DOCTORAL THESIS

Integration of Autonomous Last-Mile Minibuses into Urban Space

Krister Kalda

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Declaration:
Hereby, I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Krister Kalda ____
signature

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Autonoomsete viimase-miili minibusside integreerimine linnaruumi

KRISTER KALDA

TALTECH KIRJASTUS

Contents

List of Publications

The present Ph.D thesis is based on the following publications that are referred to in the text by Roman numbers.

I. **Kalda, K.**, Sell, R., & Soe, R. M. (2021). Use case of autonomous vehicle shuttle and passenger acceptance analysis. Proceedings of the Estonian Academy of Sciences, 70(4), 429–435.

II. **Kalda, K.**, Pizzagalli, S.-L., Soe, R.-M., Sell, R., & Bellone, M. (2022). Language of driving for autonomous vehicles. Applied Sciences, 12(11), 5406.

III. **Kalda, K.**; Sell, R.; Kivimäe, M. (2024). Enhancing Mobility as a Service with Autonomous Last-mile Shuttles and Data Exchange Layer for Public Transport. Modern materials and manufacturing 2023: Modern Materials and Manufacturing (MMM2023), Tallinn Eesti, 2.-4. mai 2023. AIP Publishing, 1−6. (AIP Conference Proceedings; 2989).

IV. Udal, A., Sell, R., **Kalda, K.**, & Antov, D. (2024). A predictive compact model of effective travel time considering the implementation of first-mile autonomous mini-buses in smart suburbs. Smart Cities, 7(6), 3914–3935.

V. **Kalda, K.**, Koskinen, K. M., Sarv, L., & Sell, R. (2025). Situational awareness in autonomous shuttle buses. Proceedings of the Estonian Academy of Sciences.

Author’s Contribution to the Publications

Contribution to the papers in this thesis are:

I. The author participated in conducting the pilot, operating the AV shuttle and creating and designing the survey as well as running the survey and collecting and analysing the results. The author contributed to paper writing and presented them also at a conference.

II. The author collaborated with the technical team in designing the pilot and running it. Creating and conducting the survey, including interviewing people on the streets, at the stops and in the AV shuttle while operating. The author managed the co-writing with other authors, set the base to the article, analysed the results, discussed them and contributed to writing the paper.

III. The author proposed ideas into how this novel system of on demand AV service should work. Conducted regular meetings with the technical team to discuss the details and the progress. Contributed to finding the existing MaaS XT solutions, their problems to help designing a better version and looking out for the needs of the next stage – integrating the service into the pilot. Contributed by connecting the writers’ contributions, collecting the information and writing the paper.

IV. The author ran the surveys and collected the data on what the article is based on. Contributed to writing the paper and the later additions after the reviews.

V. The author ran the ideation of the article with co-authors and conducted the surveys with the operators, users and everybody involved in the process of integrating AV shuttles into the open traffic as well as running the pilot. Ran the survey among people living in the pilot area. After collecting the data through surveys and interviews, analysing and writing the paper with co-authors.

Abbreviations

ASB	Autonomous Shuttle Bus
AV	Autonomous Vehicle
EDTT	Effective Daily Travel Time
HMI and eHMI	(external) human–machine interface
MaaS	Mobility as a Service
MR	Mixed reality
PT	Public transport
SA	Situational awareness
SAE	The Society of Automotive Engineers
TAM	Technology Acceptance Model
XT	X-road

1 Introduction

Autonomous shuttle buses are not only technological artefacts but socio-technical systems, where success depends equally on robust hardware and software as well as on societal readiness and trust. Their development and deployment are advancing rapidly, with pilot projects worldwide—and in Estonia through the iseAuto initiative—demonstrating both opportunities and challenges. Beyond technical feasibility, it is crucial to address how passengers and pedestrians interact with these vehicles, how they can be integrated into daily mobility patterns, and how their impact can be meaningfully evaluated [1–3].

Thus, the central research problem is not merely whether an autonomous shuttle can drive safely. Rather, it extends to how societies adapt to a new mobility paradigm in which humans and autonomous systems must coexist in shared traffic environments. This thesis addresses these challenges by combining technical design and modelling with user acceptance studies and human–vehicle interaction research, providing a comprehensive framework for understanding and shaping the role of autonomous minibuses in future smart mobility ecosystems.

This dissertation is structured into five main parts. Chapter 1 introduces the background, describes the motivation, and outlines the goals of the research. It also positions the study within the broader context of autonomous vehicles, first-/last-mile transport, user acceptance, human–machine interaction, and transport modelling. Chapter 2 discusses the methodologies that form the basis for control, validation, and verification frameworks. Chapter 3 presents case studies that evaluate these methods under real-world conditions. Chapter 4 provides experimental results, while Chapter 5 concludes with a synthesis of findings and recommendations for future research.

1.1 An Overview of the Nature of the Research Problem

1.1.1 Autonomous Vehicles and First-Mile Automated Minibuses

Autonomous driving is increasingly moving from visionary concepts towards practical implementations in urban environments. According to the SAE J3016 taxonomy, vehicle autonomy is divided into five levels: from level 0 (no automation) to level 5 (full automation in all conditions) [4]. Current commercial systems, such as Tesla Autopilot, generally operate at level 2, while low-speed autonomous shuttles have already demonstrated capabilities up to level 4 [5,6]. These vehicles are particularly well-suited for first- and last-mile transport, providing flexible connections between residential or workplace areas and major public transport hubs.

Across Europe, autonomous shuttles have been piloted to extend the reach of existing transport networks, enabling citizens to experience novel mobility solutions and generating valuable feedback on safety, trust, and usability [7]. The first major Estonian step in this direction was taken in 2017, when Tallinn University of Technology (TalTech) launched the development of its own autonomous shuttle, iseAuto [8,9]. Built on open-source software and the chassis of a compact electric vehicle, the first prototype was presented publicly in 2018 [10–12]. Further collaboration with the industrial partner AuVe Tech transformed the prototype into a street-legal vehicle by 2020 under both Estonian and EU regulations [8,63]. This milestone enabled real-world pilots in the European Commission–funded Sohjoa Baltic and FABULOS projects, where iseAuto operated in diverse traffic environments—from recreational areas such as Kadriorg Park to the dense urban setting of Ülemiste City [13–16].

In addition to extending public transport coverage, research has examined the efficiency impacts of such shuttles. Compact predictive modelling studies demonstrate that first-mile autonomous minibuses can reduce effective daily travel time in suburban areas by replacing private car use with shuttle-based feeder connections (A Predictive Compact Model of Effecti...) [17]. These findings provide municipalities with practical tools for sustainable transport planning.

1.1.2 User Acceptance

While technological development has reached the point of street-legal prototypes and pilot deployments, the long-term success of autonomous shuttles depends on public acceptance and trust. Pilot projects such as Sohjoa Baltic and FABULOS systematically collected passenger feedback, allowing the investigation of mobility acceptance factors across different demographics and traffic environments. Citizens' first-hand experiences—ranging from daily commuters in Ülemiste City to recreational park visitors in Kadriorg—revealed both curiosity and scepticism towards the new technology [1,3].

Recent research highlights that the absence of a human driver raises specific challenges for passenger situational awareness and perceived safety. Users must be informed and supported in unexpected scenarios, such as sudden stops or disruptions, to maintain trust in the system. Acceptance studies also show that communication strategies (e.g., real-time route maps, interaction with remote operators) can significantly influence whether passengers feel safe and willing to adopt the service [18–20].

In summary, user acceptance is a socio-technical issue: while technical robustness is necessary, the perception of safety, comfort, and trust plays an equally critical role. The findings underline that autonomous minibuses are not only a technological innovation but also a human-centred service requiring careful design of information flows, interaction methods, and cultural adaptation. These aspects form a central part of the research problem addressed in this dissertation.

1.1.3 Passenger Situational Awareness and Human–Vehicle Communication

The integration of autonomous shuttle buses (ASBs) raises not only technological and efficiency-related questions but also challenges concerning human situational awareness (SA) [21,22]. Autonomous transport systems fundamentally transform mobility by replacing the human driver with self-driving algorithms. Although research on SA has predominantly focused on private passenger cars, less attention has been devoted to autonomous minibuses. Yet, global trials with ASBs have demonstrated that unexpected events may still require human intervention [23,24].

In current deployments, safety operators remain present inside the vehicle to handle such events, but the long-term vision is full autonomy without onboard staff. This shift raises critical questions regarding the level of situational awareness expected from passengers [19]. In the absence of a driver, tasks traditionally managed by humans—including not only vehicle control but also non-driving responsibilities such as responding to disruptions—may shift to passengers or external support systems.

Since AVs are socio-technical systems, their acceptance and effectiveness depend on the interaction of technological, social, and contextual factors. Addressing these factors requires not only technical development but also clear communication strategies and design principles that support passenger awareness. The actual perceived user acceptance can be very different from the assumption acceptance. And people accept a new technology mostly based on perceived usefulness and perceived ease of use [74].

This dissertation contributes to this discourse by examining passenger situational awareness from the perspectives of manufacturers, policymakers, and users, and by outlining a research agenda for integrating these human factors into the design and deployment of autonomous shuttles specifically to create highest possible technology acceptance model /TAM) for AVs.

Beyond the issue of situational awareness inside the vehicle, an equally critical challenge concerns how autonomous shuttles communicate externally with their environment. In traditional traffic, communication is mediated through eye contact, gestures, and vehicle movement cues. Without a human driver, AVs must provide clear, machine-generated signals that indicate intent: whether the shuttle will stop, yield, or proceed.

Research at TalTech addressed this challenge through real-world experiments on the university campus, where 176 pedestrians interacted with the iseAuto shuttle. Surveys and interviews were conducted to evaluate how people perceived the vehicle's behaviour, whether they trusted its decisions, and whether they understood its intentions. In parallel, representatives from regulatory authorities, including the Ministry of Economic Affairs and Communications, the Estonian Transport Administration, and the City of Tallinn, were consulted to capture institutional perspectives. The results indicated that a new "language of driving" is required—comprising light signals, sounds, or other intuitive HMIs—to enable transparent and inclusive communication with all road users [18].

As a methodological proposal, a Mixed Reality (MR) simulation platform was suggested for developing and testing novel interaction concepts. Such platforms allow researchers to generate diverse scenarios, experiment with interface designs in a safe environment, and validate their effectiveness across different demographic groups, including children, elderly people, and vulnerable road users. This approach provides a scalable framework for prototyping, assessing, and refining both internal and external AV interfaces before implementation in real traffic.

1.1.4 Mobility as a Service – Micromobility in the Smart City

The emergence of Mobility as a Service (MaaS) marks a paradigm shift in how transportation is conceptualized and delivered. MaaS integrates different modes of transport into a single, user-oriented mobility service, often accessible via digital platforms [25–28]. Global examples such as Uber and Bolt illustrate the convenience of on-demand ride-hailing in urban settings. However, the true potential of MaaS becomes evident when extended to suburban and rural contexts, where conventional fixed-route public transport services are not economically viable [29]. In such areas, autonomous shuttles can function as flexible first-/last-mile connectors, linking residents to nearby bus or train stations and thereby reducing dependence on private cars.

In the Estonian context, this opportunity was addressed within the Finest Twins Future Mobility project, which investigated how MaaS solutions could be adapted to local conditions [30–33]. The research focused on three main aspects: (i) reviewing available white-label MaaS platforms across Europe, (ii) identifying those most suitable for suburban use cases, and (iii) aligning deployment strategies with EU-level frameworks for smart and sustainable mobility [32,33]. Interviews with mobility service providers complemented the analysis, revealing both opportunities and limitations for implementation in suburban environments.

As a practical outcome, a middleware platform named MaaS XT was developed to integrate various services—including self-driving shuttles, shared e-scooters, and public transport—into a seamless ecosystem [25–27]. MaaS XT not only demonstrated technical feasibility but also contributed conceptually by framing mobility as a socio-technical system, in which autonomous minibuses and micromobility options play a central role in reducing congestion, emissions, and parking pressures.

Overall, MaaS has the potential to reshape mobility patterns by providing attractive alternatives to private car use, improving accessibility for underserved regions, and supporting cities in their transition toward sustainable and user-centric transport networks [29,28,34,35].

1.1.5 Travel Time of First-Mile Autonomous Mini-Buses in Smart Suburbs

Transportation planning is a long-established field of engineering, but in recent decades it has been reshaped by the rapid development of autonomous vehicles [36–38]. Among these, shared autonomous shuttles are considered particularly promising for addressing first- and last-mile mobility challenges in suburban areas where maintaining fixed bus routes is neither economically viable nor sustainable [39–41]. While privately owned electric AVs can reduce environmental and parking pressures in city centres, the broader socio-economic benefits are expected from shared, service-based solutions that extend the accessibility of public transport networks.

The evaluation of such solutions requires appropriate indicators that capture both objective efficiency and subjective user experience. To this end, the concept of Effective Daily Travel Time (EDTT) has been introduced as a compact yet comprehensive metric [17]. EDTT goes beyond measuring minutes spent in transit by incorporating additional dimensions such as waiting times, psycho-physiological stress factors (ϕ-factors), and psychologically perceived financial costs (ψ-factors) [42–46]. This enables a more realistic representation of the travel burden faced by residents and provides a holistic tool for assessing transport interventions.

The modelling approach developed in this dissertation deliberately balances simplicity and explanatory power, following Einstein's principle of parsimony: "as simple as possible, but not simpler." The model integrates multiple transport modes (both traditional and AV-assisted), applies a simplified but generalizable spatial structure, uses empirically derived trip distribution functions, and incorporates minimalistic waiting-time sub-models that account for AV fleet size [47–52].

By applying EDTT as a unifying evaluation framework, it becomes possible to forecast the potential impact of autonomous minibuses before large-scale deployment. This allows transport planners and policymakers to proactively assess whether the introduction of first-mile AV services will genuinely improve residents' daily mobility, reduce reliance on private cars, and enhance the overall efficiency of suburban transport systems.

1.2 Definition of the Research Problem

Autonomous shuttle buses (ASBs) have been piloted for several years, typically as experimental or demonstration services in controlled areas. When deployed in open traffic, these services have so far always included a safety operator onboard, predefined routes, and fixed bus stops. This arrangement increases safety, as the operator can intervene at any moment and serves as the communicator between the vehicle and its surroundings, including pedestrians and other drivers. Moreover, fixed stops are often predefined or marked as official bus stops, making them straightforward to program into constant shuttle services.

However, such configurations do not fully realize the potential of autonomous mobility. A critical question arises: what happens when the safety operator is removed? Without human presence inside the vehicle, how can the shuttle communicate effectively with other traffic participants? Should the shuttle itself become “understandable” to humans through new interaction modes, considering that traditional audio cues are limited to internal use? Furthermore, fixed bus stops may undermine the flexibility and attractiveness of autonomous services. To truly compete with private cars, AV shuttles must evolve into digitally advanced, on-demand service providers capable of seamless integration into daily mobility routines.

The societal motivation for this research is clear. Reducing CO_2 emissions is an urgent goal, and road traffic powered by fossil fuels remains one of the largest contributors. Autonomous shuttles, as electric and shared mobility solutions, can mitigate the negative effects of growing private car ownership in cities. At the same time, people are increasingly conscious of their time budgets, often perceiving public transport as inconvenient, particularly in suburban or rural areas where bus routes are scarce and distances to the nearest stop are long. By providing on-demand access to public transport nodes, autonomous minibuses can address this gap. The elimination of driver-related costs further enhances their feasibility for operators.

On-demand AV shuttles also offer broader system-level benefits. They can reduce urban congestion by decreasing the need for private cars, alleviate parking shortages, and complement policy measures such as stricter car taxation [53]. Integrated within MaaS ecosystems, such shuttles can be ordered via mobile applications that combine real-time route planning, multimodal integration, and ticketing services, thereby improving the overall attractiveness of public transport.

Yet, despite these opportunities, it remains unclear whether theoretical advantages translate into practice. How do people behave when confronted with truly unmanned shuttles in real traffic? How do they wish to communicate with the vehicle, and what interaction modes are required to ensure trust and safety? To explore these questions, pilot deployments were conducted both in urban and suburban contexts: one connecting a seaport terminal to public transport nodes in the city, and another in a residential area 15 km outside the city centre, linking a kindergarten with a local bus station. These pilots provide valuable insights into user acceptance, communication challenges, and the socio-technical integration of autonomous shuttle services.

1.3 Research Objectives

The overarching objective of this research is to investigate how autonomous shuttle buses (AV shuttles) can become safe, understandable, and convenient components of public transport systems in both urban and suburban contexts. Specifically, the dissertation focuses on human–machine communication in situations where the vehicle operates without a driver or onboard safety operator, thereby removing the traditional human intermediary between the shuttle and other traffic participants. The aim is to understand the real needs of passengers and road users, and to identify what must be addressed for them to feel safe, informed, and willing to adopt AV shuttle services.

To achieve this, the research sets out to examine how different modes of communication—both internal (passenger-facing) and external (towards pedestrians, cyclists, and other drivers)—affect acceptance and trust in autonomous shuttles. Pilot deployments in suburban environments provide empirical insights into user perceptions and reveal what additional features or interaction methods are required. In parallel, the study explores the integration of on-demand AV shuttle services into Mobility as a Service (MaaS) platform, assessing whether such solutions can reduce private car dependence by offering more flexible, accessible, and attractive public transport options.

Finally, the research develops and applies the Effective Daily Travel Time (EDTT) model as a compact tool for evaluating the impact of autonomous shuttle deployments. By combining objective indicators of travel efficiency with subjective perceptions of stress, cost, and convenience, EDTT enables a holistic assessment of how AV shuttles influence daily mobility patterns and support broader goals of sustainability, accessibility, and user acceptance.

1.4 Hypotheses of the Research

RH1 – User Acceptance:

After pilot deployments and prolonged exposure to autonomous shuttle services, the acceptance of autonomous minibuses among passengers increases significantly, with a measurable growth of approximately 30% in reported willingness to use them compared to pre-pilot levels.

RH2 – Human–Machine Communication:

The absence of a human driver in autonomous shuttles creates a communication gap for both pedestrians and passengers. To ensure perceived safety and trust, new multimodal interaction methods—visual, auditory, and digital—are required to establish an effective "language of driving" between humans and autonomous vehicles.

