seat Adjustment – Capacity and Repeatability Among Occupants in a Modern Car,” *Ergonomics*, vol. 51, no. 2, pp. 232–241, 2008. 98

[182] H. Jonuschat, K. Stephan, and M. Schelewsky, “Understanding Multimodal and Intermodal Mobility,” in *Sustainable Urban Transport*. Emerald Group Publishing Limited, May 2015, vol. 7, pp. 149–176. 52

[183] M. S. Joseph, “Helping Users Help Themselves,” in *Proceedings of the 8th Annual Conference on User Services*, ser. SIGUCCS ’80. ACM, 1980, pp. 108–110. 15

[184] H. Jula, E. B. Kosmatopoulos, and P. A. Ioannou, “Collision Avoidance Analysis for Lane Changing and Merging,” *IEEE Transactions on Vehicular Technology*, vol. 49, no. 6, pp. 229–2308, Nov. 2000. 25

[185] S. Jumisko-Pyykkö and T. Vainio, “Framing the Context of Use for Mobile HCI,” *International Journal of Mobile Human Computer Interaction*, vol. 2, no. 4, pp. 1–28, Oct. 2010. 55

[186] M. H. Jung, H. Perfecto, and L. D. Nelson, “Anchoring in Payment: Evaluating a Judgmental Heuristic in Field Experimental Settings,” *Journal of Marketing Research*, vol. 53, no. 3, pp. 354–368, Jun. 2016. 28

[187] E. Kaiser, A. Olwal, D. McGee, H. Benko, A. Corradini, X. Li, P. Cohen, and S. Feiner, “Mutual Disambiguation of 3D Multimodal Interaction in Augmented and Virtual Reality,” in *Proceedings of the 5th International Conference on Multimodal Interfaces*, ser. ICMI ’03. ACM, 2003, pp. 12–19. 20

[188] M. Kamargianni, W. Li, M. Matyas, and A. Schäfer, “A Critical Review of New Mobility Services for Urban Transport,” *Transportation Research Procedia*, vol. 14, pp. 3294–3303, Apr. 2016. 63

[189] A. K. Karlson, A. J. B. Brush, and S. Schechter, “Can I Borrow Your Phone?: Understanding Concerns when Sharing Mobile Phones,” in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI ’09. ACM, Apr. 2009, pp. 1647–1650. 12

[190] B. Kaufmann and D. Ahlström, “Studying Spatial Memory and Map Navigation Performance on Projector Phones with Peephole Interaction,” in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI ’13. ACM, Apr. 2013, pp. 3173–3176. 19

[191] F. Kawsar and A. J. B. Brush, “Home Computing Unplugged: Why, Where and when People Use Different Connected Devices at Home,” in *Proceedings of the International Joint Conference on Pervasive and Ubiquitous Computing*, ser. UbiComp ’13. ACM, 2013, pp. 627–636. 12

[192] D. Kern and A. Schmidt, “Design Space for Driver-Based Automotive User Interfaces,” in *Proceedings of the 1st International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI ’09, Sep. 2009, pp. 3–10. 97, 134, 147

[193] F. Khatib, S. Cooper, M. D. Tyka, K. Xu, I. Makedon, Z. Popović, D. Baker, and F. Players, “Algorithm Discovery by Protein Folding Game Players,” *Proceedings of the National Academy*

of Sciences, vol. 108, no. 47, pp. 18 949–18 953, 2011. 28

[194] H.-W. Kim, A. Kankanhalli, and H.-L. Lee, "Investigating Decision Factors in Mobile Application Purchase: A Mixed-Methods Approach," *Information & Management*, vol. 53, no. 6, pp. 727–739, Sep. 2016. 180

[195] H. Kim, Z. Xiang, and D. R. Fesenmaier, "Use of The Internet for Trip Planning: A Generational Analysis," *Journal of Travel & Tourism Marketing*, vol. 32, no. 3, pp. 276–289, Apr. 2015. 24

[196] R. Klimoski and S. Mohammed, "Team Mental Model: Construct or Metaphor?" *Journal of Management*, vol. 20, no. 2, pp. 403–437, Apr. 1994. 109

[197] C. Koch and I. Brilakis, "Pothole Detection in Asphalt Pavement Images," *Advanced Engineering Informatics*, vol. 25, no. 3, pp. 507–515, Aug. 2011. 57

[198] A. E. Kohlhase and M. Kohlhase, "Modeling Task Experience in User Assistance Systems," in *Proceedings of the 27th International Conference on Design of Communication*, ser. SIGDOC '09. ACM, 2009, pp. 135–142. 16

[199] I. Kononenko, "Machine Learning for Medical Diagnosis: History, State of the Art and Perspective," *Artificial Intelligence in Medicine*, vol. 23, no. 1, pp. 89–109, Aug. 2001. 21

[200] P. Konstantopoulos, P. Chapman, and D. Crundall, "Driver's Visual Attention as a Function of Driving Experience and Visibility. Using a Driving Simulator to Explore Drivers' Eye Movements in Day, Night and Rain Driving," *Accident Analysis & Prevention*, vol. 42, no. 3, pp. 827–834, May 2010. 153

[201] E. Koukoumidis, L.-S. Peh, and M. R. Martonosi, "SignalGuru: Leveraging Mobile Phones for Collaborative Traffic Signal Schedule Advisory," in *Proceedings of the 9th International Conference on Mobile Systems, Applications, and Services*, ser. MobiSys '11. ACM, 2011, pp. 127–140. 164

[202] KPMG, "Global Automotive Executive Survey 2016: From a Product-Centric World to a Service-Driven Digital Universe," KPMG International, Tech. Rep. 17, Jan. 2016. 2, 3

[203] M. Kranz, A. Franz, M. Röckl, L. Andreas, and T. Strang, "CODAR Viewer – A Situation-Aware Driver Assistance System," in *Pervasive 2008 Demonstration*, ser. Advances in Pervasive Computing, vol. 236. Austrian Computer Society, May 2008, pp. 126–129. 134

[204] M. Kranz, E. Weber, K. Frank, and D. H. Galceran, "Open Vehicular Data Interfaces for In-Car Context Inference," in *Proceedings of the 1st International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI '09. ACM, Sep. 2009, pp. 57–62. 134

[205] M. Kranz, C. Fischer, and A. Schmidt, "A Comparative Study of DECT and WLAN Signals for Indoor Localization," in *Proceedings of the 8th Conference on Pervasive Computing and Communications*, ser. PerCom '10. IEEE, Mar. 2010, pp. 235–243. 3, 69

[206] M. Kranz, A. Schmidt, and P. Holleis, "Embedded Interaction: Interacting with the Internet of Things," *IEEE Internet Computing*, vol. 14, no. 2, pp. 46–53, Mar. 2010. 63

[207] S. Kratz and M. Rohs, "HoverFlow: Expanding the Design Space of Around-Device Interaction," in *Proceedings of the 11th International Conference on Human–Computer Interaction with Mobile Devices and Services*, ser. MobileHCI '09. ACM, Sep. 2009, pp. 4:1–4:8. 19

[208] M. Krause, V. Knott, and K. Bengler, "Traffic Light Assistant – Can Take My Eyes Off of You," *Proceedings of the Human Factors and Ergonomics Society Europe Chapter Annual Conference*, pp. 132–148, Oct. 2013. 163, 165

[209] C. Krehl, S. Sharples, and M. Flintham, “Less is More: Classifying Mobile Interactions to Support Context Sensing in Journeys,” in *Proceedings of the 27th International BCS Human Computer Interaction Conference*, ser. BCS-HCI ’13. British Computer Society, 2013, pp. 8:1–8:10. 55

[210] S. Kumar and C. M. Jagacinski, “Confronting Task Difficulty in Ego Involvement: Change in Performance Goals,” *Journal of Educational Psychology*, vol. 103, no. 3, pp. 664–682, 2011. 99

[211] K. D. Kusano and H. C. Gabler, “Safety Benefits of Forward Collision Warning, Brake Assist, and Autonomous Braking Systems in Rear-End Collisions,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 13, no. 4, pp. 1546–1555, Dec. 2012. 25