RH3 – Integration into MaaS Ecosystems:

On-demand autonomous shuttle services that provide first-/last-mile connections to public transport nodes increase the likelihood that suburban residents will choose public transport over private cars, thereby contributing to reduced congestion and emissions.

RH4 – Travel Time and Efficiency (numerical modelling):

The introduction of first-mile autonomous minibuses in suburban areas reduces Effective Daily Travel Time (EDTT) for users. EDTT can be modelled as a compact yet comprehensive metric that incorporates waiting times, perceived stress factors, and subjective costs, providing a quantifiable framework for evaluating AV shuttle deployment impacts.

Table 1. Relationship between research objectives and the included papers.

	Article 1	Article 2	Article 3	Article 4	Article 5
RH1	X				X
RH2	X	X			
RH3			X		X
RH4				X	

1.5 Research Tasks and Contribution

RT1 Conduct a user study on attitudes towards autonomous vehicles, organize a pilot deployment, and subsequently carry out a post-pilot survey to measure changes in acceptance.

RT2 Test different communication methods and interfaces for driverless shuttles and investigate the actual needs and expectations of users and other road participants. The aim is to develop optimal and sufficiently safe interaction models that ensure both passenger confidence and mutual understanding in mixed traffic.

RT3 Develop and test a prototype MaaS solution in real urban traffic that integrates on-demand autonomous shuttle services with existing public transport.

RT4 Collect empirical data from a suburban first-/last-mile AV shuttle pilot to derive and validate a compact calculation model for effective daily travel time.

This work significantly advanced the field of autonomous shuttle buses as part of smart, user-centric mobility by turning pilots, experiments, modelling and platform development into actionable methods, evidence and tools. Concretely, the dissertation delivers:

- A regulator-aligned pathway for safe street-legal deployment in mixed traffic, demonstrated through staged approval (technical inspection → closed-course tests → on-road exam) and supported by teleoperation/remote assistance as a managed fallback in real pilots (Ülemiste City, Kadriorg).

- Empirical evidence on public acceptance from a longitudinal suburban study (baseline 2021 → post-exposure 2023), identifying determinants of trust (situational awareness cues, clear passenger information, availability of assistance, time-of-day and weather effects) and showing acceptance growth after direct experience.

- An interaction design agenda for external and internal HMI: campus experiments with pedestrians and riders, complemented by mixed-/virtual-reality prototyping, yield principles of legibility, redundancy and cultural intelligibility for eHMI signals and rider-facing explanations of non-routine behaviour (e.g., abrupt braking).

- System-level integration via the MaaS-XT prototype that orchestrates on-demand AV shuttles with public transport and micromobility over the X-Road data layer, providing a reusable reference architecture, governance touchpoints and implementation lessons for APIs, SLAs and user experience.

- A compact, behaviour-aware evaluation instrument—Effective Daily Travel Time (EDTT)—that fuses objective operations with perceived costs and psycho-physiological stressors, calibrated on the suburban pilot. Scenario and sensitivity analyses quantify benefits and reveal practical policy levers (fleet sizing, headways, walkability and parking policy).

- Operational insights and artefacts to support replication: structured logs of teleoperation interventions and service performance, survey instruments, and a methodological template that links pilots → interaction design → MaaS integration → modelling in a coherent evidence chain.

- Policy-relevant guidance on risk management and public communication around incidents, the role of teleoperation during transition phases, and procurement/contracting considerations for scaling autonomous demand-responsive services.

2 Case Studies and Methodologies

2.1 Methodological Framework

The methodological framework of this dissertation is based on the integration of several case studies and pilot projects rather than a single experiment [54]. Autonomous shuttles are approached as socio-technical systems where technical functionality, regulatory conditions, infrastructural constraints, and human behaviour are intertwined. To capture this complexity, the research design combined quantitative and qualitative methods in a sequential manner, producing layered insights that developed over time.

The foundation of the research was a mixed-methods approach [54]. Surveys in 2021 and 2023 provided longitudinal data on residents' attitudes and their changes after exposure to autonomous buses. In-depth interviews with regulators, operators and manufacturers revealed institutional perspectives and decision-making logics. Focus groups allowed policymakers and experts to debate the future of regulation and infrastructure. Observations of passenger experiences enriched the empirical evidence with everyday interaction data. Finally, modelling through the Effective Daily Travel Time (EDTT) framework enabled the generalisation of findings and testing of hypothetical scenarios.

The studies were designed to be sequential, so that later stages could build on the results of earlier ones. The first survey in 2021 established a baseline. Pilot deployments followed, producing real-world data and experiential evidence. A second survey in 2023 then made it possible to assess how direct experience had influenced public perceptions. The qualitative studies further contextualised the survey results, while the EDTT model integrated all findings into a quantitative system-level framework. Figure 1 illustrates this layered methodological design.

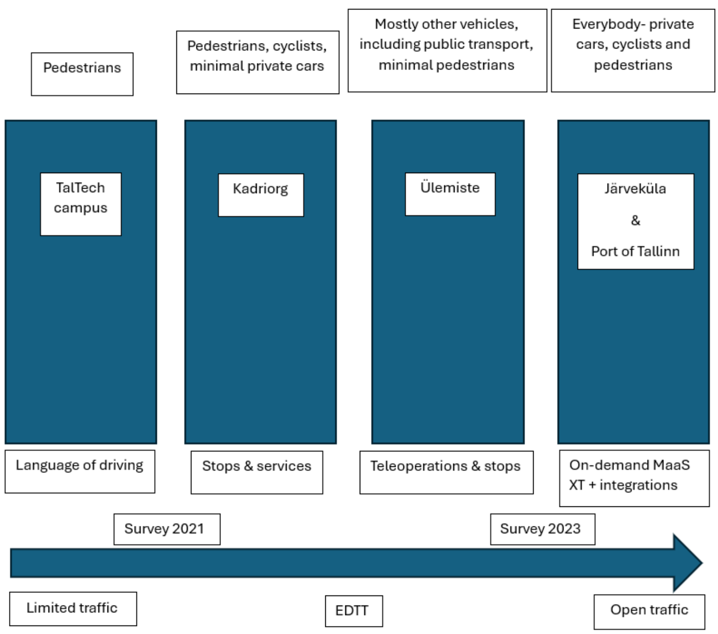

Figure 1. The empirical material of this dissertation was generated from a diverse set of sources, reflecting the layered methodological framework described above. The integration of these data sources was essential for combining technical, social, and systemic perspectives into one coherent analysis.

Within this framework, five interlinked pilots and experiments formed the empirical backbone of the dissertation:

- Ülemiste City pilot in a dense urban traffic environment, testing the first Estonian-built street-legal autonomous shuttle in mixed traffic.

- Kadriorg recreational park pilot, focusing on low-speed operation in pedestrian- and cyclist-heavy conditions.

- TalTech campus experiments, studying human–vehicle interaction and the design of communication signals between shuttles and pedestrians.

- Järveküla surveys and acceptance studies, providing a longitudinal view on public attitudes before and after exposure to shuttle services.

- MaaS-XT platform and EDTT modelling, demonstrating system-level integration of autonomous shuttles into multimodal transport and quantifying their impact on effective daily travel time.

These cases complemented each other by addressing different dimensions of the same research problem: user acceptance, technical readiness, communication and interaction, integration into mobility services, and system-level effects. Figure 2 shows the timeline of the research sequence, from the baseline survey in 2021 to the final modelling stage in 2024.

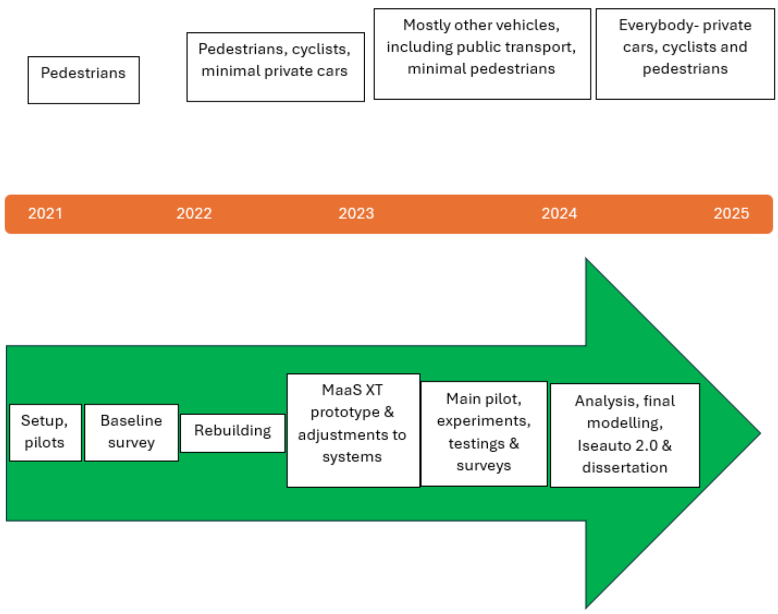

Figure 2. Timeline of pilots and research.

In summary, the methodological framework of this dissertation was designed as a layered and sequential process. It combined multiple perspectives and empirical sources to provide a holistic understanding of autonomous shuttles as part of the wider mobility ecosystem, ensuring that both micro-level interactions and macro-level travel time impacts could be studied within one coherent structure.

2.2 Legal and Technical Preparations for Pilots

Before autonomous shuttle pilots could be deployed in public space, significant legal and technical preparations were required. The regulatory environment in Estonia, as in many European countries, was not originally designed with driverless vehicles in mind. Therefore, each pilot project demanded close cooperation with transport authorities, the police, and the rescue board to establish a process for evaluating the safety and compliance of the vehicles. This process went beyond the conventional inspection of vehicles and extended into areas such as sensor validation, teleoperation procedures, and emergency protocols.

The approval procedure followed a staged model that ensured compliance with both national and European Union regulations. First, a standard technical inspection was carried out, testing basic elements such as lights, windows, tires, seats, and emergency equipment. This step ensured that the shuttle, despite its autonomy, met the same fundamental safety requirements as conventional passenger vehicles. Second, closed-area safety tests were organised to examine braking capacity, sensor accuracy, and the vehicle's response to unexpected events. Only after these tests were passed was the shuttle allowed to undergo an on-road driving exam, where its behaviour in traffic—such as turning at intersections, yielding to pedestrians, and negotiating mixed traffic with trams, buses, and scooters—was assessed. Figure 3 summarises the staged approval process.

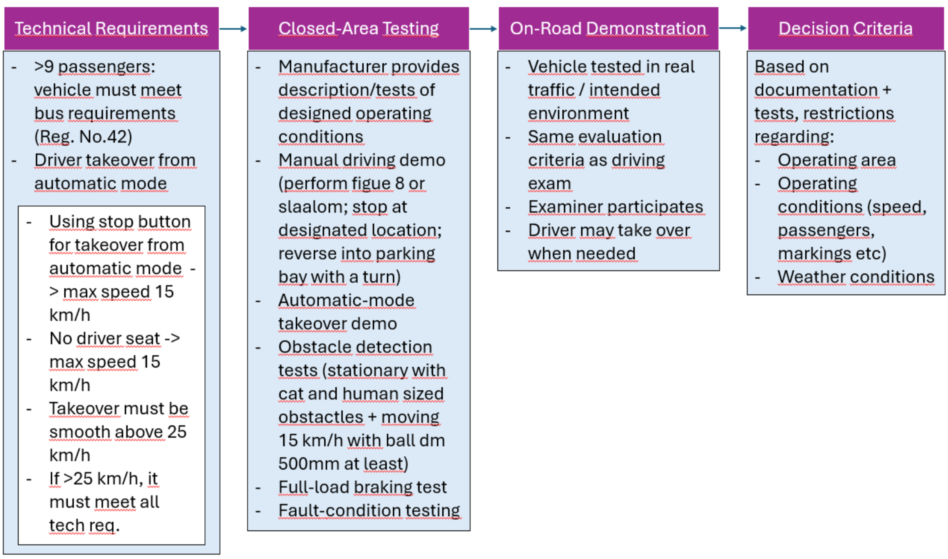

Figure 3. Stages of testing for AV approval, according to Estonian Transport Authority (2020–2023).

The legal classification of the shuttles played an important role. In Estonia, the iseAuto platform was certified as an EU M1 category vehicle, which implied a set of requirements for interior fittings, glazing, lighting, and other design aspects. These modifications, while technical in nature, were directly linked to regulatory compliance. The process of making the shuttle street-legal thus served as both a technical development milestone and a legal precedent for future autonomous vehicle deployments in Estonia.

Another critical dimension was the establishment of teleoperation and remote monitoring. Even though the shuttles operated primarily in automated mode, unexpected situations such as wrongly parked cars or temporary road obstructions required human oversight. A remote operation centre was therefore created, allowing operators to intervene when necessary. This element was not only a technical safeguard but also a legal condition for granting permission to drive in open traffic, reflecting the principle that liability and control must remain traceable in cases where the automated system alone might be insufficient.

The pilots also highlighted the importance of risk management and public communication. The traffic accident during the Ülemiste pilot, caused by a private car that ignored a “give way” sign, became a case study of how new technologies are perceived by the public. Although the accident was clearly not caused by the shuttle (a private car entered the main road from the parking lot), public opinion initially assigned blame to the autonomous system. Authorities and project partners quickly issued clarifications, but the episode demonstrated that legal compliance must be accompanied by communication strategies to manage public perception. Figure 4 shows the exact situation/accident that took place during the Ülemiste pilot.

Figure 4. Accident during Ülemiste pilot – private car entering the traffic in front of a low speed ASB.

The technical and legal preparations for these pilots therefore represent more than a bureaucratic requirement. They formed an integral part of the methodology by defining the boundary conditions within which autonomous shuttles could operate. The process ensured that the pilots were not only safe but also legitimate in the eyes of regulators, institutions, and the public. In this way, legal and technical preparations did not precede the research as a mere formality but became part of the empirical findings themselves, shaping how autonomous shuttles can be integrated into real-world traffic environments.

2.3 Case Studies: Pilots, Experiments, Surveys, Platform and Modelling

The empirical foundation of this dissertation consists of five interrelated case studies and experimental pilots. Each addressed a specific dimension of autonomous shuttle implementation, ranging from technical validation in real traffic to user acceptance, human–vehicle interaction, and system-level integration. Together they form a comprehensive body of evidence on how autonomous shuttles function not only as technological systems but as embedded components of urban and suburban mobility.

2.3.1 Ülemiste City Pilot

The Ülemiste City pilot represented the first deployment of an Estonian-built street-legal autonomous shuttle in mixed urban traffic. The route was designed deliberately to include intersections, pedestrian crossings, and shared lanes with trams and buses, thereby testing the limits of safe integration into existing traffic flows. The pilot also introduced smart bus stops that displayed real-time arrival information and adjusted schedules in case of delays.

Figure 5. Test route and stops in Ülemiste City.

The approval process involved inspections, closed-area safety tests, and an on-road driving exam before the shuttle was permitted to operate. During the pilot, shuttles maintained a cautious speed of approximately 20 km/h, below the legal maximum, to ensure a safety margin. A remote operation centre provided teleoperation capability in unexpected situations. The pilot also included one traffic accident, caused by a private car ignoring a traffic sign, which became an important episode in understanding public perceptions of risk and responsibility.

Figure 6. Teleoperation in Ülemiste remote operation station.

Figure 7. iseAuto AV shuttle deployment in Ülemiste City.

2.3.2 Kadriorg Recreational Park Pilot

Conducted in a pedestrian- and cyclist-heavy recreational environment, the Kadriorg pilot examined the shuttle's ability to operate at low speed in conditions where interactions with vulnerable road users dominated. Here, behavioural phenomena were observed in which pedestrians and cyclists deliberately tested the vehicle's automated braking system by approaching it too closely. Although no accidents occurred, these encounters highlighted the unpredictability of human behaviour and the necessity of conservative safety margins.

The pilot demonstrated that acceptance and trust are not only shaped by technical safety but also by the social dynamics of how people choose to interact with autonomous systems in public space.

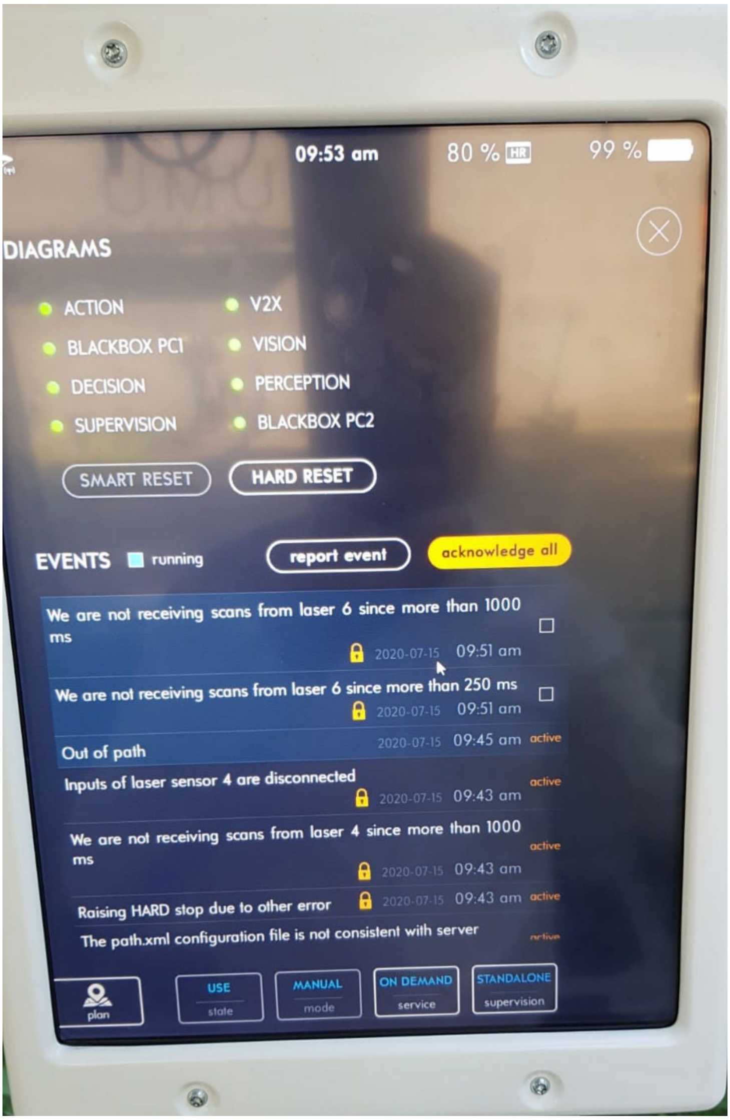

Figure 8. Operators' report screen in ASB during the Kadriorg pilot.

2.3.3 TalTech Campus Experiments

Experiments on the TalTech campus focused on communication between autonomous shuttles and pedestrians. A total of 176 participants were observed in situations such as crossing the road or walking alongside the vehicle. The experiments tested multiple modes of signalling, including auditory cues, visual displays, and light signals, to determine which forms of communication pedestrians found most intuitive.

The research also explored the concept of a "language of driving," where signals are standardised and interpretable across different contexts. This extended into augmented reality testing, enabling simulation of critical situations beyond what was feasible in physical pilots. These studies provided insight into the design of human–machine interfaces for autonomous vehicles.

Figure 9. Experimental set-up of human–vehicle interaction tests on TalTech campus.

2.3.4 Järveküla Surveys and Acceptance Studies

Figure 10. Explanation of example suburban transport task: (a) Location of Järveküla residential area (purple rectangle) in Rae municipality beyond the southern border of Tallinn city (red line). The blue line marks the major public transportation bus line 132 to Tallinn centre; (b) Current development stage of Järveküla residential area of approx. 200 houses; (c) Pilot AV shuttle minibus designed for first-mile transport service in residential areas.

Two large-scale surveys were carried out in Järveküla, Rae municipality, to investigate long-term acceptance of autonomous shuttles. The baseline survey in 2021, consisting of fifty questions, mapped mobility behaviour, perceptions of autonomous vehicles, and suggestions for local governance. The follow-up survey in 2023, conducted after a period of shuttle operation, allowed for direct comparison of attitudes before and after personal experience.

Table 2. Actual usage of transportation modes in Rae municipality by 2021 survey and the deduced parameters for modelling example of the present study. Answers from 819 residents.

2021 Survey in Rae Municipality Transportation Mode Winter-Summer	2021 Survey in Rae Municipality Transportation Mode Winter-Summer	2021 Survey in Rae Municipality Transportation Mode Winter Summer	Average	Adopted Model Parameters Parameter	Value	Symbol
1. Passenger car	80.5%	72.9%	76.7%	1. Private car	69.0%	mcar
				2. Taxi *	7.7%	mtaxi
2. Public transport (walk+bus)	15.1%	11.1%	13.1%	3. Public transport (walk+bus)	13.1%	mPT
3. Bicycle	0.7%	7.7%	4.2%	4. Bicycle	4.2%	mbic
4. Walking	2.8%	7.4%	5.1%	5. Walking	5.1%	mwalk

Table 3. Formulation of the aggregated autonomous vehicle acceptance factor based on Rae municipality 2021 survey (answers from 819 residents).

Question/Parameter	Positive Answers
Should AV become a part of public transport?	72.8%
Would you use an AV for everyday needs?	63.0% *
Would you use an AV in case of an on-site travel assistant?	48.8%
Would you use an AV in the case of a remote travel assistant?	49.9%
Would you use fully automatic AV?	35.2%
Allow children to use AV in case of an on-site travel assistant?	62.3%
Allow children to use AV in the case of a remote travel assistant?	38.8%
Allow children to use fully automatic AV?	23.1%
Consider AV safe on the street?	63.6%
Could AV replace your travelling with a car?	45.5%
Aggregated average acceptance of AVs α	50.3% **

A total of 539 rides were completed during the pilot phase, generating valuable feedback from both passengers and pedestrians. The surveys revealed not only increasing levels of trust but also nuanced concerns about safety, information provision, and the role of municipalities in supporting new transport modes.

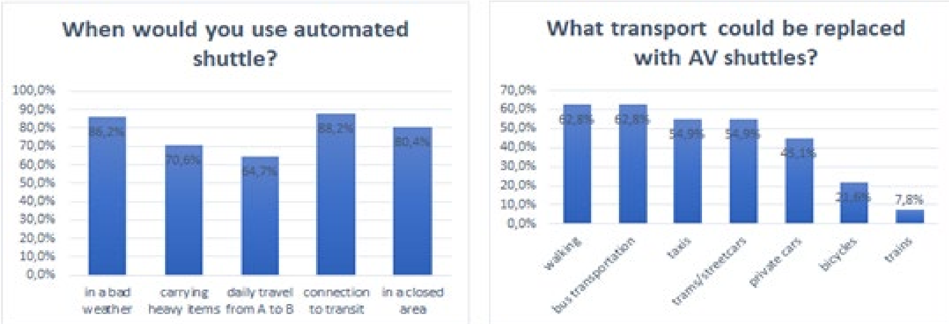

Figure 11. Survey results on passengers' estimations of AV shuttles.

To analyse TAM (Technology Acceptance Model) of the actual perceived acceptance to prior the pilot acceptance, table 3 is a summary table of all main questions and answers after the pilot had taken place and people had a chance to drive inside AV Shuttle Buses in Järveküla residential pilot area.

Table 4. Survey answers from the 2023 survey, after the pilot had taken place (165 people).

Question/Parameter	Most common answer	Second common
What kind of transport do you usually use in summer for the daily commute?	Private car 64%	Bicycle, electrical bikes 13,3%
What kind of public transport do you use most commonly during summer?	Bus 67,5%	Train 9,8%
How seldom do you use public transport during summer?	Less than a couple of times a month 47,2%	Some occasions every month 30,1%
Why do I most commonly use public transport?	Cultural events, hobbies 41,9%	To go to work 26,5%
How far is public transport from your home?	500m-1km 41,5%	Less than 500m 38,4%
Did you see an AV Shuttle in your area during the pilot time?	Yes 59,8%	No 40,2%
Have you been in traffic with AV?	Yes 53,9%	No 46,1%
Have you driven inside an AV	No 71,3%	Yes 28,7%
Would you like to ride in an AV in the future?	Yes 86,5%	I don't know 6,8%
What would make you choose public transport to replace your travelling with a private car?	Better connections 67,9%	Faster public transport 52,1%
Would you use ASB for your daily commute?	Yes 54,5%	No 32,7%

What mode of transport would you stop using to change to ASBs?	Private car 65,5%	Regular public transport 41,8%
Where in traffic would you feel most in danger when there are also ASBs in the mix of traffic?	In public transport 31,3%	Riding a bicycle/electrical bike 28,2%
I would feel safe in ASB when…	Safety operator is not on site (teleoperating) 37,9%	ASB is fully autonomous and driving with sensors 37,3%
I would allow the kids to drive in ASB, if there is:	Safety operator no on-board, but teleoperating 32,7%	Safety operators onboard the ASB 32,7%
For me to feel safe in ASB, I need to have:	Visible digital map to see, where exactly ASB is in real time 40,4%	I would like minimal interference by anybody; only important announcements are enough 23,5%
ASBs are mainly good because…	They give more chances to commute to people with special needs (elderly, children, handicapped etc) 70,8%	The help to diminish parking problems 69,6%
Would you like to have ASBs as part of the local transport?	Yes 82,3%	I don't know 14%
What is your age?	35 to 44 47,5%	25 to 34 19,8%
What is your sex?	Woman 65,9%	Man 31,7%

There is to some extent a statistical error and reliability to be considered, as in all the surveys of this thesis, there are approximately ⅔ of the answers coming from women. As well as the surveys done in the campus area (in this thesis the TalTech pilot), the most answers come from either students or pensioners with children that walk around the campus area during daytime.

2.3.5 MaaS-XT Platform and EDTT Modelling

The final element of the empirical programme was the development of the MaaS-XT platform and the Effective Daily Travel Time (EDTT) model. The MaaS-XT prototype integrated autonomous shuttles into a multimodal journey chain that also included public transport and demand-responsive services [25,26,33,55,56]. The system architecture was layered, comprising user interfaces for journey planning and ticketing, routing engines for alternative paths, and secure data exchange based on the Estonian X-Road infrastructure [57].

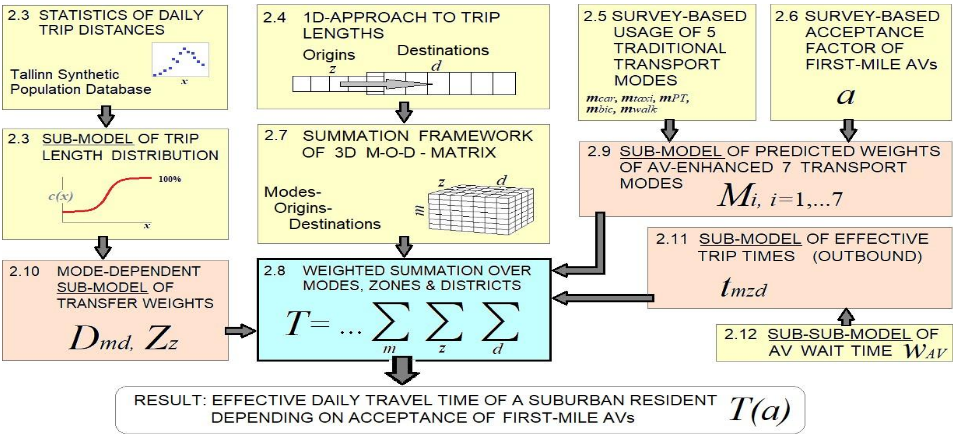

Figure 12. General structure of the calculation model. The upper corner numbers of the blocks correspond to the subsections in the paper text.

The EDTT model served as a quantitative tool to evaluate how the introduction of autonomous shuttles affected overall travel efficiency. It incorporated not only objective factors such as waiting times and average speeds but also subjective stressors such as weather conditions, rush-hour congestion, and the burden of carrying luggage. Applied to Järveküla, the model demonstrated that even a limited number of shuttles could reduce effective daily travel time in a car-dominated suburb.

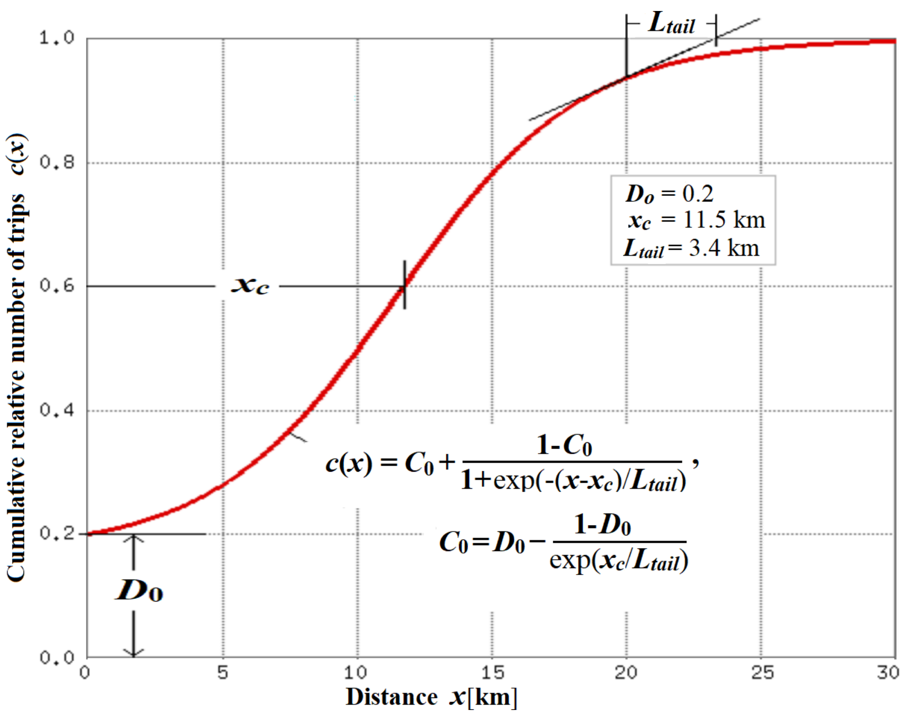

Figure 13. The constructed 3-parameter model of distribution of trip distances combining the initial short-distance contribution and the smooth sigmoid step for lengthier distances. Parameter values are estimated to represent the Järveküla example area.

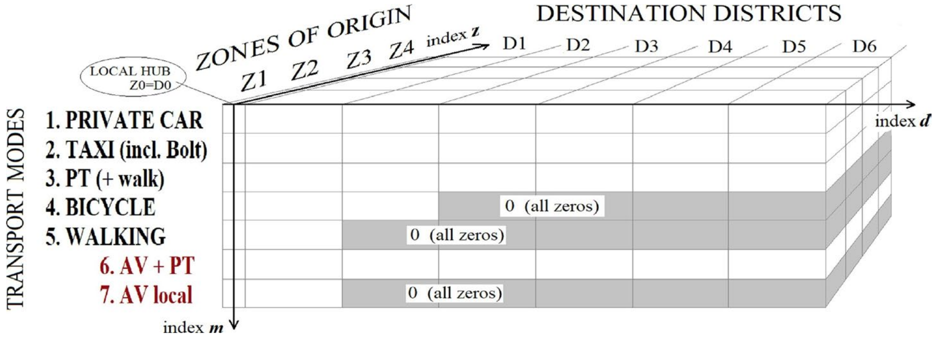

Figure 14. Explanation of concept of three-dimensional modality-origin-destination matrix used to sum up the daily transport times. Matrix defines 5 origin zones, 6 destinations districts, and 5 + 2 transportation modes. Each cell of MOD matrix is characterized by transport time with optional psych-physiological and economical extra terms and weight factors of distance and transport mode.

Table 5. Cross-use table of input data for 7 transport modes and 2 trip stages (local and remote) considered in transport times model (23). The referenced parameters are defined in the general input data table.

Parameter of Model (23) for Stages 1 and 2		**Mode 1 Private Car**	**Mode 2 Taxi**	**Mode 3 Walk + Bus**	**Mode 4 Bicycle**	**Mode 5 Walking**	**Mode 6 AV + Bus**	**Mode 7 Local AV**
Waiting time, stage 1 (local)	w_1	$w_{car}/2$	*wtaxi*	0	*wbic*	0	model (24)	model (24)
Waiting time, stage 2 (city)	w_2	$w_{car}/2$	0	*wbus*	0	0	*wbus*	0
Average speed, stage 1	v_1	*vcar*	*vcar*	*vwalk*	*vbic*	*vwalk*	*vAV*	*vAV*
Average speed, stage 2	v_2	*vcar*	*vcar*	*vbus*	*vbic*	*vwalk*	*vbus*	*vAV*
Psycho-physiological stress factor, stage 1	φ_1	*φcar*	0	*φwalk*	*φbic*	*φwalk*	0	0
Psycho-physiological stress factor, stage 2	φ_2	*φcar*	0	0	*φbic*	*φwalk*	0	0
Financial cost, stage 1	E_1	*Ecar*	*Etaxi*	0	0	0	0*	0*
Financial cost, stage 2	E_2	*Ecar*	*Etaxi*	*Ebus*	0	0	*Ebus*	0*
Cost perception factor, stage 1	ψ_1	*ψcar*	*ψcar*	0	0	0	0	0
Cost perception factor, stage 2	ψ_2	*ψcar*	*ψcar*	*ψbus*	0	0	*Ψbus*	0

2.3.6 Synthesis

Taken together, the five case studies demonstrate the value of combining pilots, controlled experiments, surveys, and modelling. Each addressed a distinct dimension of the research problem, but their integration provided a more holistic perspective. Technical validation in Ülemiste and Kadriorg revealed operational challenges in mixed and pedestrian-heavy traffic. The TalTech campus experiments highlighted the centrality of human–vehicle interaction design. The Järveküla surveys measured longitudinal acceptance and behavioural change. Finally, the MaaS-XT platform and EDTT model situated autonomous shuttles within a wider mobility ecosystem, quantifying their potential impact on suburban travel.

2.4 Data Sources and Analysis Methods

The empirical material of this dissertation was generated from a diverse set of sources, reflecting the layered methodological framework described above. The integration of these data sources was essential for combining technical, social, and systemic perspectives into one coherent analysis.

The most substantial contribution came from the two large-scale resident surveys in Järveküla, Rae municipality. The first, conducted in 2021, provided baseline information on mobility habits, expectations, and concerns regarding autonomous shuttles. The second, in 2023, followed a period of real-world exposure to autonomous bus services and enabled longitudinal comparison of acceptance levels. Together, these surveys provided quantitative evidence of how direct experience influenced perceptions over time [58–63]. Their results also highlighted specific issues, such as safety concerns, the need for clear passenger information, and trust in municipal decision-making.

Equally important were the pilot observations carried out in Ülemiste City, Kadriorg park, and the TalTech campus. These observations produced qualitative data on passenger behaviour, interactions with pedestrians and cyclists, and the practical performance of the shuttles under varying conditions. Teleoperation logs and safety operator reports further enriched the dataset by documenting instances when human intervention was necessary. These records were particularly valuable in understanding the boundary conditions of autonomous operation, including cases where technological systems alone were insufficient. Figure 8 presents an example of the operational data flow used in the Kadriorg pilot [15].

In addition to observations and surveys, semi-structured interviews were conducted with stakeholders including national regulators, municipal officials, technology providers, and transport operators. These interviews provided insight into the decision-making processes behind deployment, the rationale for specific regulatory requirements, and the anticipated role of autonomous shuttles in future mobility systems. Complementing the interviews, focus groups with experts from ministries and local authorities enabled deliberative discussion of long-term infrastructural and regulatory strategies.

System-level data was collected from the MaaS-XT platform prototype, which produced logs on route planning, booking behaviour, and multimodal integration [64,65]. These logs offered a perspective on how autonomous shuttles can be embedded into broader transport networks and how demand-responsive services interact with traditional modes of public transport. Figure 15 illustrates the architecture of the MaaS-XT data pipeline and its connection to the Estonian X-Road data exchange layer [66].