[212] B. Lamche, U. Trottmann, and W. Wörndl, “Active Learning Strategies for Exploratory Mobile Recommender Systems,” in *Proceedings of the 4th Workshop on Context-Awareness in Retrieval and Recommendation*, ser. CARR ’14. ACM, 2014, pp. 10–17. 22

[213] C. Lamsfus, D. Wang, A. Alzua-Sorzabal, and Z. Xiang, “Going Mobile: Defining Context for On-the-Go Travelers,” *Journal of Travel Research*, vol. 54, no. 6, pp. 691–701, 2015. 55

[214] T. C. Lansdown, N. Brook-Carter, and T. Kersloot, “Distraction from Multiple In-Vehicle Secondary Tasks: Vehicle Performance and Mental Workload Implications,” *Ergonomics*, vol. 47, no. 1, pp. 91–104, 2004. 98

[215] I. Lavery, S. Davey, A. Woodside, and K. Ewart, “The Vital Role of Street Design and Management in Reducing Barriers to Older Peoples’ Mobility,” *Landscape and Urban Planning*, vol. 35, no. 2-3, pp. 181–192, Aug. 1996. 42

[216] G. C. Le-Masurier, C. L. Sidman, and C. B. Corbin, “Accumulating 10,000 Steps: Does this Meet Current Physical Activity Guidelines?” *Research Quarterly for Exercise and Sport*, vol. 74, no. 4, pp. 389–394, 2003. 80

[217] J. LeClerc and S. Joslyn, “The Cry Wolf Effect and Weather-Related Decision Making,” *Risk Analysis*, vol. 35, no. 3, pp. 385–395, Jan. 2015. 94

[218] J. D. Lee and K. A. See, “Trust in Automation: Designing for Appropriate Reliance,” *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 46, no. 1, pp. 50–80, Jan. 2004. 186

[219] J. Lee and N. Moray, “Trust, Control Strategies and Allocation of Function in Human–Machine Systems,” *Ergonomics*, vol. 35, no. 10, pp. 1243–1270, Oct. 1992. 186

[220] P. Lee, D. Stewart, and J. Barker, “The Smartphone Generation Gap: Over-55? There’s No App for That,” in *Technology, Media & Telecommunications Predictions 2014*, ser. TMT. Deloitte, Jan. 2014, pp. 42–44. 119

[221] S. Lee and S. Zhai, “The Performance of Touch Screen Soft Buttons,” in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI ’09. ACM, Apr. 2009, pp. 309–318. 19

[222] M. N. Lees and J. D. Lee, “The Influence of Distraction and Driving Context on Driver Response to Imperfect Collision Warning Systems,” *Ergonomics*, vol. 50, no. 8, pp. 1264–1286, Aug. 2007. 185

[223] S. Lefevre, J. Petit, R. Bajcsy, C. Laugier, and F. Kargl, “Impact of V2X Privacy Strategies on Intersection Collision Avoidance Systems,” in *Proceedings of the Vehicular Networking Conference*, ser. VNC ’13. IEEE, Dec. 2013, pp. 1–8. 155

[224] T. Leinmüller, E. Schoch, and C. Maihofer, “Security Requirements and Solution Concepts

in Vehicular Ad hoc Networks," in *Fourth Annual Conference on Wireless on Demand Network Systems and Services*, ser. WONS '07, Jan. 2007, pp. 84–91. 155

[225] J. Leino, S. Finnberg, and K.-J. Räihä, "The Times They Are A-Changin': Mobile PIM is Leaving the Paper Trail Behind," in *Proceedings of the 24th BCS Interaction Specialist Group Conference*, ser. BCS '10. British Computer Society, 2010, pp. 259–268. 22

[226] J. Letchner, J. Krumm, and E. Horvitz, "Trip Router with Individualized Preferences (TRIP): Incorporating Personalization into Route Planning," in *Proceedings of the 18th Conference on Innovative Applications of Artificial Intelligence - Volume 2*, ser. IAAI '06. AAAI Press, 2006, pp. 1795–1800. 24

[227] Q. Li and C. E. Kurt, "GIS-Based Itinerary Planning System for Multimodal and Fixed-Route Transit Network," in *Proceedings of the Transportation Symposium*. Iowa State University, 2000, pp. 47–50. 24

[228] W. Li, T. Grossman, and G. Fitzmaurice, "GamiCAD: A Gamified Tutorial System for First Time AutoCAD Users," in *Proceedings of the 25th Annual Symposium on User Interface Software and Technology*, ser. UIST '12. ACM, Oct. 2012, pp. 103–112. 26

[229] S.-H. Liao, "Expert System Methodologies and Applications – A Decade Review from 1995 to 2004," *Expert Systems with Applications*, vol. 28, no. 1, pp. 93–103, Jan. 2005. 17

[230] H. Lieberman and T. Selker, "Out of Context: Computer Systems That Adapt To, and Learn From, Context," *IBM Systems Journal*, vol. 39, no. 3 & 4, pp. 617–632, Nov. 2000. 17

[231] T. Liebig, N. Piatkowski, C. Bockermann, and K. Morik, "Dynamic Route Planning with Real-Time Traffic Predictions," *Information Systems*, vol. 64, pp. 258–265, Mar. 2017. 25

[232] S. L. Lim, P. J. Bentley, N. Kanakam, F. Ishikawa, and S. Honiden, "Investigating Country Differences in Mobile App User Behavior and Challenges for Software Engineering," *IEEE Transactions on Software Engineering*, vol. 41, no. 1, pp. 40–64, Jan. 2015. 180

[233] T. Lin, H. Rivano, and F. L. Mouel, "A Survey of Smart Parking Solutions," *IEEE Transactions on Intelligent Transportation Systems*, vol. 18, no. 12, pp. 3229–3253, Dec. 2017. 56

[234] W. H. Ling and W. C. Seng, "Traffic Sign Recognition Model on Mobile Device," in *Proceedings of the IEEE Symposium on Computers Informatics*, Mar. 2011, pp. 267–272. 26

[235] T. Litman, *Keep Moving, Towards Sustainable Mobility*. Eleven International Publishing, 2012, ch. Current Mobility Trends – Implications for Sustainability, pp. 23–44. 2, 52

[236] A. L. Liu, H. Hile, H. Kautz, G. Borriello, P. A. Brown, M. Harniss, and K. Johnson, "Indoor Wayfinding: Developing a Functional Interface for Individuals with Cognitive Impairments," *Disability and Rehabilitation: Assistive Technology*, vol. 3, no. 1-2, pp. 69–81, 2008. 25

[237] B. Liu, M. S. Andersen, F. Schaub, H. Almuhimedi, S. Zhang, N. Sadeh, A. Acquisti, and Y. Agarwal, "Follow My Recommendations: A Personalized Privacy Assistant for Mobile App Permissions," in *Proceedings of the Twelfth USENIX Conference on Usable Privacy and Security*, ser. SOUPS '16. USENIX Association, 2016, pp. 27–41. 93

[238] H. H. Liu, "Assessment of Rolling Walkers Used by Older Adults in Senior-Living Communities," *Geriatrics & Gerontology International*, vol. 9, no. 2, pp. 124–130, Jun. 2009. 181

[239] L. Liu, E. Stroulia, I. Nikolaidis, A. Miguel-Cruz, and A. R. Rincon, "Smart Homes and Home Health Monitoring Technologies for Older Adults: A Systematic Review," *International Journal of Medical Informatics*, vol. 91, pp. 44–59, Jul. 2016. 56

[240] R. B. Lopes, T. Coelho, and B. S. Santos, “Visually Supporting Location and Routing Decisions in Tourist Trip Planning: An Exploratory Approach,” in *Proceedings of the 20th International Conference on Information Visualisation*, ser. IV ’16, Jul. 2016, pp. 236–241. 23

[241] C. M. Lowry, M. D. Kostka-Rokosz, and W. W. McCloskey, “Evaluation of Personal Digital Assistant Drug Information Databases for the Managed Care Pharmacist,” *Journal of Managed Care Pharmacy*, vol. 9, no. 5, pp. 441–448, Sep. 2003. 21

[242] X. Lu, C. Wang, J.-M. Yang, Y. Pang, and L. Zhang, “Photo2Trip: Generating Travel Routes from Geo-Tagged Photos for Trip Planning,” in *Proceedings of the 18th International Conference on Multimedia*, ser. MM ’10. ACM, Oct. 2010, pp. 143–152. 24

[243] K. Lunze and M. K. Paasche-Orlow, “Financial Incentives for Healthy Behavior,” *American Journal of Preventive Medicine*, vol. 44, no. 6, pp. 659–665, Jun. 2013. 180

[244] M. M. Lusardi, G. L. Pellecchia, and M. Schulman, “Functional Performance in Community Living Older Adults,” *Journal of Geriatric Physical Therapy*, vol. 26, no. 3, pp. 14–22, Dec. 2003. 122

[245] J. A. MacDonald, P. P. Henry, and T. R. Letowski, “Spatial Audio Through a Bone Conduction Interface,” *International Journal of Audiology*, vol. 45, no. 10, pp. 595–599, Jul. 2006. 19

[246] R. Macefield, “How to Specify the Participant Group Size for Usability Studies: A Practitioner’s Guide,” *Journal of Usability Studies*, vol. 5, no. 1, pp. 34–45, Nov. 2009. 33

[247] T. Mahatody, M. Sagar, and C. Kolski, “State of the Art on the Cognitive Walkthrough Method, Its Variants and Evolutions,” *International Journal of Human-Computer Interaction*, vol. 26, no. 8, pp. 741–785, Jul. 2010. 178

[248] A. Malokin, G. Circella, and P. L. Mokhtarian, “How Do Activities Conducted While Commuting Influence Mode Choice? Testing Public Transportation Advantage and Autonomous Vehicle Scenarios,” in *Proceedings of the 94th Annual Meeting of the Transportation Research Board*, ser. TRB ’15, Jan. 2015, pp. 1–22. 41

[249] E. Mann and C. Abraham, “The Role of Affect in UK Commuters’ Travel Mode Choices: An Interpretative Phenomenological Analysis,” *British Journal of Psychology*, vol. 97, no. 2, pp. 155–176, May 2006. 53

[250] H. B. Mann and D. R. Whitney, “On a Test of Whether one of Two Random Variables is Stochastically Larger than the Other,” *The Annals of Mathematical Statistics*, vol. 18, no. 1, pp. 50–60, Mar. 1947. xv, 160

[251] U. Männi, “Smart Sensing and Time of Arrival-Based Location Detection in Parking Management Services,” in *Proceedings of the 12th Biennial Baltic Electronics Conference*, Oct. 2010, pp. 213–214. 25

[252] C. Marache-Francisco and E. Brangier, “Perception of Gamification: Between Graphical Design and Persuasive Design,” in *Design, User Experience, and Usability. Health, Learning, Playing, Cultural, and Cross-Cultural User Experience*. Springer Berlin Heidelberg, 2013, pp. 558–567. 119

[253] G. Marchionini, “Exploratory Search: From Finding to Understanding,” *Communications of the ACM*, vol. 49, no. 4, pp. 41–46, Apr. 2006. 98

[254] ——, “Human–Information Interaction Research and Development,” *Library & Information Science Research*, vol. 30, no. 3, pp. 165–174, Sep. 2008. 22

[255] D. Marchiori, E. K. Papies, and O. Klein, “The Portion Size Effect on Food Intake. An

Anchoring and Adjustment Process?" *Appetite*, vol. 81, pp. 108–115, Oct. 2014. 28

[256] K. Mariager-Anderson, P. Cort, and R. Thomsen, "In Reality, I Motivate Myself! – Low-Skilled Workers' Motivation: Between Individual and Societal Narratives," *British Journal of Guidance & Counselling*, vol. 44, no. 2, pp. 171–184, Feb. 2016. 27

[257] C. Marin-Lamellet and S. Haustein, "Managing the Safe Mobility of Older Road Users: How to Cope with Their Diversity?" *Journal of Transport & Health*, vol. 2, no. 1, pp. 22–31, Mar. 2015. 48

[258] J.-J. Martinez and C. C. de Wit, "A Safe Longitudinal Control for Adaptive Cruise Control and Stop-and-Go Scenarios," *IEEE Transactions on Control Systems Technology*, vol. 15, no. 2, pp. 246–258, Mar. 2007. 25

[259] S. Mathur, T. Jin, N. Kasturirangan, J. Chandrasekaran, W. Xue, M. Gruteser, and W. Trappe, "ParkNet," in *Proceedings of the 8th International Conference on Mobile Systems, Applications, and Services*, ser. MobiSys '10. ACM, Jun. 2010, pp. 123–136. 41

[260] S. Mattes, "The Lane-Change-Task as a Tool for Driver Distraction Evaluation," *Quality of Work and Products in Enterprises of the Future*, vol. 57, p. 60, 2003. 102, 115

[261] T. Matthews, T. Judge, and S. Whittaker, "How Do Designers and User Experience Professionals Actually Perceive and Use Personas?" in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '12. ACM, May 2012, pp. 1219–1228. 48

[262] A. J. May, T. Ross, S. H. Bayer, and M. J. Tarkiainen, "Pedestrian Navigation Aids: Information Requirements and Design Implications," *Personal and Ubiquitous Computing*, vol. 7, no. 6, pp. 331–338, Dec. 2003. 25

[263] J. McGonigal, *Reality Is Broken: Why Games Make Us Better and How They Can Change the World*. The Penguin Group, Dec. 2011. 28

[264] McKinsey & Company and Bloomberg, "An Integrated Perspective on the Future of Mobility," McKinsey & Company, Inc. and Bloomberg New Energy Finance, Tech. Rep., Oct. 2016. 39

[265] G. Meyer and S. Shaheen, Eds., *Disrupting Mobility*. Springer International Publishing, 2017. 70

[266] M. D. Meyer, "Intermodal and Multimodal Considerations and Developments," in *Sustainable Built Environment*, ser. Encyclopedia of Life Support Systems. Encyclopedia of Life Support Systems (ELOSS) / UNESCO, Nov. 2009, vol. 2, ch. 15, pp. 333–345. 13

[267] D. R. Michael and S. Chen, *Serious Games: Games That Educate, Train, And Inform*. Thomson Course Technology, Oct. 2005. 27

[268] C. Middleton, R. Scheepers, and V. K. Tuunainen, "When Mobile Is the Norm: Researching Mobile Information Systems and Mobility as Post-Adoption Phenomena," *European Journal of Information Systems*, vol. 23, no. 5, pp. 503–512, Sep. 2014. 54

[269] P. Mistry and P. Maes, "SixthSense: A Wearable Gestural Interface," in *ACM SIGGRAPH ASIA 2009 Sketches*, ser. SIGGRAPH ASIA '09. ACM, 2009, pp. 11:1–11:1. 19

[270] W. J. Mitchell, C. E. Borroni-Bird, and L. D. Burns, *Reinventing the Automobile: Personal Urban Mobility for the 21st Century*. The MIT Press, 2010. 2

[271] G. K. Mitropoulos, I. S. Karanasiou, A. Hinsberger, F. Aguado-Agelet, H. Wieker, H.-J. Hilt, S. Mammar, and G. Noecker, "Wireless Local Danger Warning: Cooperative Foresighted Driving Using Intervehicle Communication," *IEEE Transactions on Intelligent Transportation Systems*, vol. 11, no. 3, pp. 539–553, Sep. 2010. 154

[272] J. Molina-García, J. F. Sallis, and I. Castillo, "Active Commuting and Sociodemographic Factors Among University Students in Spain," *Journal of Physical Activity and Health*, vol. 11, no. 2, pp. 359–363, Feb. 2014. 13