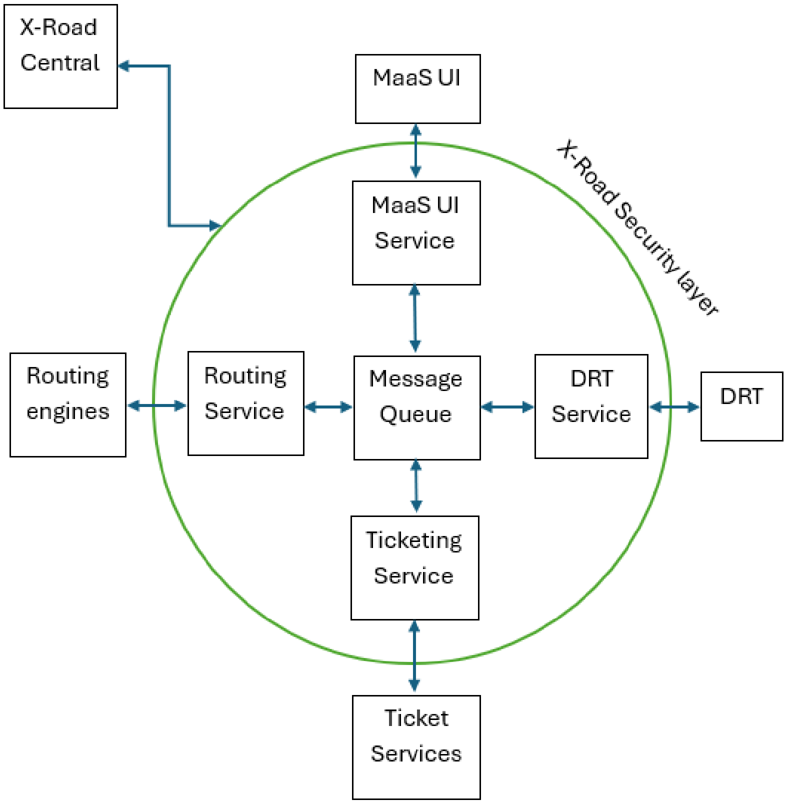

Figure 15. MaaS XT platform architecture.

Finally, simulation data was generated through the Effective Daily Travel Time (EDTT) model. This model combined survey results, observed travel times, and contextual factors such as weather and congestion into a single aggregated metric [67,68]. Its compact structure allowed for efficient testing of hypothetical scenarios, such as the introduction of additional shuttle services or changes in travel demand. The EDTT simulations thus provided a bridge between empirical observations and predictive system-level analysis [69,70]. Figure 16 shows an example of EDTT output comparing baseline car-dominated mobility patterns with a scenario including autonomous shuttles.

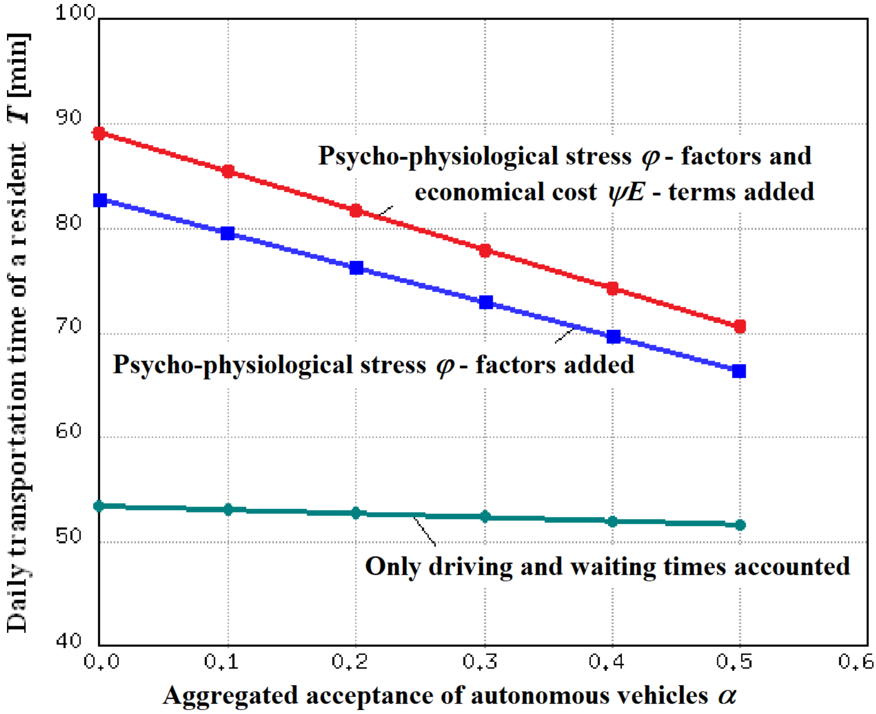

Figure 16. The main output of the model: daily effective transportation times of an average suburban resident versus the aggregated parameter of autonomous vehicle acceptance α.

The analysis of these diverse data sources followed a triangulation strategy. Survey data was processed using statistical methods to identify significant changes over time, while qualitative material from interviews and focus groups was coded thematically to reveal institutional and behavioural patterns. Observational and operational data were examined to detect recurring types of intervention or disruption. Finally, the EDTT model provided a framework for synthesising all inputs into a coherent quantitative outcome. The combination of these techniques ensured robustness, as no single data source was treated as definitive; instead, findings were validated through comparison across multiple methods and contexts.

2.5 Synthesis of Results Across Case Studies

The five case studies presented in this dissertation are complementary in nature, each addressing a different aspect of autonomous shuttle deployment while collectively forming a coherent methodological whole. The synthesis of results across these studies highlights both the potential and the challenges of integrating autonomous shuttles into existing mobility systems.

At the technical level, the Ülemiste City and Kadriorg pilots demonstrated that autonomous shuttles can operate reliably in open traffic and pedestrian-rich environments. Their performance confirmed the feasibility of street-legal deployment under carefully controlled conditions, supported by teleoperation and safety monitoring. However, they also revealed critical limitations, such as vulnerability to unexpected human behaviour and the continued need for regulatory oversight. The technical findings therefore underline the dual nature of autonomy: on the one hand, it reduces routine human error, but on the other hand, it introduces new dependencies on infrastructure, regulation, and emergency response protocols.

At the human–vehicle interaction level, the TalTech campus experiments demonstrated the importance of communication between autonomous shuttles and other road users. The study of signalling methods showed that pedestrians expect clear and intuitive cues about shuttle intentions, and that ambiguity can significantly reduce perceived safety. These findings directly link to the broader concept of a "language of driving," suggesting that the successful integration of autonomous shuttles requires not only technical safety but also socially interpretable communication standards.

The longitudinal surveys in Järveküla provided evidence of shifting public acceptance. Initial attitudes were characterised by cautious curiosity, often mixed with scepticism. After direct exposure to shuttle services, however, survey responses showed higher levels of trust and willingness to use autonomous transport, especially during daytime. This shift confirms the hypothesis that experience is a decisive factor in acceptance, but it also points to the persistence of concerns about safety at night and in adverse weather conditions. The surveys also revealed that acceptance is not uniform across demographic groups, with younger residents displaying higher readiness to adopt the technology compared to older populations.

The MaaS-XT platform and the EDTT model extended these findings from individual experiences to systemic integration. The platform demonstrated that autonomous shuttles can be successfully embedded in multimodal transport chains, providing first- and last-mile connectivity that complements existing public transport. The EDTT model quantified the benefits by showing that even limited deployment of shuttles could significantly reduce effective daily travel times in suburban areas dominated by private cars. This modelling result is particularly important for policymakers, as it provides a measurable indicator of efficiency that goes beyond perceptions and anecdotal evidence.

Bringing these findings together, the case studies highlight a consistent pattern: acceptance and effectiveness of autonomous shuttles emerge when technical reliability, human–vehicle communication, and system-level integration are considered jointly. No single dimension is sufficient on its own. Technical readiness without user trust leads to limited adoption; positive user experiences without systemic integration fail to generate measurable efficiency gains; and modelling without empirical grounding risks producing unrealistic scenarios. The triangulation of methods and results in this dissertation was therefore essential to establish a balanced understanding.

The synthesis also reveals broader implications for future research and policy. First, pilots must be designed not only as technical demonstrations but as social experiments that expose vehicles to real-world unpredictability. Second, regulatory frameworks should evolve to reflect the dual role of teleoperation as both a technical backup and a legal safeguard. Third, communication standards for human–vehicle interaction should be developed in parallel with technical systems to ensure clarity for all road users. Finally, integration into Mobility-as-a-Service platforms and quantitative modelling tools such as EDTT are necessary to demonstrate the tangible value of autonomous shuttles at the system level.

Together, these insights form the methodological and empirical contribution of this dissertation. They show that autonomous shuttles cannot be studied in isolation but must be understood as part of a socio-technical ecosystem where technology, people, institutions, and infrastructure continuously shape one another.

3 Experiments and Results

This chapter consolidates empirical evidence from a sequence of pilot deployments, field experiments, surveys, and modelling activities carried out between 2020 and 2023 in Tallinn and its suburban areas. The aim was to examine the feasibility, user experience, communication interfaces, and systemic implications of integrating autonomous shuttle buses into real-world mobility networks. The studies followed a structured progression from vehicle-level validation in mixed traffic environments, through human–vehicle interaction in controlled settings, to broader ecosystem integration and predictive modelling of travel time impacts. Together, these stages provide a comprehensive picture of how autonomous shuttles function within urban mobility systems and how users and institutions respond to their presence.

The Ülemiste City pilot focused on the operational and perceptual aspects of deploying autonomous shuttles in a complex mixed-traffic environment. The pilot was designed to assess whether an Estonian-built autonomous shuttle, certified as an EU M1 category vehicle, could navigate real traffic conditions while maintaining regulatory compliance and passenger trust. Prior to deployment, the vehicles underwent a sequence of inspections and closed-course tests, followed by a route-specific driving examination observed by regulatory authorities. Three shuttles operated along a 2.4-kilometre route linking key urban nodes, including offices, commercial centres, and transport hubs. The service ran without dedicated lanes, interacting with trams, buses, cyclists, pedestrians, and e-scooters. Over two months of operation, the fleet covered approximately 2,500 kilometres and served more than five hundred passengers. Remote teleoperation was available as a fallback mechanism for non-routine situations, demonstrating a pathway towards increased autonomy while maintaining human oversight for edge cases [6,22]. A single traffic collision occurred when a private vehicle violated a give-way sign and struck the shuttle, highlighting both the robustness of the regulatory response and the need for clear public communication to address perceptions of blame in incidents involving autonomous vehicles. Passenger surveys conducted after the rides revealed high levels of satisfaction with overall service quality, traffic safety, personal security, and ease of use. Most respondents expressed willingness to use the service during daytime, with a somewhat lower but still significant willingness to ride at night. Qualitative feedback indicated that direct experience helped to dispel prior uncertainty and strengthened trust in the technology.

Experiments conducted on the TalTech university campus shifted the focus from regulatory and operational issues to human–vehicle interaction in an open but controlled environment. These studies observed both passengers and pedestrians as they encountered the shuttle, analysing how communication modes influenced perceived safety and clarity. Passenger surveys captured a diverse sample, revealing generally positive perceptions of safety, tempered by occasional concerns related to unexpected braking and language accessibility of onboard announcements. Most participants found the simple cue of the vehicle arriving and doors opening sufficient for boarding, but many preferred supplementary audio or visual signals, supporting the development of layered human–machine interfaces. Most respondents were open to fully driverless operation provided that the system demonstrated safety and reliability, with concerns focusing less on driving performance and more on issues such as personal security and the availability of assistance. Pedestrian interaction studies showed that while most people were aware that the shuttle had no driver, a significant proportion relied on vehicle behaviour alone to infer crossing safety. Only a minority noticed the dedicated audio-visual signals intended to indicate when it was safe to cross, revealing both opportunities and challenges for designing a standardised and culturally legible "language of driving" for autonomous vehicles. Preferences for control modes reflected conditional trust: most respondents supported automated operation with remote operator intervention at complex nodes, aligning with a staged approach to autonomy. Participant feedback emphasised the importance of multilingual communication, clear explanations for braking events, improved external cues, and interior features such as seatbelts and ambient design that contribute to comfort and trust.

In parallel, interviews and surveys conducted in Rae Parish and along a port corridor provided broader societal and stakeholder perspectives on autonomous shuttle deployment. Interviews with manufacturers, service providers, and policymakers identified recurring themes, including the importance of transparent passenger information, cultural variability in interpreting gestures and signals, regulatory clarity, and the emerging role of passengers in a driverless cabin. A large-scale pre-deployment survey in 2021 indicated cautiously positive attitudes toward autonomous vehicles, with a significant share of respondents undecided and open to persuasion through design and experience. Perceived safety in mixed traffic was divided, with particular concern for vulnerable road users such as cyclists and scooter riders. Comfort levels were similar for teleoperated and onboard-operator configurations, while fully autonomous sensor-only operation was viewed more sceptically, especially in the context of child passengers. Many respondents, however, anticipated benefits such as improved mobility for vulnerable groups and reduced parking pressure. A follow-up survey in 2023 showed that direct exposure to shuttle services substantially increased both awareness and acceptance, with a clear shift in willingness to use autonomous transport daily. The findings suggest that experience plays a decisive role in normalising perceptions of safety and usefulness, while issues such as child ridership continue to require higher levels of reassurance and supervision.

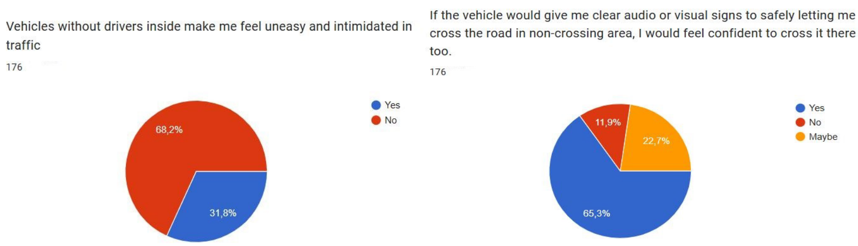

Figure 17. Two examples of the second survey 2023 in Rae Parish, both with 176 answers and both showing an increase of trust by 20% after the people had a chance to commute and communicate with ASBs, compared to the survey in 2021 before the pilot.

At the ecosystem level, a prototype of the MaaS XT platform was developed to test the integration of autonomous shuttles into a multimodal mobility environment. The prototype demonstrated the feasibility of securely orchestrating multiple transport providers through Estonia's X-Road infrastructure, enabling journey planning, routing, and ticketing across different modes. Autonomous shuttles were incorporated as routable resources, linking suburban homes to transport hubs and ferry terminals in a seamless itinerary. The experiment exposed practical challenges related to service-level agreements, variability in application programming interfaces, and user interface latency, but ultimately validated that autonomous shuttles can be functionally embedded within mainstream Mobility-as-a-Service platforms, which is essential for scaling and habit formation.

To generalise the empirical findings and assess the systemic impact of autonomous shuttle adoption, a compact predictive model was developed to estimate Effective Daily Travel Time (EDTT) for suburban residents. The model integrated survey data observed operational characteristics, and contextual variables such as stress factors and perceived costs. Baseline EDTT was approximately fifty minutes per day. Simulations revealed that the introduction of autonomous shuttles alone yields modest reductions in pure travel time, but when psycho-physiological stress factors are included, EDTT declines by nearly one-fifth at realistic levels of adoption. This reduction reflects the shift from stressful private car use and long first-mile walking segments to shuttle-based feeder services. The model further highlighted key policy levers, including increasing bus frequency, expanding shuttle fleets, improving walkability, and adjusting parking policies, all of which can enhance the overall efficiency and attractiveness of multimodal travel chains involving autonomous shuttles.

Across these different scales—vehicle operation, human experience, and network integration—the experiments demonstrate that autonomous shuttles can operate safely in mixed traffic at low speeds with teleoperation support, that clear and culturally appropriate communication is essential for user trust, and that integration into broader mobility ecosystems can translate localised improvements into system-level benefits [71–73]. Direct exposure consistently emerged as a powerful driver of acceptance, underscoring the value of real-world pilots as both technical tests and social experiments [1,3]. At the same time, the studies revealed important limitations, including the lack of winter operation data, the geographic specificity of survey samples, and simplifying assumptions in the EDTT model that require further empirical refinement. Overall, the results indicate that autonomous shuttles can enhance daily mobility when deployed within carefully designed regulatory, communicative, and systemic frameworks, and that their potential is best understood through a combination of empirical observation and predictive modelling.

4 Summary

This dissertation investigates how autonomous shuttle buses (ASBs) can be made safe, understandable, and convenient components of public transport in urban and suburban contexts. Treating AV shuttles as socio-technical systems, the work combines technical development and validation with human–vehicle interaction research, user acceptance studies, legal/regulatory preparation, and system-level modelling. The central premise is that deployment success depends not only on robust automation and vehicle engineering but equally on human factors, governance, and integration into everyday mobility services.

Methodologically, the thesis follows a layered, sequential design. Quantitative surveys (baseline and post-exposure) are combined with qualitative interviews and focus groups, field observations, controlled campus experiments on external human–machine interfaces (eHMIs), and pilots in mixed traffic. A prototype Mobility-as-a-Service (MaaS-XT) platform demonstrates technical integration into multimodal journey chains, while a compact Effective Daily Travel Time (EDTT) model quantifies system-level impacts by combining objective travel components (e.g., waiting, speed) with subjective costs and psycho-physiological stress factors. The empirical programme spans dense urban and pedestrian-rich settings (Ülemiste City, Kadriorg park), campus-based HMI experiments, and a suburban deployment with longitudinal acceptance tracking (Järveküla).

Key findings on technical feasibility and operations show that low-speed ASBs can operate reliably in open traffic with teleoperation as a safety fallback. A staged approval process—technical inspection, closed-course tests, and on-road examination—proved essential to assure regulators and the public. Real-world incidents underscored the importance of transparent communication: even when the AV is not at fault, the attribution of blame can be biased towards new technology unless stakeholders respond clearly and promptly.

Human–vehicle interaction results confirm the need for a clearer “language of driving” for autonomous shuttles. Pedestrians expect legible intent signalling (e.g., yielding/starting), and riders value layered information explaining non-routine behaviours (e.g., abrupt braking). Experiments with audio-visual cues and light-based eHMIs indicate that intelligibility, cultural legibility, and redundancy improve perceived safety. Mixed-reality and virtual-reality tools offer a scalable path to prototype, compare, and stress-test interaction concepts across diverse user groups, including children, older adults, and vulnerable road users.