[273] A. Möller, F. Michahelles, S. Diewald, L. Roalter, and M. Kranz, "Update Behavior in App Markets and Security Implications: A Case Study in Google Play," in *Proceedings of the 3rd International Workshop on Research in the Large. Held in Conjunction with Mobile HCI*, B. Poppinga, Ed., Sep. 2012, pp. 3–6. 155

[274] A. Möller, S. Diewald, L. Roalter, and M. Kranz, "M3I: A Framework for Mobile Multimodal Interaction," in *Mensch & Computer 2014 – Tagungsband*. De Gruyter Oldenbourg, Sep. 2014, pp. 355–358. 20

[275] A. Möller, M. Kranz, S. Diewald, L. Roalter, R. Huitl, T. Stockinger, M. Koelle, and P. Lindemann, "Experimental Evaluation of User Interfaces for Visual Indoor Navigation," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '14. ACM, Apr. 2014, pp. 3607–3616. 25

[276] S. A. Munson and S. Consolvo, "Exploring Goal-Setting, Rewards, Self-Monitoring, and Sharing to Motivate Physical Activity," in *Proceedings of the 6th International Conference on Pervasive Computing Technologies for Healthcare*, ser. PervasiveHealth '12. IEEE, 2012, pp. 25–32. 81

[277] E. Murphy-Hill and G. C. Murphy, *Recommendation Systems in Software Engineering*. Springer, 2014, ch. Recommendation Delivery, pp. 223–242. 15

[278] K. Myers, M. Gervasio, and A. Pfeffer, "An Intelligent Personal Assistant for Task and Time Management," *AI Magazine*, vol. 28, no. 2, pp. 47–61, 2007. 17

[279] R. Nair and E. Miller-Hooks, "Fleet Management for Vehicle Sharing Operations," *Transportation Science*, vol. 45, no. 4, pp. 524–540, Nov. 2011. 56

[280] P. Neis, "Measuring the Reliability of Wheelchair User Route Planning based on Volunteered Geographic Information," *Transactions in GIS*, vol. 19, no. 2, pp. 188–201, 2015. 24, 26, 179

[281] H. Nicolau and J. Jorge, "Elderly Text-Entry Performance on Touchscreens," in *Proceedings of the 14th International SIGACCESS Conference on Computers and Accessibility*, ser. ASSETS '12. ACM, 2012, pp. 127–134. 93

[282] J. Nielsen and T. K. Landauer, "A Mathematical Model of the Finding of Usability Problems," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '93. ACM, May 1993, pp. 206–213. 176

[283] L. Nielsen, *Personas – User Focused Design*. Springer London, 2013. 49

[284] L. Nigay and J. Coutaz, "A Design Space for Multimodal Systems: Concurrent Processing and Data Fusion," in *Proceedings of the INTERACT '93 and CHI '93 Conference on Human Factors in Computing Systems*, ser. CHI '93. ACM, May 1993, pp. 172–178. 18, 20

[285] NIST, "Guidelines for Managing the Security of Mobile Devices in the Enterprise," National Institute of Standards and Technology (NIST), Special Publication 800-124, Revision 1, 2013. 9

[286] D. Norman, J. Miller, and A. Henderson, "What You See, Some of What's in the Future, and How We Go About Doing It: HI at Apple Computer," in *Conference Companion on Human Factors in Computing Systems*, ser. CHI '95. ACM, May 1995, p. 155. 30

[287] D. A. Norman, "Design Rules Based on Analyses of Human Error," *Communications of the*

ACM, vol. 26, no. 4, pp. 254–258, Apr. 1983. 30

[288] ——, “Natural User Interfaces Are Not Natural,” *Interactions*, vol. 17, no. 3, pp. 6–10, May 2010. 130

[289] O. Nov and O. Arazy, “Personality-Targeted Design: Theory, Experimental Procedure, and Preliminary Results,” in *Proceedings of the Conference on Computer Supported Cooperative Work*, ser. CSCW ’13. ACM, 2013, pp. 977–984. 118

[290] D. G. Novick and K. Ward, “Why Don’t People Read the Manual?” in *Proceedings of the 24th International Conference on Design of Communication*, ser. SIGDOC ’06. ACM, 2006, pp. 11–18. 98

[291] S. Nylander, J. Fådal, and S. Mottaghy, “Couch Mobility: The Cell Phone’s Most Important Feature at Home is Mobility,” in *CHI ’12 Extended Abstracts on Human Factors in Computing Systems*, ser. CHI EA ’12. ACM, May 2012, pp. 1973–1978. 12

[292] L. D. Olvera, A. Guézéré, D. Plat, and P. Pochet, “Improvising Intermodality and Multimodality. Empirical Findings for Lomé, Togo,” *Case Studies on Transport Policy*, vol. 3, no. 4, pp. 459–467, Dec. 2015. 37

[293] R. Oostendorp, D. Krajzewicz, L. Gebhardt, and D. Heinrichs, “Intermodal Mobility in Cities and its Contribution to Accessibility,” *Applied Mobilities*, pp. 1–17, Jan. 2019. 37, 45

[294] O. Oviedo-Trespalacios, M. King, A. Vaezipour, and V. Truelove, “Can Our Phones Keep Us Safe? a Content Analysis of Smartphone Applications to Prevent Mobile Phone Distracted Driving,” *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 60, pp. 657–668, Jan. 2019. 184

[295] M. Panou, K. Touliou, E. Bekiaris, and E. Gaitanidou, “Pedestrian and Multimodal Route Guidance Adaptation for Elderly Citizens,” in *IST-Africa, 2010*, May 2010, pp. 1–7. 68

[296] R. Parasuraman and C. A. Miller, “Trust and Etiquette in High-Criticality Automated Systems,” *Communications of the ACM*, vol. 47, no. 4, pp. 51–55, Apr. 2004. 185

[297] C. J. D. Patten, A. Kircher, J. Östlund, L. Nilsson, and O. Svenson, “Driver Experience and Cognitive Workload in Different Traffic Environments,” *Accident Analysis & Prevention*, vol. 38, no. 5, pp. 887–894, Sep. 2006. 161

[298] J. Paundra, L. Rook, J. van Dalen, and W. Ketter, “Preferences for Car Sharing Services: Effects of Instrumental Attributes and Psychological Ownership,” *Journal of Environmental Psychology*, vol. 53, pp. 121–130, Nov. 2017. 54

[299] N. M. Peel, S. S. Kuys, and K. Klein, “Gait Speed as a Measure in Geriatric Assessment in Clinical Settings: A Systematic Review,” *The Journals of Gerontology: Series A*, vol. 68, no. 1, pp. 39–46, Aug. 2012. 84, 91

[300] C. Perera, A. Zaslavsky, P. Christen, and D. Georgakopoulos, “Context Aware Computing for The Internet of Things: A Survey,” *IEEE Communications Surveys & Tutorials*, vol. 16, no. 1, pp. 414–454, May 2014. 55

[301] H. Persson, H. Åhman, A. A. Yngling, and J. Gulliksen, “Universal Design, Inclusive Design, Accessible Design, Design for All: Different Concepts – One Goal? On the Concept of Accessibility – Historical, Methodological and Philosophical Aspects,” *Universal Access in the Information Society*, vol. 14, no. 4, pp. 505–526, May 2014. 3

[302] I. N. Pettersen and C. Boks, “The Ethics in Balancing Control and Freedom When Engineering Solutions for Sustainable Behaviour,” *International Journal of Sustainable Engineering*, vol. 1, no. 4, pp. 287–297, Dec. 2008. 180

[303] T. Petzoldt, N. Bär, C. Ihle, and J. F. Krems, "Learning Effects in the Lane Change Task (LCT) – Evidence from Two Experimental Studies," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 14, no. 1, pp. 1–12, 2011. 108

[304] T. Petzoldt, S. Brüggemann, and J. F. Krems, "Learning Effects in the Lane Change Task (LCT) – Realistic Secondary Tasks and Transfer of Learning," *Applied Ergonomics*, vol. 45, no. 3, pp. 639–646, 2014. 108

[305] B. Pfleging, S. Schneegass, and A. Schmidt, "Multimodal Interaction in the Car: Combining Speech and Gestures on the Steering Wheel," in *Proceedings of the 4th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI '12. ACM, Oct. 2012, pp. 155–162. 20

[306] R. Philipsen, T. Schmidt, J. van Heek, and M. Ziefle, "Fast-Charging Station Here, Please! User Criteria for Electric Vehicle Fast-Charging Locations," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 40, pp. 119–129, Jul. 2016. 54

[307] W. Piechulla, C. Mayser, H. Gehrke, and W. König, "Reducing Drivers' Mental Workload by Means of an Adaptive Man–Machine Interface," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 6, no. 4, pp. 233–248, Dec. 2003. 161

[308] M. Pielot, K. Church, and R. de Oliveira, "An In-Situ Study of Mobile Phone Notifications," in *Proceedings of the 16th International Conference on Human–Computer Interaction with Mobile Devices & Services*, ser. MobileHCI '14. ACM, Sep. 2014, pp. 233–242. 18

[309] R. Popescu-Zeletin, I. Radusch, and M. A. Rigani, *Vehicular-2-X Communication: State-of-the-Art and Research in Mobile Vehicular Ad Hoc Networks*. Springer, 2010. 147

[310] A. Popleteev, V. Omami, and O. Mayora, "Indoor Positioning Using FM Radio," *International Journal of Handheld Computing Research*, vol. 1, no. 3, pp. 19–31, Jul.–Sep. 2010. 69

[311] S. Poslad, *Ubiquitous Computing: Smart Devices, Environments and Interactions*. Wiley, Apr. 2009. 10, 11

[312] J. A. Pratt, "Where Is the Instruction in Online Help Systems?" *Technical Communication*, vol. 45, no. 1, pp. 33–37, 1998. 15

[313] L. Press, "Dynabook Revisited – Portable Computers Past, Present and Future," *Communications of the ACM*, vol. 35, no. 3, pp. 25–32, Mar. 1992. 21

[314] J. Prillwitz and S. Barr, "Moving Towards Sustainability? Mobility Styles, Attitudes and Individual Travel Behaviour," *Journal of Transport Geography*, vol. 19, no. 6, pp. 1590–1600, Nov. 2011, special section on Alternative Travel futures. 2

[315] M. Rahmani, E. Jenelius, and H. N. Koutsopoulos, "Non-Parametric Estimation of Route Travel Time Distributions from Low-Frequency Floating Car Data," *Transportation Research Part C: Emerging Technologies*, vol. 58, Part B, pp. 343–362, Sep. 2015, big Data in Transportation and Traffic Engineering. 68

[316] A. Rakotonirainy and R. Tay, "In-Vehicle Ambient Intelligent Transport Systems (I-VAITS): Towards an Integrated Research," in *Proceedings of the 7th International Conference on Intelligent Transportation Systems*. IEEE, Oct. 2004, pp. 648–651. 25

[317] M. Rantakokko, M. Mänty, and T. Rantanen, "Mobility Decline in Old Age," *Exercise and Sport Sciences Reviews*, vol. 41, no. 1, pp. 19–25, Jan. 2013. 42

[318] R. L. Rasmussen, C. Overgaard, H. Bøggild, and L. L. H. Thomsen, "An Explorative Evaluation Study of the Mechanisms Underlying a Community-Based Fitness Centre in Denmark - Why Do Residents Participate and Keep up the Healthy Activities?" *Health & Social Care in*

the Community, vol. 26, no. 6, pp. 898–907, Jul. 2018. 188

[319] M. A. Recarte and L. M. Nunes, “Mental Workload While Driving: Effects on Visual Search, Discrimination, and Decision Making,” *Journal of Experimental Psychology: Applied*, vol. 9, no. 2, pp. 119–137, Jun. 2003. 165

[320] L. M. Reeves, J. Lai, J. A. Larson, S. Oviatt, T. S. Balaji, S. Buisine, P. Collings, P. Cohen, B. Kraal, J.-C. Martin, M. McTear, T. V. Raman, K. M. Stanney, H. Su, and Q. Y. Wang, “Guidelines for Multimodal User Interface Design,” *Communications of the ACM*, vol. 47, no. 1, pp. 57–59, Jan. 2004. 20

[321] K. Rehrl, S. Bruntsch, and H.-J. Mentz, “Assisting Multimodal Travelers: Design and Prototypical Implementation of a Personal Travel Companion,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 8, no. 1, pp. 31–42, Mar. 2007. 26

[322] S. Rendle, Z. Gantner, C. Freudenthaler, and L. Schmidt-Thieme, “Fast Context-Aware Recommendations with Factorization Machines,” in *Proceedings of the 34th International Conference on Research and Development in Information*, ser. SIGIR ’11. ACM, Jul. 2011, pp. 635–644. 57

[323] P. Resnick and H. R. Varian, “Recommender Systems,” *Communications of the ACM*, vol. 40, no. 3, pp. 56–58, Mar. 1997. 15

[324] M. Rettig, “Nobody Reads Documentation,” *Communications of the ACM*, vol. 34, no. 7, pp. 19–24, Jul. 1991. 15

[325] F. Ricci and F. Del Missier, *Designing Personalized User Experiences in eCommerce*. Springer Netherlands, 2004, ch. Supporting Travel Decision Making Through Personalized Recommendation, pp. 231–251. 23

[326] F. Ricci, L. Rokach, and B. Shapira, *Recommender Systems Handbook*. Springer US, 2011, ch. Introduction to Recommender Systems Handbook, pp. 1–35. 15

[327] G. Richter, D. R. Raban, and S. Rafaeli, *Studying Gamification: The Effect of Rewards and Incentives on Motivation*. Springer International Publishing, 2015, ch. 2, pp. 21–46. 119

[328] P. Riley, S. Bührmann, P. Hoenninger, and J. Christiaens, “Intermodal Passenger Transport in Europe: Passenger Intermodality from A to Z,” LINK – The European Forum on Intermodal Passenger Travel, Brochure, Mar. 2010. 13, 14

[329] S. Robinson, M. Jones, P. Eslambolchilar, R. Murray-Smith, and M. Lindborg, “I Did It My Way: Moving Away from the Tyranny of Turn-by-Turn Pedestrian Navigation,” in *Proceedings of the 12th International Conference on Human–Computer Interaction with Mobile Devices and Services*, ser. MobileHCI ’10. ACM, Sep. 2010, pp. 341–344. 25

[330] M. Rohs, J. Schöning, M. Raubal, G. Essl, and A. Krüger, “Map Navigation with Mobile Devices: Virtual Versus Physical Movement with and Without Visual Context,” in *Proceedings of the 9th International Conference on Multimodal Interfaces*, ser. ICMI ’07. ACM, 2007, pp. 146–153. 20

[331] C. O. Rolim, F. L. Koch, C. B. Westphall, J. Werner, A. Fracalossi, and G. S. Salvador, “A Cloud Computing Solution for Patient’s Data Collection in Health Care Institutions,” in *Proceedings of the 2nd International Conference on eHealth, Telemedicine, and Social Medicine*, Feb. 2010, pp. 95–99. 21

[332] D. E. Rosenberg, D. L. Huang, S. D. Simonovich, and B. Belza, “Outdoor Built Environment Barriers and Facilitators to Activity among Midlife and Older Adults with Mobility Disabilities,” *The Gerontologist*, vol. 53, no. 2, pp. 268–279, Sep. 2012. 42

[333] S. Rosenbloom, "Sustainability and Automobility Among the Elderly: An International Assessment," *Transportation*, vol. 28, no. 4, pp. 375–408, Nov. 2001. 2

[334] P. Royston, "Approximating the Shapiro-Wilk W-Test for Non-Normality," *Statistics and Computing*, vol. 2, no. 3, pp. 117–119, Sep. 1992. xvi, 89

[335] J. Rudd, K. Stern, and S. Isensee, "Low vs. High-Fidelity Prototyping Debate," *interactions*, vol. 3, no. 1, pp. 76–85, Jan. 1996. 33