User acceptance increased markedly after direct exposure. Baseline perceptions—cautiously positive yet uncertain—shifted towards greater trust and stated willingness to use the service following pilots that provided real rides and visible safeguards (e.g., teleoperation). Acceptance is heterogeneous: daytime rides are preferred, adverse weather remains a concern, and demographic effects appear, with younger users generally more ready to adopt. Communication quality and perceived availability of assistance are recurring determinants of comfort.

At ecosystem level, MaaS-XT demonstrates that ASBs can be orchestrated as routable, on-demand resources within a multimodal platform using secure data exchange. Practical challenges (API diversity, service-level coordination, UI latency) are surmountable with a middleware approach and clear governance. Embedding ASBs within MaaS is pivotal for habitual use, enabling first/last-mile connectivity to public transport nodes and reducing dependence on private cars.

The EDTT model provides a compact evaluation lens that fuses operational and experiential factors. In the suburban use case, baseline EDTT was on the order of one hour per day; scenarios with realistic ASB adoption showed substantial EDTT reductions driven not only by shorter access times but also by lower perceived stress relative to solo car travel and long first-mile walks. Sensitivity analyses highlight actionable levers—fleet sizing, bus headways, walkability, and parking policy—that amplify benefits when implemented jointly.

Table 6. Confirmations of the research hypothesis.

	Confirmed	Partially confirmed	Refuted
RH1	X (supported but requires statistical justification)		
RH2	X		
RH3		X (due to the lack of behavioural data)	
RH4	X		

5 Conclusions and Future Research

Across pilots, experiments, surveys, and modelling, the thesis demonstrates that low-speed autonomous shuttle buses can operate safely in mixed traffic when supported by a regulator-aligned staging of approvals and teleoperation as a fallback. Intelligible external human–machine interfaces and layered rider information are pivotal for perceived safety and trust and should be designed for cultural legibility and redundancy. Public acceptance increases markedly after direct exposure; determinants include clear communication, visible safeguards, and availability of assistance, with stronger acceptance for daytime operation. At ecosystem level, embedding shuttles as on-demand, routable resources within MaaS is critical for habit formation and scale, and is achievable via middleware and governance that harmonise service interfaces and responsibilities. Finally, the EDTT framework compactly links operational and experiential factors, highlighting practical policy levers—fleet sizing, headways, walkability, and parking policy—that jointly translate local service improvements into system-level benefits. Contributions are fourfold: (i) a structured, real-world evidence base for driverless shuttle operation in mixed traffic under a regulator-aligned approval pathway; (ii) an interaction design agenda and empirical grounding for eHMI and rider information to support situational awareness and trust; (iii) a reference architecture and pilot for MaaS-level integration of on-demand ASBs; and (iv) the EDTT framework that compactly quantifies user-centric efficiency gains and supports ex-ante planning decisions. Overall, the thesis shows that autonomous shuttles deliver the greatest value when technical reliability, human-centred communication, and MaaS-level integration are pursued together. This integrated approach enables safe operations, raises public acceptance through experience and intelligible signalling, and translates local service improvements into measurable, system-level benefits for sustainable suburban and urban mobility.

Since all these, characteristically different pilots gave a multifaceted overview of the criteria on where and under what conditions the use of autonomous public vehicles could be effective at this point of time, here are some conclusions, assumptions and requirements for the following solution options:

a) the use of autonomous vehicles

During the interviews (digital surveys don’t give that clear understanding of the real attitudes and as detailed reflections as interviews do) there is a clear interest and will to get autonomous shuttle buses to the streets in urban areas. There may be interest in cities also, but technically they need to be improved to be able to commute in heavy traffic without a safety operator onboard. When a vehicle passes all the tests of authorities unmanned, then they are ready for the open traffic. But as traffic is very complex, humans make mistakes and illogical last second decisions, teleoperated fully autonomous services can first be taken into secluded areas or areas with very little or next to any traffic. The highest cost for operating such services is the human who drives the bus but taking this out of the equation then this could be also economically beneficial.

After secluded areas, come the suburbs, where the local public transport stops are scarce and can be very far from even residential areas. Specially for people with special needs, like elderly, children and handicapped - quite commonly these people also don’t drive private cars and are exactly those who could benefit the most out of AV services to take them to these local stops and stations. But these studies and pilots showed that even more than getting to other public transport, that would take these people to the city, the need is to get to the local services – shopping centres, doctors' office or even schools and kindergartens.

b) their interaction based on this study

The assumption is that people are afraid of AVs, but as these studies pointed out very clearly – once the service is public, the authorities have given permission to carry people in AV shuttles – people trust very easily and on the contrary to assumptions, they prefer not to be bothered with safety operators or excessive security measures. This is a little different for older and Russian speaking demographic groups, but overall people are ready. And they are even more ready, once they have seen and tried the AV shuttle services themselves. This has happened in each of the pilot areas, where we've been twice – first testing has shown more reluctance and scepticism and the second round, people are significantly more willing to use AV shuttles.

The interaction with the shuttles has worked well, although people and especially older demographics, would like the AV shuttles to use more audio. The visual signage in front windows can be not visible in direct sunlight and not so well seen on the side of the shuttle, but overall people trust these signs and shuttles themselves have been programmed to not risk anything. This accordingly may be a little uncomfortable for passengers, who then must wonder about the sudden and substantial stops the shuttle must do to minimize these risks.

c) implementation of a demand-based public transport solution

On-demand will make the service even more convenient. During our pilot, we had set that the order had to be made in the telephone app at least 2 hours prior to the AV shuttle arriving close to the person's house. This had pros and cons. Positive is that the person can be sure and the app will confirm the date and time. This can be then adjusted to transfers to city buses or getting to the right place on time. But sometimes, of course there is a last-minute wish, then the person must go outside to find the AV shuttle on its route and then use it. The smart bus stops of course will also help, as they show how far in real time the next shuttle is. But of course, taking your own private car has an edge in such situations, as that can be used exactly on that second when there is the need.

To have a fully functional on-demand public service app, with a chance to also buy tickets, reserve electrical bikes, then there can be so many other perks, which can push people to still leave their cars at home and not worry about parking costs in the city, train station or ports, when next mean of transport is a ship etc. When everything can be brought together in one app, then this will start the essential need for such MaaS XT service and further along teach people to leave their cars at home or not even own them, as there is always a service close by through the phone. It will surely take some time and lots of testing. But as these pilots have shown, there are already people ready for such services.

Limitations include seasonal constraints (limited winter operation), geographic and demographic specificity of survey samples, and simplifying assumptions within the EDTT model that warrant further calibration. Future work should extend long-duration pilots across seasons and cities, formalise standardised eHMI taxonomies and testing protocols, scale teleoperation and remote assistance infrastructures, and integrate richer behavioural data (e.g., psychophysiological indicators) into planning models. 1) Extend multi-season, multi-site pilots (including winter conditions) to validate robustness and refine operational envelopes. 2) Formalise standardized eHMI taxonomies and cross-cultural testing protocols; compare modality combinations and attention capture. 3) Scale teleoperation and remote assistance: define safety cases, human-factors rules of engagement, staffing ratios, and escalation flows. 4) Enrich behavioural modelling by fusing psychophysiological indicators and privacy-preserving sensing with demand and performance data; incorporate these into EDTT calibration. 5) Optimise autonomous demand-responsive transit: fleet sizing, dispatch algorithms, and equity-of-access impacts in suburbs and small towns. 6) Advance regulatory and economic frameworks for liability, procurement, and SLAs within MaaS; develop cost-benefit methods that include user experience benefits captured by EDTT. 7) Quantify externalities and network effects—congestion, parking, urban logistics interfaces, and micromobility coordination—to support city-scale deployment strategies.

As numerous previous studies have shown that the following main categories can generally be used to assess the acceptability of using autonomous public transport:

- Operational efficiency
- Technological capability
- Solution acceptability and user experience
- Environmental efficiency
- Economic efficiency
- System-level and societal impact

To study and analyse these efficiency criteria and their impact and influence in correlation to each other, scientific validation of these indicators, their specific quantitative interpretation could give further insight to TAM as well as a fruitful base to integrating AV services into the public transport.

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When I registered for the Ph.D. position the whole autonomous vehicles subject was in fast development both in the world and specifically here in Estonia. We had launched at TalTech the first AV shuttle publicly three years before and were ready to start the development of a more advanced version 2.0. Having started—my two supervisors Prof. Assist. Prof. Dr. Ralf-Martin Soe combined two worlds I wanted to bring together—from one side the autonomous vehicles and from the other the smart city and people who will have to start living in the world and move in the traffic, where these AV shuttles are driving around. That sounded like the future and something that will interest both me and the society. Which also brought me to the subject of this thesis.

The success in my studies could not have achieved without the unconditional support and guidance of my supervisors. Both have been actively drawing my attention to everything that grew also my interest and understanding how important this research is. Being a novice on technical side, professor Dr. Raivo Sell showed so much patience and kindness to guide and support in all the technical issues and needed knowledge. This Ph.D. thesis would not have come together without his support in so many levels, not to forget the personal dilemmas and questioning of my abilities. Also, the guidance in choosing what and how to conduct research and what to choose for investigations and ultimately writing topics. Not knowing all my possibilities and angles of the work, assistant professor Dr. Ralf-Martin Soe helped bringing in additional specialists (Prof. Dr. Mauro Bellone) to help writing one of the articles as well as introducing some of the tools to help my work.

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KRISTER KALDA

DEC. 2025

TALLINN, ESTONIA

Abstract

Integration of Autonomous Last-Mile Minibuses into Urban Space

Autonomous shuttle buses (ASBs) are emerging as a promising solution for first- and last-mile mobility, yet their successful deployment depends not only on technical maturity but also on user acceptance, intelligible human–vehicle interaction, regulatory readiness, and system-level integration. This PhD thesis investigates ASBs as socio-technical systems and examines how they can become safe, understandable, and attractive components of public transport in urban and suburban contexts.

The research is based on a layered, mixed-methods framework combining real-world pilots, field experiments, longitudinal surveys, interviews with stakeholders, platform development, and predictive modelling. Empirical evidence was gathered through multiple case studies in Estonia, including mixed-traffic and pedestrian-rich pilots (Ülemiste City and Kadriorg Park), controlled human–vehicle interaction experiments on a university campus, and a suburban first-mile deployment with before-and-after acceptance surveys (Järveküla). In parallel, a prototype Mobility-as-a-Service platform (MaaS-XT) was developed to integrate on-demand autonomous shuttles with public transport and micromobility. To evaluate system-level impacts, a compact modelling framework—Effective Daily Travel Time (EDTT)—was introduced, combining objective travel components with subjective psycho-physiological and perceived cost factors.

The results demonstrate that low-speed autonomous shuttles can operate safely in open traffic when supported by a regulator-aligned approval process and teleoperation as a fallback. User acceptance increases significantly after direct exposure, with trust shaped by situational awareness, clear passenger information, and the perceived availability of assistance. Experiments confirm the need for a clear and culturally legible “language of driving,” using layered external and internal human-machine interfaces to communicate vehicle intent and non-routine behaviour. At ecosystem level, MaaS-XT shows that autonomous shuttles can be orchestrated as routable, on-demand resources within multimodal mobility services. EDTT modelling indicates that first-mile autonomous shuttles can substantially reduce the effective daily travel burden in car-oriented suburbs, especially when combined with supportive policy levers such as fleet sizing, public transport headways, walkability, and parking management.

Overall, the thesis contributes empirical evidence, design principles, integration architectures, and evaluation tools demonstrating that the benefits of autonomous shuttle buses are realised when technical reliability, human-centred communication, and MaaS-level integration are addressed together. The findings provide actionable guidance for policymakers, transport planners, and developers aiming to scale autonomous shuttle services as part of sustainable and user-centric mobility systems.

Lühikokkuvõte

Autonoomsete viimase-miili minibusside integreerimine linnaruumi

Autonoomsed bussid (ASB) on kujunemas paljulubavaks lahenduseks esimese ja viimase miili liikumisvajaduste katmisel, kuid nende edukas kasutuselevõtt ei sõltu üksnes tehnoloogilisest küpsusest. Sama olulised on kasutajate vastuvõtlikkus, arusaadav inim-sõiduki suhtlus, regulatiivne valmisolek ning süsteemitasandi lõimimine olemasolevatesse liikumisteenustesse. Käesolev doktoritöö käsitleb autonoomseid busse sotsio-tehniliste süsteemidena ning uurib, kuidas neist võivad kujuneda turvalised, mõistetavad ja atraktiivsed ühistranspordi komponendid nii linna- kui ka äärelinlikus keskkonnas.

Uurimus põhineb kihilisel ja kombineeritud metoodikal, mis hõlmab reaalseid pilootprojekte, välieksperimente, ajalise distantsiga korduvaid küsitlusi, sidusrühmade intervjuusid, platvormi arendust ning prognoosivat modelleerimist. Empiirilised andmed koguti mitmest Eesti juhtumiuuringust, sealhulgas segaliikluse ja jalakäijaterohke keskkonna pilootidest (Ülemiste City ja Kadrioru park), kontrollitud inimese ja sõiduki vahelistest suhtluse katsetest ülikoolilinnakus ning äärelinlikust esimese miili piloodist koos enne- ja pärast küsitlustega (Järveküla). Paralleelselt arendati välja liikuvusteenuste platvormi prototüüp MaaS-XT, mis lõimib nõudepõhised autonoomsed bussid ühistranspordi ja mikromobiilsusega. Süsteemitasandi mõjude hindamiseks töötati välja kompaktne modelleerimisraamistik – efektiivne päevane liikumisaeg (EDTT), mis ühendab objektiivsed ajakulud subjektiivsete psühhofüsioloogiliste ja tajutud kuluteguritega.

Tulemused näitavad, et madalal kiirusel liikuvad autonoomsed süstikbussid suudavad avatud liikluses turvaliselt toimida, kui neid toetab regulatiivsete nõuetega kooskõlas olev etapiline heakskiitmisprotsess ning kaugjuhtimine varumehhanismina. Kasutajate aktsepteeritus suureneb märgatavalt pärast vahetut kogemust, kusjuures usaldust mõjutavad eelkõige olukorrateadlikkus, selge reisijainfo ning abi kättesaadavuse tajumine. Eksperimendid kinnitavad vajadust arusaadava ja kultuuriliselt sobiva autonoomsete sõidukite “liikluskeele” järele, mis põhineb mitmekihilistel välistel ja sisemistel inim-masinliidestel sõiduki kavatsuste ja ebatavalise käitumise selgitamiseks. Süsteemitasandil demonstreerib MaaS-XT, et autonoomseid busse on võimalik käsitleda nõudepõhiste ja marsruuditavate ressurssidena multimodaalsetes liikumisteenustes. EDTT modelleerimine näitab, et esimese miili autonoomsed süstikbussid võivad autokesksetes äärelinnades märkimisväärselt vähendada elanike tajutud igapäevast liikumiskoormust, eriti juhul, kui rakendatakse toetavaid poliitikameetmeid, nagu sobiv sõidukipargi suurus, ühistranspordi tihedus, parem jalakäidavus ja parkimispoliitika.

Kokkuvõttes pakub doktoritöö empiirilisi tõendeid, disainipõhimõtteid, integratsiooniarhitektuure ja hindamisvahendeid, mis näitavad, et autonoomsete süstikbusside tegelik väärtus avaldub siis, kui tehniline töökindlus, inimkeskne suhtlus ja MaaS-tasandi lõimimine on käsitletud ühtse tervikuna. Tulemused annavad praktilisi suuniseid poliitikakujundajatele, transpordiplaneerijatele ja arendajatele autonoomsete süstikteenuste laiendamiseks kestlike ja kasutajakesksete liikumissüsteemide osana.

Appendix

Paper 1

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MANUFACTURING ENGINEERING

Use case of Autonomous Vehicle shuttle and passenger acceptance analysis

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Abstract. Autonomous vehicles (AVs) are moving from test areas to the streets, which is one of the key components of smart cities and the future of mobility as a service (MaaS). In 2020, two AV services were operated in Tallinn. This paper focuses on one of these services, and its set-up process. The pilot project took place in Ülemiste City, a tech park with 10 000 people working daily in the area, and it connected the offices with the airport and a shopping centre. The autonomous shuttle iseAuto, created first at TalTech, was used for the service (on streets with heavy traffic, including some complex crossings). Our findings associated with the Ülemiste experiment are presented in the context of legal requirements set upon autonomous vehicles to be street legal. Some events that occurred during the operation (including an accident) are addressed and a summary of the feedback from clients is presented. Further studies should focus on the extended concept of smart cities with a roadmap for the nearest future.

Key words: autonomous vehicles, smart city, self-driving car, last-mile shuttle.

1. INTRODUCTION

Autonomous driving is revolutionizing transportation and is going to change the whole paradigm in the near future. The autonomy is divided into five levels by the Society of Automotive Engineers SAE J3016 [1], where Level 0 refers to no autonomy at all and Level 5 means full autonomy in any conditions. Most of today's advanced and well known self-driving cars, such as Tesla Autopilot, are in Level 2 while low-speed autonomous vehicle (AV) shuttles/robot buses operate up to Level 4. First/last-mile AV shuttles have gained much interest recently by cities to pilot new transport opportunities in a specific area or route to extend the main public transport lines. The pilot experiments allow us to introduce self-driving technology to citizens of the community and test their maturity in real traffic and urban environments. Tallinn University of Technology (TalTech) started to develop a self-driving autonomous last-mile shuttle – iseAuto [2,3] in June 2017 in cooperation with the private company Silberauto. By using open source software and the chassis of existing electric vehicles, it was feasible to achieve a fully functional AV shuttle within only one year of intensive development. The first prototype shuttle called "iseAuto" was ready exactly a year later (in 2018) for the university's 100th anniversary celebrations. The next logical steps to be taken were to get the vehicle into real open traffic, with an ultimate goal to create a whole new autonomous traffic solution with safer and more environmentally sustainable mobility. Based on the prototype vehicle, several more mature vehicles were created by the industrial partner Auve Tech – the successor of Silberauto.

By 2020, iseAuto was developed to the level (according to both Estonian and EU rules) of being street legal. The most significant changes that had to be made to the prototype were related to the windows, more specifically to the material of the glass, which in accident situations has to break as safely as possible considering the

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passengers inside. The changes concerned also some other rules of M1 and M2 class vehicles set to windscreen wipers, air conditioning, lights, reflectors, seats and interior lighting. Two pilot testing sessions were simultaneously launched in open traffic during the last summer months.