[336] J. Ruiz, Y. Li, and E. Lank, "User-Defined Motion Gestures for Mobile Interaction," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '11. ACM, May 2011, pp. 197–206. 19

[337] S. Rümelin and A. Butz, "How to Make Large Touch Screens Usable While Driving," in *Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI '13. ACM, Oct. 2013, pp. 48–55. 185

[338] G. D. Ruxton, "The Unequal Variance t-Test Is an Underused Alternative to Student's t-Test and the Mann-Whitney U Test," *Behavioral Ecology*, vol. 17, no. 4, pp. 688–690, May 2006. xv, 104

[339] R. M. Ryan and E. L. Deci, "Intrinsic and Extrinsic Motivations: Classic Definitions and New Directions," *Contemporary Educational Psychology*, vol. 25, no. 1, pp. 54–67, Jan. 2000. 26, 27

[340] ——, "Self-Determination Theory and the Facilitation of Intrinsic Motivation, Social Development, and Well-Being," *American Psychologist*, vol. 55, no. 1, pp. 68–78, Jan. 2000. 26, 27

[341] D. Saha and A. Mukherjee, "Pervasive Computing: A Paradigm for the 21st Century," *Computer*, vol. 36, no. 3, pp. 25–31, Mar. 2003. 18

[342] A. Sahami Shirazi, N. Henze, T. Dingler, M. Pielot, D. Weber, and A. Schmidt, "Large-Scale Assessment of Mobile Notifications," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '14. ACM, Apr. 2014, pp. 3055–3064. 17

[343] M. Salonen and T. Toivonen, "Modelling Travel Time in Urban Networks: Comparable Measures for Private Car and Public Transport," *Journal of Transport Geography*, vol. 31, pp. 143–153, Jul. 2013. 53

[344] D. D. Salvucci, "Distraction Beyond the Driver: Predicting the Effects of In-Vehicle Interaction on Surrounding Traffic," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '13. ACM, Apr. 2013, pp. 3131–3134. 98

[345] L. T. Sarjakoski and A.-M. Nivala, "Adaptation to Context — A Way to Improve the Usability of Mobile Maps," in *Map-Based Mobile Services*. Springer, 2005, pp. 107–123. 55

[346] J. Sauer and A. Sonderegger, "The Influence of Prototype Fidelity and Aesthetics of Design in Usability Tests: Effects on User Behaviour, Subjective Evaluation and Emotion," *Applied Ergonomics*, vol. 40, no. 4, pp. 670–677, Jul. 2009. 189

[347] J. Sauro and J. R. Lewis, *Quantifying the User Experience – Practical Statistics for User Research*, S. Elliot, Ed. Elsevier BV, 2012. 32

[348] B. Schilit, N. Adams, and R. Want, "Context-Aware Computing Applications," in *Proceedings of the 1st Workshop on Mobile Computing Systems and Applications*, ser. WMCSA '94. IEEE Computer Society, 1994, pp. 85–90. 12

[349] A. Schmeil and W. Broll, "MARA – A Mobile Augmented Reality-Based Virtual Assistant," in

Proceedings of the Virtual Reality Conference, ser. VR '07. IEEE, Mar. 2007, pp. 267–270. 22

[350] M. Schmettow, "Sample Size in Usability Studies," *Communications of the ACM*, vol. 55, no. 4, pp. 64–70, Apr. 2012. 32

[351] A. Schmidt, M. Beigl, and H. w. Gellersen, "There is more to Context than Location," *Computers and Graphics*, vol. 23, pp. 893–901, 1998. 55

[352] R. K. Schmidt, T. Leinmüller, and B. Böddeker, "V2X Communication," in *Proceedings of the 17th Aachen Colloquium on Automobile and Engine Technology*, Oct. 2008, pp. 1–17. 147

[353] K. A. Schutzer and B. S. Graves, "Barriers and Motivations to Exercise in Older Adults," *Preventive Medicine*, vol. 39, no. 5, pp. 1056–1061, Nov. 2004. 127

[354] M. Seredynski, B. Dorronsoro, and D. Khadraoui, "Comparison of Green Light Optimal Speed Advisory Approaches," in *Proceedings of the 16th International Conference on Intelligent Transportation Systems*, ser. ITSC '13. IEEE, Oct. 2013, pp. 2187–2192. 185

[355] S. Shaheen and N. Chan, "Mobility and the Sharing Economy: Potential to Facilitate the First- and Last-Mile Public Transit Connections," *Built Environment*, vol. 42, no. 4, pp. 573–588, Dec. 2016. 37

[356] N. A. Shaked, "Avatars and Virtual Agents – Relationship Interfaces for the Elderly," *Healthcare Technology Letters*, vol. 4, no. 3, pp. 83–87, Jun. 2017. 94

[357] N. J. Sheehan and P. Millicheap, "Talk the Walk: The Importance of Teaching Patients How to Use Their Walking Stick Effectively and Safely," *Musculoskeletal Care*, vol. 6, no. 3, pp. 150–154, Sep. 2008. 52

[358] M. Shirgaokar, "Expanding Seniors' Mobility through Phone Apps: Potential Responses from the Private and Public Sectors," *Journal of Planning Education and Research*, pp. 1–14, Apr. 2018. 54

[359] B. Shneiderman, C. Plaisant, and M. Cohen, *Designing the User Interface: Strategies for Effective Human-Computer Interaction*. Pearson, 2016. 54, 194

[360] M. Siegrist, B. Geilhof, M. Halle, S. Diewald, M. Kranz, and J. Güttler, "Personalisierte Mobilität, Assistenz und Service Systeme in einer alternden Gesellschaft: Abschlussbericht für das Forschungsvorhaben mit dem Titel PASSAge," Technische Universität München, Tech. Rep., Sep. 2015. 42

[361] R. J. Sigal, G. P. Kenny, D. H. Wasserman, and C. Castaneda-Sceppa, "Physical Activity/Exercise and Type 2 Diabetes," *Diabetes Care*, vol. 27, no. 10, pp. 2518–2539, 2004. 80

[362] W. J. Slegers, "Building Automotive Product Lines Around Managed Interfaces," in *Proceedings of the 13th International Software Product Line Conference*, ser. SPLC '09. Carnegie Mellon University, Aug. 2009, pp. 257–264. 134

[363] A. Smirnov, A. Kashevnik, N. Shilov, N. Teslya, and A. Shabaev, "Mobile Application for Guiding Tourist Activities: Tourist Assistant – TAIS," in *Proceedings of the 16th Conference of Open Innovations Association FRUCT*, Oct. 2014, pp. 95–100. 23

[364] A. Smirnov, N. Teslya, and A. Kashevnik, *Context-Aware Routing Service for an Intelligent Mobile-Tourist Guide*. Springer International Publishing, 2017, pp. 243–258. 24, 55

[365] J. D. Smith, T. C. N. Graham, D. Holman, and J. Borchers, "Low-Cost Malleable Surfaces with Multi-Touch Pressure Sensitivity," in *2nd Annual International Workshop on Horizontal Interactive Human-Computer Systems*, ser. TABLETOP '07. IEEE, Oct. 2007, pp. 205–208.