The focus of these two pilot projects was on the self-driving shuttle usage by all sectors of the population and different groups of public transport users, whether for business or pleasure, under two different conditions of traffic density. Both projects were funded by the European Commission, one project was called Sohjoa Baltic [4] and the other FABULOS [5]. In the Sohjoa Baltic project, which was launched in the recreational park area of Kadriorg, a French AV shuttle Navya Evo was used. But in the FABULOS project, which had its Estonian leg of the test area in Ülemiste City (a tech park with offices for thousands of people, also with the Estonian international Tallinn Airport in the area) – the first ever Estonian built first/last-mile autonomous shuttle iseAuto was made street legal and tested by authorities to grant it the right to drive in real open traffic. FABULOS in Estonia (later in the autumn also in Greece, in a city called Lamia) brought together four partners – TalTech, Auve Tech, Fleet Complete and Modern Mobility. In Estonia, there were also the external consortium partners: Ülemiste City, Ministry of Economic Affairs and Communications, Tallinn Transport Department, Estonian Road Administration, Bercman Technologies, and Ericsson Eesti. In the Sohjoa project, a mobility acceptance factor was investigated [6] and specific feedback gathered. In this paper, the feedback is analysed and the findings are presented.

2. USE CASE IN ÜLEMISTE CITY

Cities around the world are experimenting with driverless autonomous vehicles, in particular with AV shuttles to be prepared for future mobility. Several studies in the United States [7] and Europe [8] have demonstrated that innovative cities are willing to deploy autonomous shuttles in the near future and citizens have mostly positive attitudes towards AV shuttles on the streets. In order to set up the use case in Ülemiste as required by the project, several modifications and upgrades were necessary to get legal permission for driving on the public roads. So far iseAuto has been tested only in closed areas (e.g., on a dedicated road on the university campus), but the initial idea was also to turn iseAuto into the first street-legal autonomous vehicle in Estonia. This process generally is, and in this case was, closely observed by different traffic authorities – The Estonian Road Administration, the Estonian Police and the Estonian Rescue Board. The legal environment is not yet mature for self-driving vehicles and differs considerably country by country even within Europe. Detailed analysis was also conducted by the Sohjoa Baltic project which included the legal environment of the Baltic Sea Region as well [9].

First, the authorities tested the hardware (a standard procedure for every vehicle) – whether the lights, windows, seats, tires, etc. are in the adequate condition. Then, test drives were conducted in the designated testing spaces, where they followed how the safety person operated the shuttle in case of need and emergencies. For example, it was observed how the control of the bus was transferred from automated driving to manual control. The braking system, the ability to identify objects in different sizes while driving in automated mode was tested, and how the vehicle acted when it had problems with IT systems. Last but not least, also a driving exam was organized in the area where iseAuto was planned to be operated, with the aim of experiencing and observing all different potential situations in traffic, as well as testing how the AV really acts in crossings and in relation to other members (including people) both in static and moving condition. After tests and modifications according to the prescribed rules of the authorities, the shuttles were restructured to meet the standards and were granted the permission to enter the public road traffic as EU M1 category vehicles. In parallel, new intelligent functions such as human-autonomous vehicle interaction methods [10] were experimented on TalTech campus by the Autonomous Vehicles research group.

The route in Ülemiste was chosen due to its different kinds of crossings, turns and the density of both traffic and people with the purpose of connecting the offices of Ülemiste City with a large shopping mall and a hotel in that area, as well as with the international Tallinn Airport. The route and list of bus stops are shown in Fig. 1.

Three AV shuttles were dedicated to the service, with engineers and technicians working daily on the details to advance the buses for the service and thus for future developments. Also, the operator's interface was developed on the accompanying tablet with controls connected to the controls of the shuttle. One of the important functions under testing was teleoperation, see the remote operation workstation in Fig. 2. Teleoperation enables the vehicle to be taken over in case human supervision is needed. This happens usually when unexpected situations occur on the route and shuttles cannot handle them on their own. Teleoperation is also vital to get the autonomous vehicles to Level 5, so that there will not even be a safety operator onboard the vehicle in the future. One of the ultimate goals is to control the traffic from afar, and thus the traffic will become safer to all members when the so-called human errors are eliminated.

The shuttles were not provided any special separate lanes, but were really merged into open traffic. The max-

Fig. 1. Test route and stops in Ülemiste City.

Fig. 2. Teleoperation in Ülemiste remote operation station.

imum speed allowed on the route was 30 km/h, but the speed was maintained around max 20 km/h, just for extra safety reasons. The drive included both left and right turns, crossing of the tram and bus lanes prioritized for public transport which serviced the airport. At the same time it was important not to forget the pedestrians, bikes and especially electric scooters of the people working in a tech savvy environment. For passengers, it was free of charge to use the services and the operational schedule was daily between 10:00 and 16:30. All the vehicles used on the route and one backup bus doing the demo ride can be seen in Fig. 3.

Another main focus of the pilot project was to test smart bus stops, with actual real-time info about the arrivals and departures displayed in the stations the whole time, while also recalculating if there had to be longer stops on the way or if the shuttle had to be removed from the rotation. These stops were crucially located: two stops in the middle of the business park, close to the offices, the third at the public transport hub of the airport (where also city trams and buses had their airport stations, linking thus the whole route to the city centre as well) and the forth stop was next to the hotel, being at the same time close to the shopping centre. Since the test pilot project ran only during summer months, the operation in drastic weather conditions that Estonia occasionally has during autumn and especially in winter months could not be tested, but there was heavy rain and winds alternating with mostly nice and sunny weather. There were wrongly parked cars on the shuttles' predetermined driving way, but since the AVs can easily pass obstacles, nothing more serious than a sudden stop happened in these special cases. As all the passengers have to wear a seatbelt and be seated, nobody was frightened (according to our survey on board and on the Internet during the service; this was one of our concerns and questions).

But the pilot project did feature one (and the first) major traffic accident, which taught first and foremost communication skills and that a predetermined action plan had to be adopted between the partners for all occasions – also risk management with a clear communication plan in unexpected situations. The accident was not caused by technical issues or the autonomous shuttle's safety operator. In fact, he could not expect it as the accident was

Fig. 3. iseAuto AV shuttle deployment in Ülemiste City.

caused by a private car that neglected the "give way" traffic sign, drove out on the road in the last second, and due to that the collision happened. The public and the media were fast to put the blame on the AV shuttle, but it was inspected quickly by the police and already in a couple of hours a press release was sent to all the main media channels to correct their assumptions. Nevertheless, it did expose the attitude of the public and the media who first want to judge a new technology which, on the contrary, makes the future traffic safer. In fact, humans make by far more mistakes than IT solutions and radar/lidar/sensor technology guiding the safety of AVs.

However, it has to be pointed out that not so much in a tech park such as Ülemiste City (where innovation-minded people are mostly working), but in the other above-mentioned pilot project launched in Kadriorg, in an area with a number of bikers and recreational park visitors, substantially more potential collision situations occurred (although due to the special attention of the safety operators not a single crash happened). Some of the bikers and walkers wanted to test the automated braking system by getting too close to the vehicle, which caused unnecessary dangerous situations both for the passengers inside the vehicle and the pranksters outside. Regardless of it nothing serious happened, and the only reason to postpone the start of the day or sometimes stop the service was related to making technical updates to the shuttles.

We carried out surveys in both pilot projects and used quite many of the similar questions for later comparison. In this research, however, we display the outcome of the major findings obtained directly from the Ülemiste City pilot project, where for the first time the first Estonian-built fully legal Level 4 autonomous vehicle was used in open traffic.

The aim of the survey was to learn more about what people really think regarding autonomous vehicles, more specifically about first/last-mile AVs, and to reflect their user experience. The survey was carried out during the two months that the pilot project took place in Ülemiste. It will even be used in future surveys as a refence and quideline to some of the questions that need to be asked again and again in the course of time, to identify the change in attitudes and overall knowledge about the potential and opportunities that this kind of new transport offers.

3. USE CASE SURVEY

Altogether we had 514 passengers. The operation on the public streets lasted for two months (mostly June and July 2020). The length of the route was 2.4 km and the total mileage of the shuttles was 2 500 km.

When talking to the passengers during their drive, they expressed that once using the AV, they appreciated it more than they thought they would when not really knowing what it meant to drive in one. For the project, it also shows in the unexpectedly high marks on safety. 10% (51) of all the passengers participated in the survey, some examples of the research results are presented in Tables 1 and 2 and illustrated by charts in Figs 4 and 5.

4. CONCLUSIONS

While the project introduced many new challenges that had not been tested before, it also gave many new insights and indicated daily what changes were needed to make

Table 1. Pedestrian feedback on safety and attitude

Average score for overall experience	6.57 (out of 7.00 maximum)
Average score for traffic safety	5.95
Average score for personal safety	6.27
Average score for ease of use	6.45

Table 2. Pedestrian feedback on the usage intention

I would use an automated shuttle bus during daytime	94.1% (out of 51 pax)
I would use an automated shuttle bus during nighttime	59.9%
I would never use an automated shuttle bus	0.04%

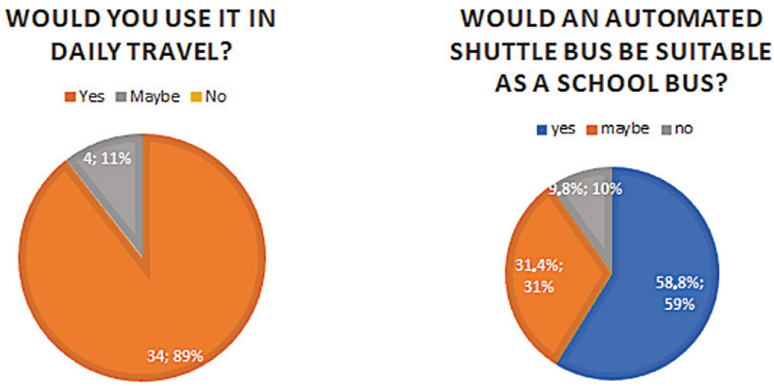

Fig. 4. Two charts on passengers' safety perception.

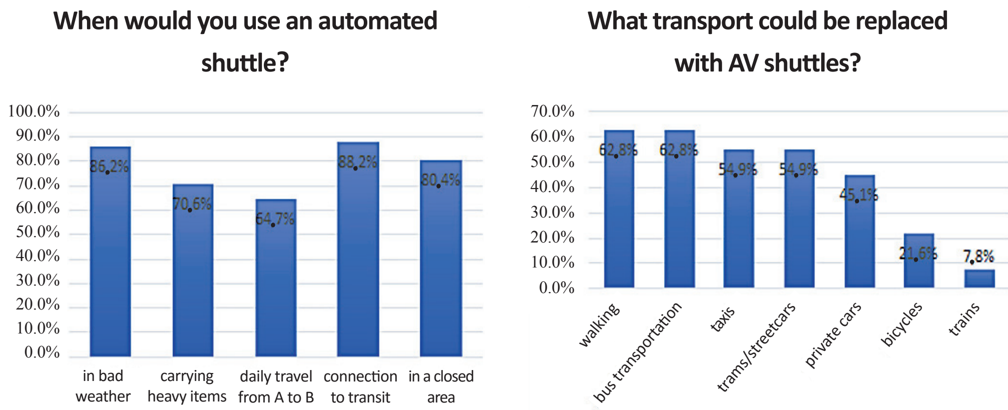

Fig. 5. Survey results on passengers' estimations of AV shuttles.

shuttles safer and more convenient for both the operators and clients. People are interested in trying autonomous vehicles, although quite many seem to be sceptical of AVs' chance to ever fully replace driver-driven vehicles in the traffic.

Now that this use case has come to an end, iseAuto has received a license to drive in real traffic, and the development of these shuttles to become part of MaaS components in public city transport has taken a huge step forward. We have received valuable feedback from daily users that confirm the need and safety expectations of the AV shuttles coming into service. After the successful pilot project in Tallinn, a pilot project under FABULOS consortium was launched on the streets of a city called Lamia (in Greece), where the local authorities also followed the requirements that the Estonian authorities had established for the vehicle and observed the same rules for that leg of the project as well.

The next three major steps to follow from these 2020 projects are: a shuttle service without any operator onboard in 2021 (closer to Level 5 – fully autonomous); creation of transport corridors by servicing rural areas with on-demand first/last-mile autonomous shuttles that will take people closer to the major public transport stops more conveniently (which will at the same time create a more sustainable and healthier environment); and the overall AV integration into the public transport ecosystem in 2022 (with cyber security being also an important issue in all forthcoming developments, due to the fact that AVs are connected and teleoperated over the Internet).

The ultimate goal is to encourage more and more people to use public transport instead of contributing to ever intensifying traffic on the streets with their private cars, in addition to not having sufficient parking spaces available in the cities.

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Eesti esimene pilootprojekt pärisliikluses Eesti esimese tänavalegaalse neljanda taseme isejuhtiva sõidukiga

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Isejuhtivad sõidukid sisenevad testialadelt tänavatele, mis on üheks võtmekomponendiks ka tarkades linnades ja tuleviku mobiilsusteenuste (MaaS) osa. 2020. aastal pakuti Tallinnas kaht isejuhtiva sõiduki teenust. Artiklis on keskendutud ühele neist, sisaldades infot, kuidas see üles ehitati. Pilootprojekt toimus Ülemiste linnaku tehnopargis, kus igapäevaselt töötab 10 000 inimest. Teenus ühendas kontorid lennujaama ja ostukeskusega. Selleks teenuseks kasutati isejuhtivat bussi iseAuto, mille esimene prototüüp loodi Tallinna Tehnikaülikoolis (tänavatel, kus toimus tavaliiklus ja kus olid ka mõned keerulised ristmikud). On esitatud ka Ülemiste eksperimendi testide tulemused, mis on seotud seaduse nõuetega isejuhtivatele sõidukitele, samuti juhtumid, mis toimusid eksperimendi käigus, sh liiklusõnnetus. On ka kokkuvõte küsitlusest, mille korraldasime sõitjate seas, ja edasised uurimused, mis peaksid keskenduma tarkade linnade kontseptsiooni edasiarendamiseks lähitulevikus.

Paper 2

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applied sciences

MDPI

Article

Language of Driving for Autonomous Vehicles

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Abstract: Environmental awareness and technological advancements for self-driving cars are close to making autonomous vehicles (AV) a reality in everyday scenarios and a part of smart cities' transportation systems. The perception of safety and trust towards AVs of passengers and other agents in the urban scenario, being pedestrians, cyclists, scooter drivers or car drivers, is of primary importance and the theme of investigation of many research groups. Driver-to-driver communication channels as much as car-to-driver human–machine interfaces (HMI) are well established and part of normal training and experience. The situation is different when users must cope with driverless and autonomous vehicles, both as passengers and as agents sharing the same urban domain. This research focuses on the new challenges of connected driverless vehicles, investigating an emerging topic, namely the language of driving (LoD) between these machines and humans participating in traffic scenarios. This work presents the results of a field study conducted at Tallinn University Technology campus with the ISEAUTO autonomous driving shuttle, including interviews with 176 subjects communicating using LoD. Furthermore, this study combines expert focus group interviews to build a joint base of needs and requirements for AVs in public spaces. Based on previous studies and questionnaire results, we established the hypotheses that we can enhance physical survey results using experimental scenarios with VR/AR tools to allow the fast prototyping of different external and internal HMIs, facilitating the assessment of communication efficacy, evaluation of usability, and impact on the users. The aim is to point out how we can enhance AV design and LoD communications using XR tools. The scenarios were chosen to be inclusive and support the needs of different demographics while at the same time determining the limitations of surveys and real-world experimental scenarios in LoD testing and design for future pilots.

Keywords: AV shuttle; self-driving vehicle; language of driving; simulations; interaction

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1. Introduction

Autonomous vehicles (AVs) are one of the dominant topics in engineering research, and a large number of private and academic organizations are investing resources to develop effective autonomous agents that will be populating our streets in the coming years. One major dilemma faced by autonomous cars is understanding the intentions of other road users and how to communicate with them [1]. Though localization, mapping, route planning, and control of AVs are widely studied, and the literature already offers working solutions in static environments, road users are non-static, complex, interactive agents having their own goals, utilities, and decision-making systems [2]; their study is an emerging research topic. Human–AV interaction (HAVI) with pedestrians must take these interactive agents into account in order to predict their actions and plan accordingly. The mode and intent of communication from the AVs to other road users are two fundamental requirements for the future of transportation systems. Clear messages and information are necessary to avoid misunderstandings between vehicles and pedestrians leading to unexpected behaviors, unnecessary vehicle yielding, or dangerous situations.

The current driving domain is dominated by human drivers and well-established communication channels based on human-to-human (eye contact, head positions, gestures) and machine-to-human (speed, direction, sound) cues [3]. This is supported by well-established and defined methods to communicate the vehicle status and intentions. This situation will slowly shift to a mixed agent domain, where autonomous vehicles will coexist together with human drivers. The fast development of these technologies foresees a future scenario where autonomous vehicles will dominate road traffic, and the presence of human-controlled agents will be minimal. Nevertheless, the presence of human agents or other road users in the traffic flow will probably endure. In this context, AVs should be able to communicate their status in a clear and understandable way, by making use of specific Human–Machine Interface (HMI) systems and interpreting human decisions by detecting pedestrians' movement cues and behavioral patterns [4].

HMI solutions taking into consideration the new Language of Driving (LoD) between machines and human agents need to be assessed and validated through user-based research studies. Furthermore, different road users' needs and abilities should be taken into consideration. Pedestrians and AV shuttle passengers might vary in different contexts or moments of the day. Scenarios like big hospital compounds, schools, or simply residential districts need to be considered with children, elderly people, and other fragile user groups being involved in testing and assessing HMI solutions for AV buses.

This work aims at tackling this topic by presenting results from a real-world experimental study carried out at Tallinn University of Technology campus and involving 176 pedestrians interacting with the ISEAUTO autonomous driving shuttle. For further details about the ISEAUTO autonomous shuttle and connected research, please refer to [5–7]. We present here the results from the survey collected during the experimental sessions. The survey and interview results are evaluated via focus group interviews with key public sector representatives from the Ministry of Economic Affairs and Communications, the Estonian Transport Administration, and the City of Tallinn. Based on the findings, we propose an architecture for a Mixed Reality (MR) simulation application aimed at designing, testing, and assessing external and internal HMIs for AV shuttle interactions with pedestrians and passengers. This approach can deliver fast prototyping of different design solutions, repeatability, and an inclusive and safe testbed for interface validation with human agents. VR technologies and devices could easily integrate physiological sensors and motion-tracking systems to optimize the understanding of the street user response to AV movements and behavior, allowing for fast adaptation to different requirements and user skills and abilities.

2. Related Studies

The recent literature shows that the two main aspects of Human–AV interaction (HAVI) are pedestrian–vehicle interaction, which is addressed in works such as [8] or [9], and pedestrian trajectory prediction [10]. One of the first open traffic use cases of the autonomous vehicle shuttle and passenger acceptance analysis [11] in Estonia and Europe gave rise to the creation of questions for interviews conducted with people in traffic, which are referenced here. Pedestrians often use explicit means of communication, such as a handwave, to resolve conflicts in traffic scenes, e.g., yielding to the driver or requesting the right of way [1]. Pedestrian–vehicle interaction usually requires a model that can describe individual pedestrian motion under the influence of nearby pedestrians, vehicles, and traffic lights [12]. Many other studies focus on AV-to-pedestrian communication and the language of driving evaluation by means of real-world experiments or simulations. Furthermore, some comparable cross-country data with similar AV pilots are available in [13], which brought up the need to investigate how the authorities see the future of AVs in a broader context (resulting in such an interview, included as part of this current article).

Faas et al. [14] proposed a longitudinal study to assess the impact of AV external HMI (eHMI) on pedestrians crossing the street. The study proposed three scenarios based on the AV mode and intent communication, namely no communication (baseline), light-based status communication, and status plus intention communication. The proposed experiment makes use of a monitor-based video projection of a vehicle approaching while detecting user crossing onset time, as well as a rich variety of subjective metrics by means of standardized and ad hoc tools. Results show how the eHMI supports the pedestrian in accepting the missing driver, while making him or her feel safer and more efficient in making a decision. The study points out that training and education is necessary to optimize the understanding of the signs and that learnability improves over time. Another study by the same authors [15] shows the importance of external HMI in the case of tinted windshields or distracted drivers, demonstrating the need of AV mode communication regardless of driver state.

The study by Ackermann et al. [16] employs a user-centered design approach to detect requirements for eHMI through focus group interviews and, in a second phase, proposes a video simulation-based experiment testing eHMI solutions with pedestrians. Both phases show interesting results for the definition of efficient human–AV communication. The interview sessions pinpointed some fundamental requirements, including the use of uniform symbolism or language, intuitive comprehensibility, clear reference to the pedestrian, and similarity to current communication. Experimental results compared HMI solutions differing for position, technology, coding type (textual or symbolic), and type of information provided. Results show that projection cues are preferred to LED light strips, while text messages are ranked higher than symbols. Nevertheless, the latter are not always understood and recognized. The windscreen was ranked as the most comfortable position for messages, and in general the users preferred pedestrian advice over AV status information only.

The Study by Dey et al. [17] explores the impact of the approaching vehicle appearance and behavior on the pedestrian decision-making process while crossing a street. Results show that while distance and behavior of the car play a crucial role in making a decision, vehicle design and appearance do not have much influence on pedestrians. Results from a field experimental study presented in [18] show that most pedestrians are able to manage a road crossing scenario with an autonomous vehicle without any eHMI or cues from the driver. Nevertheless, as some of the pedestrians hesitated or did not proceed in crossing the road, the authors foresee the necessity for a clear communication channel from the AV towards the other traffic agents. This is generally a common approach for inclusive design methodologies.

Several studies attempted an evaluation and assessment of design solutions based on pedestrian response using VR. De Clercq et al. [19], for instance, employed a VR immersive environment to test a combination of behaviors, eHMI, and vehicle type on pedestrian road-crossing scenarios. Results show that eHMI improves the feeling of safety for yielding vehicles while it does not influence decisions for non-yielding vehicles. The study demonstrates how text-based messages represent the most unambiguous communication method, which does not require any learning or training phase to understand the sign state change meaning. Texts are nevertheless not the most universal methods to deliver a message, as they require focused attention, they might not be readable by all users, and they might be more affected by weather conditions.

The study by Stadler et al. [20] argues that VR is a suitable tool to replace real-world tests on eHMI usability in AV–pedestrian communication. The experimental setup employed an immersive environment, accessed by Head-Mounted Display (HMD), and proposed different eHMI solutions (e.g., LED strip, symbols, arrows) for the virtual AV. Efficiency, effectiveness, and satisfaction parameters were assessed by means of qualitative and quantitative data analysis on users' reaction and decision process while crossing the street. The study validates the use of VR for assessing eHMI and underlines the advantages of rapid prototyping and user testing in a simulated environment. The same conclusions are supported by the study presented in Deb et al. [21]. The results support the use of immersive VR and real-world movements against different AV behaviors. The study assesses user experience (UX), usability, presence, and sickness symptoms and collects quantitative data related to street crossing time and user head and body position in space. The conclusions are positive in terms of crossing time correspondence with real-world scenarios in the literature, usability, and cyber sickness. The prototype presented in [22] integrates eye tracking in a modular VR architecture for testing eHMI communication for autonomous public transportation buses. Sight analysis eventually supported the evaluation of pedestrian attention on the proposed communication systems and solutions. Rettenmeier et al. [23] address the AV-to–car driver communication in difficult traffic scenarios by means of eHMI solutions.

Other studies address the evaluation and design of Internal Human–Machine Interfaces (iHMI) for autonomous vehicles by making use, for instance, of hybrid on-road simulations for internal human–vehicle interface assessment. The system is described in [24] and proposes a wizard driver-based AV experience where the user is able to interact with the car console through tracked virtual hands in an immersive VR scenario. The goals are keeping the prototyping costs low, having a realistic experience, and improving the variety and quality of UIs and interactions between the user and AV. The study by Flohr et al. [25] addresses the user experience of shared AVs aimed at public transport. HMI assessment and prototyping is achieved by adopting an immersive video-based system architecture aimed at the evaluation of human factors during travel and the improvement of trust. The study by Morra et al. [26] proposes an immersive AV passenger simulator supported by physiological and qualitative data analysis to assess the user experience of AV state feedback and performance.

As already mentioned, the inclusiveness of frail subjects in the experience of use of shared AV systems should be one of the focal points of research in this field in the coming years. Considering these vehicles will be supporting local mobility, including daily routes covered by the elderly or children going to school, understanding the needs, type, and specificities of the LoD and HMI communication channels is crucial. A few recent studies have addressed these requirements by testing internal and external HMIs in ad hoc experimental setups with children, such as in Charisi et al. [27], or detecting preferences and the usability of AV interfaces in elderly users, for instance in the works by Morgan et al. [28], Voinescu et al. [29], and Othersen et al. [30]. The definition of a universal LoD that would be suitable in different contexts and open to easy interpretation from any user is nevertheless in its initial phase and needs efficient and reliable tools for faster design and assessment.

3. Language of Driving

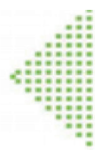
Autonomous Vehicle technology has been introduced into our daily living experiences, and to date, the vast majority of accidents involving AVs have been as a result of humans hitting AVs [31]. This is happening at a rate higher than human agents hitting other humans. An imminent challenge, as pointed out in the study by Favaro et al. [32], is the transition period during which human road users have to interact and communicate with AVs. Vehicle manufacturers are already developing AVs fitted with virtual eyes or panel displays that contain messages intended for pedestrians, in an attempt to bridge this communication gap.

Many studies have tested and assessed different external interfaces for AV communication during simple interactions such as road crossing or traffic yielding. Nevertheless, the language of driving is quite complex and not yet defined in any formal manner. As introduced in the first SAE Edge article [33], driving is a highly complex task that requires drivers to communicate and interact with other road users to signal their intent and safely operate their vehicle. Drivers, cyclists, and pedestrians receive messages from other traffic agents, including micro-accelerations, braking, honking, eye contact, and physical gestures. Meaningful predictions and assumptions are inferred from these messages, allowing road users to understand the driving intention and on-road maneuvers. This form of communication is modulated by road conditions such as weather, time of day, and traffic congestion. Furthermore, this language has different dialects, determined by culture and geographical location. For instance, drivers in India have their own language to communicate their intentions, emotions, and greetings via the car horn [34]. Given the intricacies of communicating and understanding the language of an air horn, there is much work to be done regarding the unspoken and underexplored language of driving.

It is evident that the LoD needs to be defined before developing software or interfaces supporting the interaction between road users and AVs. Once defined, the AV behavior can be verified against responsiveness to human communications. One last critical point in this novel field is the level of safety and acceptance of risk. As much as flawed human driving behavior is tolerated, this seems not to be a feasible option for an AV. The level of safety in traditional traffic interactions seems to be higher, probably because communication between agents is more understandable and humans can easily infer the point of view and messages of other human drivers. A massive upgrade in the language of driving for AVs may be the key to the acceptance of the risk.

Our vehicle currently provides several signaling symbols to pedestrians by means of a LED light panel. A blinking red cross pattern is used when the ISEAUTO shuttle detects an object that is on its way; it is intended to alert people when a dangerous situation might occur. Eventually, the signal aims to warn the pedestrians that they should not cross the street. Animated green arrows are displayed when the vehicle detects agents next to, or on, a crosswalk. The green arrows are an invitation to cross. The last symbol, vertical stripes, communicates that the AV has detected a pedestrian crossing (see Table 1). All symbols are displayed concurrently on one horizontal panel in the middle and two vertical panels on the sides.

Table 1. LED signaling patterns used by the AV bus to communicate with other traffic participants.

Trigger	The vehicle is approaching a pedestrian crossing; pre-defined either by vector map or V2I communication	Objects detected by the sensors	Objects detected by the sensors
Situation	The vehicle is approaching a pedestrian crossing	The vehicle is approaching the pedestrian crossing and objects are detected on the zebra or nearby	The vehicle is driving on the road, and objects are detected close to waypoints or their moving trajectory is about to cross with the vehicle
Visualization			

4. Method

It is important to ensure that the users of public transport feel comfortable in using autonomous buses and that pedestrians feel safe sharing their environment with AVs. Therefore, it is important to collect feedback both from the passengers and pedestrians during the pilots. As we ran this particular pilot without the operators on board, it was especially important to determine what the subjects think about such a setting and what can be improved. For example, what do the passengers think about how the bus and its remote operator should communicate with them and how do pedestrians understand when they can safely cross the road? The answers to such questions are critical for the further development of autonomous buses.

4.1. Experimental Setup

The experimental setup included one self-driving shuttle minibus, driving fully autonomously on the TalTech campus road, which is semi-open for public traffic (see Figure 1). In addition to the vehicle, the setup consisted of two smart bus stops, one smart pedestrian crossing, and one pedestrian crossing without a special traffic sign. Vehicle operation was monitored in real time by a remote operator.

Figure 1. Typical pedestrian crossing scenario for AVs.

The current research focuses on the pilot projects that took place mainly during the summer months of 2021 (no winter conditions). The initial plan was also to use spring for the pilot, but due to COVID-19, we had to postpone the start. There was a pre-marketed service as a press release; it was featured on university web pages and on both the university and institute's social media, suggesting that people come and test the AV service every weekday from 4–6 PM. The time was chosen specifically because many people leave their offices at that time; thus, not just students would be interviewed, but employees. This is also the time at which local people, including the elderly, walk around the campus area.

In order to maximize the passengers' response and receive a broader opinion, we decided to conduct interviews instead of using a post-travel web survey.

The number of passengers that used the service was 539 passengers, but the answers and the analysis were based on two different aspects—those riding on an AV shuttle and those who happened to be participating in traffic scenarios with the AVs (for example, crossing the road in front of the AV shuttle). Both on-board (53 interviews) and on the side observations (176 interviews) were included.

4.2. Focus Group Interview

In addition to the survey, a focus group interview took place mid-February 2022 with three public sector experts on AV implementation, representing the Ministry of Economic Affairs and Communications (responsible for AV nationwide regulation), the Estonian Transport Administration (responsible for AV implementation and permits), and a transport expert from the capital City of Tallinn who was involved in the implementation of several AV pilots from the city perspective. From the research team, we had four members asking mainly pre-structured questions. The focus group interview took place online and lasted 90 min. The interview was recorded and later transcribed with Otter.AI software. The main questions relevant to this study are, for example, "*How do you envisage the AVs in Estonia, in Europe, and globally in 1, 5, and 10 years? (fully autonomous?)*" and "*How does the current infrastructure in Tallinn and Estonia allow the traffic to adapt to AVs, and what could be the changes needed in the long run?*".

5. Results

5.1. Survey among Passengers

During the pilot, we interviewed 53 passengers, who either occasionally happened to be in the area or had read about the pilot and wanted to try the AV shuttle. The pilot took place at the campus of Tallinn University of Technology; therefore, one has to take into consideration that the participants might be more knowledgeable about the existence of autonomous vehicles as compared to the general population. Still, for many people, it was their first experience with an autonomous bus.

Of the respondents, 52.8% were men and 47.2% were women; 34% of the respondents were under the age of 18 (youth in school, aged 15–18). One quarter (24.5%) belonged to the age group 18–30 years (mostly students commuting in the campus area). Slightly over one-fifth (20.8%) belonged to the age group 31–45 years, and 17% to the age group of 46–60. Just two respondents were over 60 years of age. Just over half—52.8%—of respondents had a university degree, 30.2% had primary education (children), and 17% had secondary education (high school or vocational degree); 59.6% were employed, and the rest were students (40.4%).

The results showed that 48.1% answered that they use public transport on a daily basis, and 17.3% were weekly users; 30.8% of the respondents answered that they use it less often. Just two people (3.8%) answered that they never use any public transport. In terms of the reasons for participation, 40.4% of the respondents knew about the pilot through personal invitation to try it out, 25% had heard about it from the media, 23.1% saw the bus on the street and approached it, 19.2% had heard about it from a family member, and 28.6% received the information from their teacher or via their school/university.

First, we asked participants to rate the overall feeling of safety on a scale of 1–7. Nobody felt completely unsafe. Two people rated it as "3", and one person as "4"—mainly because of unexpected braking, and they did not have their safety belts on. Moreover, it felt unexpected that after the safety stop, the doors remained closed, and the bus audio was only in English and not in the local language. There remains much uncertainty about autonomous vehicles taking over the traffic. Many are skeptical about autonomous and non-autonomous cars driving on the streets together, which creates prejudice that autonomous cars might not be safe enough for everyday traffic. However, while riding in the AV, they saw that at low speeds, it was quite safe and there was a great focus on safety in general: 18.9% of the participants rated the overall safety with "5", and 39.6% rated it with "6". A little over one-third (35.8%) of all respondents rated the overall safety with "7". This means that over 75% of all respondents feel "very safe" while riding on the autonomous vehicle, even without the safety operator onboard. This encourages us to look further into the possibilities of connected and cooperative autonomous vehicles (CCAMs).

Next, we wanted to know how the passengers felt about their personal safety. The results were quite similar, with just minor changes: 7.6% of the passengers who gave the lowest scores ("3" or "4") and can be considered the most skeptical, explained their low grades with a worry that "at least somebody should be onboard", "the seatbelt was missing", and "it created a little phobia, being in a closed room and the robot bus communicating in a foreign language". A total of 28.3% of people rated it with a level of "5", which is substantially higher compared to the previous question, showing that people are more worried about their personal safety than about the overall traffic safety. The majority still considered it "very safe", with 30.2% of people rating it "6" and 34% rating it with "7".

Furthemore, this research aims to understand to what extent people are ready to travel by an autonomous bus. The results show that the autonomous buses could have more functions than just providing the last-mile service. While slightly less than one-third of the respondents preferred to use the service in the range of last-mile service, over half of the people answered that they would like to use the service for longer distances. However, over 60% of the respondents prefer to use the service in the range of up to 5 km. Interviews clearly showed that people feel that the vehicles are reliably controlled over such a distance. Slow speed has another strong effect on these answers, as most people felt it would be a waste of time if autonomous buses would serve longer distances. Nevertheless, almost a quarter of passengers who answered the survey (24.5%) indicated that they do not really see reasons to limit these distances. Some added that with bad weather or missing other means of transport, such a service could be really helpful, especially for the elderly and disabled people living in rural areas, where getting to the food store or to the town center can be a struggle. In addition, elderly people might even prefer a slower ride.

The survey also investigated how autonomous buses should let awaiting passengers know that the boarding has started. People who are used to public transport were sure that simply arriving at a bus stop and opening the doors is enough information for them to enter the vehicle (67.3% of all respondents). As it was a multiple-choice question, there was a significant number of respondents who wished to receive an audio signal (57.7% of all respondents). For example, this could be a voice saying that it is safe to board the vehicle. A total of 28.8% of respondents would like to have blinking lights or signs. Only one stated that there should be a button to open the doors and an audio signal that the doors are closing and the drive will start. It was rather common that people asked for audio messages in different languages, mainly because they wanted to have all possible ways of indicating information.

Going even deeper into the actual perception of a fully driverless bus service (even without the remote operator), we first and foremost wanted to know how ready people are to have such a service, where there is not even a teleoperator controlling the vehicle while they are riding in the bus. A total of 60.4% of respondents answered that they would use the service even without a remote operator. However, many people specified that they would use it if the technology is proven to be safe and it is used also by other users. A little over a quarter of respondents (28.3%) questioned the safety aspects more strongly, saying that they might use the fully autonomous shuttle services, and 11.3% answered that they would never use such a service. The biggest concern was personal safety, especially if when considering mass transit. There were respondents who added that having a remote operator who keeps an eye on the situation in the bus should be reduced to the minimum. Others feared vandalism, drunk people, or bullying and added that because of these reasons, there should always be a safety operator onboard.

We asked people whether the type of driving control of the AV, remote or autonomous, should also be communicated to the passengers; 51.9% of the respondents answered that this information is important for them, as they want to be informed at all times about what is happening with the bus, bearing in mind that this is a novel experience for everybody. Some respondents said their opinion might change in the future when AVs will be more common, and 48.1% expected public transport to be safe and not to be allowed on the streets if otherwise and thus did not need such information.