19

[366] I. Solís-Marcos and K. Kircher, "Event-Related Potentials as Indices of Mental Workload While Using an In-Vehicle Information System," *Cognition, Technology & Work*, vol. 21, no. 1, pp. 55–67, Apr. 2018. 185

[367] E. Soloway, M. Guzdial, and K. E. Hay, "Learner-Centered Design: The Challenge for HCI in the 21st Century," *interactions*, vol. 1, no. 2, pp. 36–48, Apr. 1994. 30

[368] A. Sonderegger and J. Sauer, "The Influence of Design Aesthetics in Usability Testing: Effects on User Performance and Perceived Usability," *Applied Ergonomics*, vol. 41, no. 3, pp. 403–410, May 2010. 189

[369] N. K. Sondheimer and N. Relles, "Human Factors and User Assistance in Interactive Computing Systems: An Introduction," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 12, no. 2, pp. 102–107, Mar. 1982. 29, 30

[370] J. Sonnenberg, "Service and User Interface Transfer from Nomadic Devices to Car Infotainment Systems," in *Proceedings of the 2nd International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI '10. ACM, Nov. 2010, pp. 162–165. 130

[371] A. C. Sparkes, "Ethnography and the Senses: Challenges and Possibilities," *Qualitative Research in Sport and Exercise*, vol. 1, no. 1, pp. 21–35, Jan. 2009. 18

[372] F. Steinberger, R. Schroeter, and C. N. Watling, "From Road Distraction to Safe Driving: Evaluating the Effects of Boredom and Gamification on Driving Behaviour, Physiological Arousal, and Subjective Experience," *Computers in Human Behavior*, vol. 75, pp. 714–726, Oct. 2017. 118

[373] M. F. Story, J. L. Mueller, and R. L. Mace, *The Universal Design File: Designing for People of All Ages and Abilities*. ERIC, 1998. 188, 194

[374] D. L. Strayer, J. M. Cooper, M. M. McCarty, D. J. Getty, C. L. Wheatley, C. J. Motzkus, R. M. Goethe, F. Biondi, and W. J. Horrey, "Visual and Cognitive Demands of CarPlay, Android Auto, and Five Native Infotainment Systems," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 61, no. 8, pp. 1371–1386, Apr. 2019. 136

[375] F. Strohmeier, "Barriers and their Influence on the Mobility Behavior of Elder Pedestrians in Urban Areas: Challenges and Best Practice for Walkability in the City of Vienna," *Transportation Research Procedia*, vol. 14, pp. 1134–1143, Apr. 2016. 43

[376] J. C. Stutts, W. W. Hunter, and W. E. Pein, "Pedestrian Crash Types: 1990s Update," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1538, no. 9, pp. 68–74, 1996. 98

[377] M. Sun, L. E. Burke, Z.-H. Mao, Y. Chen, H.-C. Chen, Y. Bai, Y. Li, C. Li, and W. Jia, "eButton: A Wearable Computer for Health Monitoring and Personal Assistance," in *Proceedings of the 51st ACM/EDAC/IEEE Design Automation Conference*, ser. DAC '14, Jun. 2014, pp. 1–6. 21

[378] C. R. Sunstein, "Nudging: A Very Short Guide," *Journal of Consumer Policy*, vol. 37, no. 4, pp. 583–588, Oct. 2014. 28

[379] K. Swearingen and R. Sinha, "Beyond Algorithms: An HCI Perspective on Recommender Systems," in *ACM SIGIR Workshop on Recommender Systems*, vol. 13, 2001, pp. 1–11. 16

[380] P. Tarasewich, C. S. Campbell, T. Xia, and M. Dideles, "Evaluation of Visual Notification Cues for Ubiquitous Computing," in *Proceedings of the 5th International Conference on Ubiquitous Computing*, ser. UbiComp '03. Springer, Oct. 2003, pp. 349–366. 19

[381] L. Taylor, “No Place to Hide? the Ethics and Analytics of Tracking Mobility Using Mobile Phone Data,” *Environment and Planning D: Society and Space*, vol. 34, no. 2, pp. 319–336, Oct. 2015. 57

[382] Z. Taylor and I. Józefowicz, “Intra-Urban Daily Mobility of Disabled People for Recreational and Leisure Purposes,” *Journal of Transport Geography*, vol. 24, pp. 155–172, Sep. 2012. 42

[383] R. H. Thaler and S. Benartzi, “Save More Tomorrow™: Using Behavioral Economics to Increase Employee Saving,” *Journal of Political Economy*, vol. 112, no. 1, pp. 164–187, Feb. 2004. 28

[384] S. Thoma, T. Lindberg, and G. Klinker, “Speed Recommendations During Traffic Light Approach: A Comparison of Different Display Concepts,” in *Proceedings of the Human Factors and Ergonomics Society Europe Chapter Annual Meeting*. HFES, Oct. 2007, pp. 1–13. 162, 163

[385] M. Tonnis, V. Broy, and G. Klinker, “A Survey of Challenges Related to the Design of 3D User Interfaces for Car Drivers,” in *3D User Interfaces*, ser. 3DUI ’06. IEEE, Mar. 2006, pp. 134–142. 97, 182

[386] M. Torrens, P. Hertzog, L. Samson, and B. Faltings, “Reality: A Scalable Intelligent Travel Planner,” in *Proceedings of the 2003 ACM Symposium on Applied Computing*, ser. SAC ’03. ACM, 2003, pp. 623–630. 23

[387] Tory and T. Moller, “Evaluating Visualizations: Do Expert Reviews Work?” *IEEE Computer Graphics and Applications*, vol. 25, no. 5, pp. 8–11, Sep. 2005. 31

[388] N. K. F. Tsang, G. K. Y. Chan, and K. K. F. Ho, “A Holistic Approach to Understanding the Use of Travel Guidebooks: Pre-, During, and Post-Trip Behavior,” *Journal of Travel & Tourism Marketing*, vol. 28, no. 7, pp. 720–735, Oct. 2011. 192

[389] M. Turk, “Multimodal Interaction: A Review,” *Pattern Recognition Letters*, vol. 36, pp. 189–195, Jan. 2014. 20

[390] P. Turner and S. Turner, “Is Stereotyping Inevitable When Designing with Personas?” *Design Studies*, vol. 32, no. 1, pp. 30–44, Jan. 2011. 48

[391] A. Tversky and D. Kahneman, “Judgment Under Uncertainty: Heuristics and Biases,” *science*, vol. 185, no. 4157, pp. 1124–1131, 1974. 28

[392] Y. Tyrinopoulos and C. Antoniou, “Factors Affecting Modal Choice in Urban Mobility,” *European Transport Research Review*, vol. 5, no. 1, pp. 27–39, Dec. 2012. 45

[393] E. Uhlemann, “Connected Vehicles – The Battle of Technologies or the Battle of Business Models?” *IEEE Vehicular Technology Magazine*, vol. 13, no. 1, pp. 14–18, Mar. 2018. 184

[394] United Nations, *The Report on the World Social Situation 2018*. United Nations Publications, Sep. 2018, ch. Persons with Disabilities: Breaking Down Barriers, pp. 63–76. 42

[395] F. van der Ploeg and S. Poelhekke, “Globalization and the Rise of Mega-Cities in the Developing World,” *Cambridge Journal of Regions, Economy and Society*, vol. 1, no. 3, pp. 477–501, Mar. 2008. 2

[396] H. A. van Klink and G. C. van den Berg, “Gateways and Intermodalism,” *Journal of Transport Geography*, vol. 6, no. 1, pp. 1–9, Mar. 1998. 13

[397] M. W. van Someren, Y. F. Barnard, and J. A. C. Sandberg, *The Think Aloud Method: A Practical Approach to Modelling Cognitive Processes*. Academic Press, 1994. 76

[398] M. van Steen and A. S. Tanenbaum, “A Brief Introduction to Distributed Systems,” *Comput-*

ing, vol. 98, no. 10, pp. 967–1009, Aug. 2016. 139, 143

[399] C. L. Ventola, "Mobile Devices and Apps for Health Care Professionals: Uses and Benefits," *Pharmacy and Therapeutics*, vol. 39, no. 5, pp. 356–364, May 2014. 21

[400] A. P. O. S. Vermeeren, E. L.-C. Law, V. Roto, M. Obrist, J. Hoonhout, and K. Väänänen-Vainio-Mattila, "User Experience Evaluation Methods: Current State and Development Needs," in *Proceedings of the 6th Nordic Conference on Human-Computer Interaction Extending Boundaries*, ser. NordiCHI '10. ACM, Oct. 2010, pp. 521–530. 32

[401] P. Victor, M. De Cock, and C. Cornelis, *Trust and Recommendations*. Springer US, 2011, ch. 20, pp. 645–675. 16

[402] S. Vogelsang, C. Digmayer, and E.-M. Jakobs, "User Requirements on Intermodal Traveler Information Systems," in *Proceedings of the International Professional Communication Conference*, ser. IPCC '15. IEEE, Jul. 2015, pp. 1–9. 53

[403] P. Voigt and A. von dem Bussche, *The EU General Data Protection Regulation (GDPR)*. Springer International Publishing, 2017. 178

[404] K. Voit, K. Andrews, and W. Slany, "Why Personal Information Management (PIM) Technologies are not Widespread," in *Proceedings of the ASIS&T Workshop on Personal Information Management*, 2009, pp. 60–64. 22

[405] N. Waara, "Older and Disabled People's Need and Valuation of Traveler Information in Public Transport," in *Proceedings of the European Transport Conference*, ser. ETC '09. Association for European Transport, Oct. 2009, pp. 1–21. 3

[406] Y. Wang, J. Jiang, and T. Mu, "Context-Aware and Energy-Driven Route Optimization for Fully Electric Vehicles via Crowdsourcing," *IEEE Transactions on Intelligent Transportation Systems*, vol. 14, no. 3, pp. 1331–1345, Sep. 2013. 24

[407] D. Warnock, M. McGee-Lennon, and S. Brewster, "The Role of Modality in Notification Performance," in *Proceedings of the 13th International Conference on Human-Computer Interaction*, ser. INTERACT '11. Springer, Sep. 2011, pp. 572–588. 20

[408] M. O. Watson and P. M. Sanderson, "Designing for Attention with Sound: Challenges and Extensions to Ecological Interface Design," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 49, no. 2, pp. 331–346, Apr. 2007. 20

[409] E. Weingarten, Q. Chen, M. McAdams, J. Yi, J. Hepler, and D. Albarracín, "From Primed Concepts to Action: A Meta-Analysis of the Behavioral Effects of Incidentally Presented Words," *Psychological Bulletin*, vol. 142, no. 5, pp. 472–497, May 2016. 28

[410] M. Weiser, "The Computer for the 21st Century," *Scientific American*, vol. 265, no. 3, pp. 94–104, Sep. 1991. 10

[411] S. Whittaker, "Personal Information Management: From Information Consumption to Curation," *Annual Review of Information Science and Technology*, vol. 45, no. 1, pp. 1–62, 2011. 22

[412] B. Whitworth, "Polite Computing," *Behaviour & Information Technology*, vol. 24, no. 5, pp. 353–363, 2005. 16

[413] R. H. Wiggins, "Personal Digital Assistants," *Journal of Digital Imaging*, vol. 17, no. 1, pp. 5–17, Mar. 2004. 21

[414] F. Wilcoxon, "Individual Comparisons by Ranking Methods," *Biometrics Bulletin*, vol. 1, no. 6, pp. 80–83, Dec. 1945. xv, xvi, 168

[415] D. Wilfinger, M. Murer, A. Baumgartner, C. Döttlinger, A. Meschtscherjakov, and M. Tscheligi, "The Car Data Toolkit: Smartphone Supported Automotive HCI Research," in *Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI '13. ACM, Oct. 2013, pp. 168–175. 119

[416] M. W. Wilson, "Location-Based Services, Conspicuous Mobility, and the Location-Aware Future," *Geoforum*, vol. 43, no. 6, pp. 1266–1275, Nov. 2012. 3

[417] M. Winikoff, L. Padgham, J. Harland, and J. Thangarajah, "Declarative & Procedural Goals in Intelligent Agent Systems," in *Proceedings of the 8th International Conference on Principles of Knowledge Representation and Reasoning*, ser. KR '02. Morgan Kaufmann, 2002, pp. 470–481. 17

[418] Y. Wu, L. N. Boyle, D. V. McGehee, L. S. Angell, and J. Foley, "Task Analysis of Vehicle Entry and Backing," in *Proceedings of the 4th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI '12. ACM, 2012, pp. 195–200. 98

[419] K. Yeung, "Nudge as Fudge," *The Modern Law Review*, vol. 75, no. 1, pp. 122–148, Dec. 2011. 28

[420] Z. Yovcheva, D. Buhalis, and C. Gatzidis, "Smartphone Augmented Reality Applications for Tourism," *e-Review of Tourism Research (eRTR)*, vol. 10, no. 2, pp. 63–66, 2012. 23

[421] S. Yuan, W. Ma, S. Kanthawala, and W. Peng, "Keep Using My Health Apps: Discover Users' Perception of Health and Fitness Apps with the UTAUT2 Model," *Telemedicine and e-Health*, vol. 21, no. 9, pp. 735–741, Sep. 2015. 195

[422] J. Zamora, "I'm Sorry, Dave, I'm Afraid I Can't Do That," in *Proceedings of the 5th International Conference on Human Agent Interaction*, ser. HAI '17. ACM, 2017, pp. 253–260. 94

[423] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for Smart Cities," *IEEE Internet of Things Journal*, vol. 1, no. 1, pp. 22–32, Feb. 2014. 41

[424] A. Zelinsky and J. Heinzmann, "Real-Time Visual Recognition of Facial Gestures for Human-computer Interaction," in *Proceedings of the 2nd International Conference on Automatic Face and Gesture Recognition*, Oct. 1996, pp. 351–356. 19

[425] L. Zhang, P. H. Pathak, M. Wu, Y. Zhao, and P. Mohapatra, "AccelWord: Energy Efficient Hotword Detection Through Accelerometer," in *Proceedings of the 13th Annual International Conference on Mobile Systems, Applications, and Services*, ser. MobiSys '15. ACM, 2015, pp. 301–315. 19

[426] W. Zhang, Y.-H. Huang, M. Roetting, Y. Wang, and H. Wei, "Driver's Views and Behaviors about Safety in China – What Do They NOT Know about Driving?" *Accident Analysis & Prevention*, vol. 38, no. 1, pp. 22–27, Jan. 2006. 53

[427] B. Zhou, Q. Li, Q. Mao, W. Tu, and X. Zhang, "Activity Sequence-Based Indoor Pedestrian Localization Using Smartphones," *IEEE Transactions on Human-Machine Systems*, vol. 45, no. 5, pp. 562–574, Oct. 2015. 93

[428] L. Zhou, A. S. Mohammed, and D. Zhang, "Mobile Personal Information Management Agent: Supporting Natural Language Interface and Application Integration," *Information Processing & Management*, vol. 48, no. 1, pp. 23–31, Jan. 2012. 22

[429] G. Zichermann and C. Cunningham, *Gamification by Design: Implementing Game Mechanics in Web and Mobile Apps*. O'Reilly Media, Aug. 2011. 28

[430] M. Ziefle and S. Bay, “Mental Models of a Cellular Phone Menu: Comparing Older and Younger Novice Users,” in *Mobile Human-Computer Interaction – MobileHCI 2004*, ser. Lecture Notes in Computer Science. Springer, Sep. 2004, vol. 3160, pp. 25–37. 124

[431] M. Ziefle and W. Wilkowska, “What Makes People Change Their Preferences in Public Transportation – Opinions in Different User Groups,” in *Internet of Things. IoT Infrastructures*. Springer International Publishing, Jun. 2015, pp. 137–143. 45

[432] H. Zimmermann, “OSI Reference Model – The ISO Model of Architecture for Open Systems Interconnection,” *IEEE Transactions on Communications*, vol. 28, no. 4, pp. 425–432, Apr. 1980. 132

[433] K. G. Zografos and K. N. Androutsopoulos, “Algorithms for Itinerary Planning in Multimodal Transportation Networks,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 9, no. 1, pp. 175–184, Mar. 2008. 52

[434] K. G. Zografos, K. N. Androutsopoulos, and J. D. Nelson, “Identifying Travelers’ Information Needs and Services for an Integrated International Real Time Journey Planning System,” in *Proceedings of the 13th International Conference on Intelligent Transportation Systems*, ser. ITS ’10. IEEE, Sep. 2010, pp. 998–1004. 54

[435] M. Zyda, “From Visual Simulation to Virtual Reality to Games,” *Computer*, vol. 38, no. 9, pp. 25–32, Sep. 2005. 27