While riding on the bus, we asked people how they would want to be in contact with the remote control centre. We noticed some differences in the answers based on nationality. Estonians do not need to communicate unless necessary. People with Russian backgrounds are willing to use the remote support and wish to have more communication channels. We let people choose from several predefined options, as shown in the following figure.

As shown in Figure 2, 52.8% of respondents would like to have an onboard phone that enables them to contact the operators; 47.2% of respondents answered that just a phone number to call, when needed, is enough. The rest of the answers were substantially less popular: 17% answered that they would like to have a video call possibility with remote operators, and 15.1% did not need any kind of connection with the operator, referring to their previous public transport, where they did not communicate with drivers or the public transportation office regarding any issues. Only 7.5% of respondents wanted a continuous video and audio stream from the bus to the remote control centre. The goal of this question is twofold, as it indirectly addresses privacy issues; passengers willing to be connected to the remote operator (using an audio–video stream) are also less concerned about data privacy.

When asking the passengers when they would use such a service the most, we gave the interviewees a specific set of choices. Passengers' answers were equally distributed between using self-driving buses for daily commuting (26.4%) and in closed areas such as campuses, industrial parks, airports, hospitals, etc., or in bad weather conditions (24.5%). Surprisingly, the possibility of using the service as a link to transport hubs or other public transport options was not the most popular answer. This could have been affected by the actual area where the pilot took place, as there were no visible bus stops in the vicinity.

As people could choose only one answer, the most preferred option was using the service for daily commuting, which can include many of the other reasons mentioned separately. Some passengers who gave a different answer added that they would also use it on other occasions.

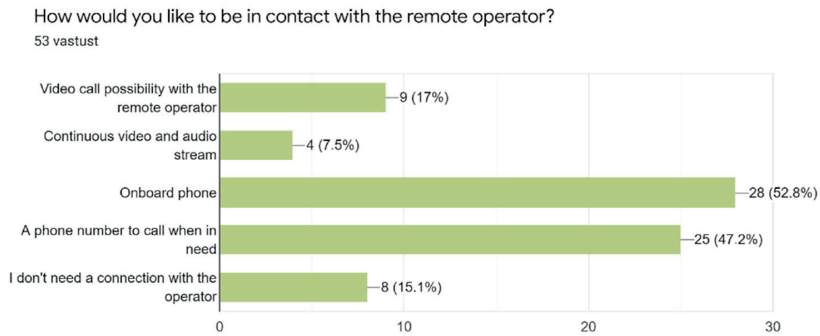


Figure 2. Results to the question "How would you like to be in contact with the remote operator?".

At the end of the interview, passengers were asked to rate their overall experience on a scale of 1–5. The average score was 4.44, which can be considered very high. While 50% of all participants gave "5", and 46.2% gave a strong "4", only one person gave a "3", and one person a "2".

5.2. Survey among Other Road Users

The second part of the survey during the pilot in Tallinn involved a different subject group in the assessment of the pedestrian-to-AV interaction in normal traffic conditions. This survey was conducted among the other participants in the traffic, who were not riding on the AV. This mostly includes pedestrians, and to a lesser extent, the users of light modes of transportation (bicycles and scooters). Visual communication between people in traffic plays an important role in dealing with different situations. For example, pedestrians rely on visual contact with drivers to assess whether it is safe to cross the road. As the end goal of building AVs is to remove safety operators from autonomous buses, it is important to collect feedback on how autonomous buses without an operator on board should and could communicate with other traffic participants (Language of Driving—LoD). To gain more in-depth insight, we gathered input through 176 structured interviews, which were conducted on the streets of the pilot area at the TalTech campus.

Out of 176 people, 50.3% fell into the age group of university students (18–30 years), 17.1% were aged 31–45, and just as many were aged 15–18. A total of 11.4% were aged 46–60. The smallest response rate was from the 60+ age group, with only 4.1% of total respondents. Of the respondents, 54.5% male and 45.5% female, and 51.3% of interviewees had a university degree (the pilot took place in TalTech campus area), 30% had secondary education (high school/vocational school), and 18.7% had primary education.

The first question aimed at assessing the state of awareness of the pedestrians towards the AV and the fact that there is no driver in the vehicle. The results show that 93.7% were aware of this, and only 6.3% did not understand that the bus was moving totally by itself.

Interestingly, 68.2% of respondents answered that they were not uneasy or intimidated by the driverless vehicle. Many of them added that the autonomous buses are so slow that, if necessary, they have plenty of time to step aside or react. Finally, 31.8% of people answered that they feel uneasy and intimidated while sharing the road with autonomous vehicles; many of them felt it is just odd and noticeable, and thus it makes them be more attentive.

On the pilot site, there was one "official" and one "unofficial" pedestrian crossing. The latter refers to a place where it is convenient for people to cross the road. This gave us a possibility to also address the safety issues related to crossing the road in front of a fully driverless vehicle (see Figures 3 and 4).

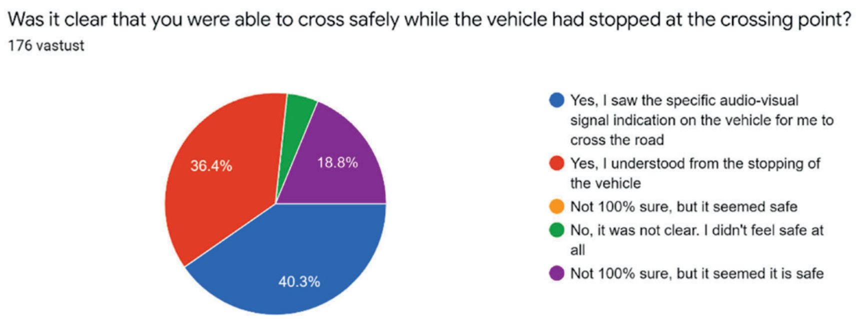


Figure 3. Answers to the question "Was it clear that you were able to cross safely while the vehicle had stopped at the crossing point?".

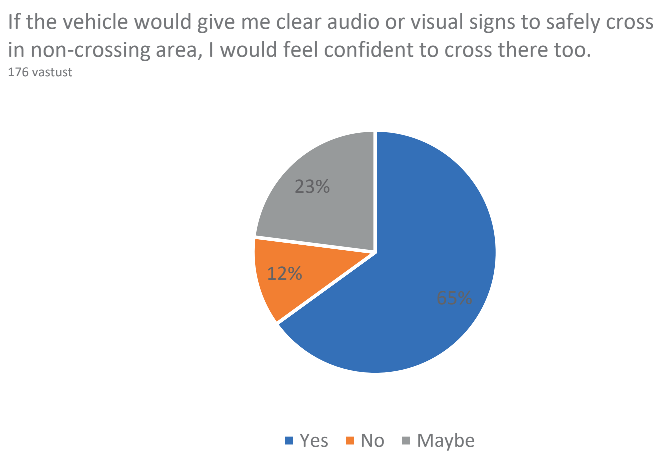


Figure 4. "If the vehicle would give me clear audio or visual signs to safely cross in a non-crossing area, I would feel confident to cross there too".

As shown in Figure 3, only 40.3% of the respondents answered that they saw the specific audio-visual signal indicating that it was safe to cross while the vehicle was stopped in front of the pedestrian crossing; 36.4% of the respondents answered they understood that it was safe to cross solely from the stopping of the bus; 18.8% were not sure, although they did cross the road as it seemed safe; 4.5% of the respondents answered that it was not clear at all whether they could cross the road, and they did not feel safe to do so. The results show that there is room to improve the audio-visual signals by making them more understandable. It is of utmost importance that people feel safe in such situations, as it will also affect the overall perception of safety in traffic with autonomous vehicles.

When we asked about whether the respondents would feel confident to cross the street in a non-crossing area if the bus were to give audio-visual signs that it is safe to cross, 65% of the respondents answered affirmatively, 23% answered "maybe" and added that the decision would depend on the overall street traffic, and 12% were sure they would not cross the street even if the vehicle gave them the priority and yielded. We also have to keep in mind that some people would not cross anywhere where it is not strictly permitted.

A further question addressed the topic of who should be in control of the vehicle, as there might be a physical operator or a computer operator using artificial intelligence

(AI) to drive the shuttle. This resulted in creating confusion for some of the respondents. Many of them did not understand what exactly artificial intelligence (AI) means, including its limitations and how it makes decisions. As the survey was conducted at the university campus, many of the respondents were connected to the university as students or employees and had a better understanding. Therefore, we did not have to provide a very in-depth explanation of AI to them. Most of the respondents considered AI to be more intelligent than a human, having the knowledge, precision, and even better and faster reaction time than humans do.

Of the respondents, 61.7% answered that AI should have control over the vehicle; however, in more difficult situations such as at crossings, a remote operator should take over. Over one quarter of the respondents indicated that full AI mode is also acceptable, and 12% thought that the vehicle should be under the remote operator's control at all times. This reveals a well-known aspect of technological anxiety, as passengers and other road users prefer the remote operator to take control in places where the vehicle interferes with road users.

5.3. Additional Suggestions from Participants

During the two surveys, we also received a number of comments as open suggestions for the future development of autonomous robot buses. Such comments covered several topics, which are summarized below.

- Speed—people want the buses to drive faster (this was the most common comment).
- Vehicle-to-passenger communication:
    a The bus should preferably deliver messages in several languages;
    b The bus should be more communicative and explain what and why it is doing something (e.g., why the bus has braked suddenly);
    c There was a suggestion to play lounge music inside the bus.
- Language of driving:
    - More audio should be used to communicate with other participants in the traffic, as the signs shown in Table 1 were not fully understood or it was hard to see them under direct sunlight. The audio message should also be shown as text on the screen(s), as it can be hard to hear in traffic;
    - Some suggested using only text instead of the signs in Table 1.
- Design:
    - Both the interior and outer design should be more appealing;
    - The use of brighter colors was recommended to better differentiate AV buses from regular vehicles.
- Smart bus stops and the size of the bus:
    - The one who orders the bus should also be the one who enters the vehicle, as these shuttles are quite small in size, taking up to 6 people;
    - The size of the bus should be bigger and accommodate at least 10 people.
- Passenger and traffic safety:
    - Worry about not having a safety operator was expressed, as some passengers or even vandals might damage the bus;
    - Passengers also worried about the missing seatbelts, which can easily be added and, according to the law, should be there if there is a wish for such buses to be operated in open traffic.

5.4. Survey among Public Sector Experts

This section summarizes the focus group interview conducted with three public sector AV experts (see also Section 4.2). On one hand, the public sector experts stated that the technology is not ready for fully autonomous service, but they envision it to be in the future. For example, the Tallinn City Transport Expert commented, *"I think accessibility* *is a very powerful concept because if you talk about automation, then you do not need a driver anymore. You do not have to have a driver's license anymore in the future and everybody can order AVs in front of their homes"*. However, no expert could predict when this would happen—either in 15 years, 50 years, or maybe never. The experts agreed that predictions made 5–10 years ago were more optimistic than the reality of today. Furthermore, this fully automated service does not work for everybody; for people with disabilities, this process likely cannot be fully automated, as there is still a need for care workers to assist people, according to the Transport Policy Expert working for the Ministry of Economic Affairs and Communications. In addition, one counterargument for fully automated transport is the social dimension—people appreciate human connection, even in the transport system.

Among the experts, the question regarding responsibility makes fully automated systems more complex. In legal practice so far, the operator (either remotely or on board) is mainly liable in the case of accidents. Even though there could be real issues could with the hardware and software of the vehicle, assigning this responsibility to companies is currently a more challenging process, and by default, the operator is responsible. However, the experts agree that the issue is more difficult when a single operator is assigned to multiple AVs. Furthermore, another issue is how to deal with remote operators that are outside the legal framework—e.g., outside Estonia/or even outside the European Union.

Technology readiness remains a key challenge on this path toward fully automated vehicles in open traffic. Operationally, AVs are not considered equal to human-driven vehicles. According to the expert working for the Estonian Transport Administration, for safety reasons, they do not allow AVs to carry out road tests over 30 km/h, which is a threshold where more critical accidents start to happen. However, in the future, automation could potentially increase safety, as most accidents are currently caused by human error, and this is expected to decrease with AVs. All experts agree that safety remains central to AVs, both as an enabler and as a key risk. The experts also agree that the potential efficiency when AVs are shared is an enabler of this technology, as this can reduce congestion, cut emissions, and make the transport sector less labor-dependent. The experts also pointed out additional risks, for instance, cybersecurity and the hybrid transport environment, including communication between normal cars and AVs. On the other side, the advancement of mobile internet connections, such as 5G and 6G, could be an enabler for this technology to move forward.

One more radical consideration stated was that the change in infrastructure is irrelevant, as AVs could cope with any infrastructure. However, the experts agreed that common international standards are important to speed up the development of infrastructure. Internet connectivity and digital standards (e.g., transport communication APIs) are the key in this regard.

5.5. Survey Summary and Interview Conclusions

As autonomous vehicles are novel traffic agents, people seem to be very positive about them in their reactions and their assessment. At the same time, many cannot compare them other than against the usual public transport. One of the most important outcomes from the interviews is that people are wishing and waiting for the first- and last-mile shuttles to come into operation and serve more specific destination needs, as the lengthening of the existing public transport is meant for the masses.

The interviews took place in fair weather conditions, and interviewees did not have heavy items to carry. Nevertheless the users foresee the advantages of AV in unexpected circumstances, for instance, in adverse weather. The most important factor in using AV services is safety. The passengers rated safety with high scores, at least in an area (the university campus) without particularly heavy traffic. Although the bus was driving on a public road with some overtaking of parked cars, and was being overtaken by other faster vehicles, according to the answers, the passengers felt comfortable regardless of their gender or age; however, most people do not expect AVs to be driving fast or for long distances.

The machine requires adequate means for communication, to be able to make humans feel safe in traffic and to respond to human interactions and signals. At the present, the channels supporting vehicle-to-user communication are limited to visual signage, lights, and audio signals, recorded or in real time. Moreover there are limitations in the embodiment of such visual signals in the vehicle. These signs have to be universally understood and translatable in an instant. Building many different signals on the vehicle requires time-consuming design, prototyping, and extensive testing, as in the current stage only three different signals were tested (see Table 1). These were visible, and people understood the red cross and green arrow by the colors—red always signals that something needs your attention and green is giving “the green light”. The crossing zebra sign was confusing (the sign for letting people know that the shuttle is acknowledging the pedestrian crossing) as was turning the sign into green arrows once it stopped, to show that it is safe to cross.

There are other ways to communicate in the language of driving, such as the text in the front panel with short but well-understood messages; however, language might be an issue, unless it says “stop” or something universally understood. This area remains to be studied thoroughly, as it can be considered an open field of research.

6. Avenues for Future Research

The results drawn from the interviews and survey reveal a series of criticalities and limitations, both in the design and assessment methods of the system, which we believe can be, at least partially, overcome by adopting Extended Reality (XR) technologies and simulations. Future works intend to create modular simulation scenarios aimed at the design, prototyping, and assessment of internal and external HMIs specific to AV shuttles, facilitating the evaluation of users’ behavior and response. Some of the most problematic aspects of the passenger experience in the ISEAUTO autonomous bus are related to system modality feedback, teleoperated or in autonomous mode, emergency state, door opening signals, AV positioning and route navigation, and the type of communication and support that would be feasible to offer from a remote operator in case of necessity. Another important aspect is the inclusiveness of the messages, which in the experimental study only referred to language and cultural background differences. It is also clear that the presented experimental setup and methods have some flaws related to users, repeatability, and adjustability of the machine parameters and features. With the proposed scenarios, we intend to create a XR testbed that would enable fast and safe assessment prior to real world investigations.

The first proposed scenario focuses on Internal Human–Machine Interfaces (iHMIs), which would support wellbeing, a feeling of safety, and efficient communication on the state of the system from the AV to the passengers. This specific topic is not yet properly addressed in the literature, but it is essential for the future development and success of sustainable local mobility based on autonomous buses. The test of iHMIs for the ISEAUTO shuttle can be achieved by contextual experiments supported by Augmented Reality (AR) hardware solutions (e.g., see-through head mounted displays). By overlapping ad hoc interfaces on existing objects and augmenting real-world scenarios, we aim at testing multiple iHMI alternatives, such as navigation dashboards, audio visual alarms, video and voice operator feedback, holograms, and buttons or touch displays, without any physical modification to the original AV structure and body.

The second scenario will focus on testing and prototyping different solutions for the AV external HMI (eHMI), including the language of driving (LoD). An immersive virtual scenario would support the validation of existing solutions in a safe and repeatable experimental setup, which could be more inclusive for frail subjects (impaired users, elderly people, children). This would also allow the fast prototyping of new interfaces by rapidly modifying and assessing their position, size, the type of messages, language, and communication channels (voice, sound, gestures, etc.) [34]. The simulator would also support the test of user–AV interaction in specific road scenarios, including emergency situations, collisions, road crossings, and bus stop interactions (e.g., door opening speed). Moreover, the integration of simultaneous agents' interactions and the detection of user response to different vehicle types or design solutions for the ISEAUTO shuttle would be easily achieved in a virtual environment. The development of simulation-based user-centered studies enables the easier integration of technologies aimed at physiological data collection and analysis. We believe that passengers and other road users' stress levels can be assessed by detecting heart rates and analyzing heart rate variability during the experimental sessions. Passengers' attention can be studied by collecting eye and head movement data, in relation to the size and position of the proposed interface solutions. Conclusions can also be inferred from the analysis of posture and movements while, for instance, the user is virtually approaching a crossroad or the AV at the bus stop. The flexibility of XR scenarios allows the fast setup and assessment of specific use case tasks that the passenger might have to perform (contacting the operator, unlocking the doors, interacting with a dashboard, purchasing a ticket).

The third proposed scenario focuses on operator and XR Digital Twin (DT) tools for remote maintenance and servicing. DTs are simulations of complex systems and processes, which are updated and synchronized through the exchange of data and information with the real-world counterpart. DTs are already successfully used in industry for control and teleoperation [35]. This is a fundamental aspect both from a technical point of view and from the point of view of the users' feelings of trust, safety, and support while using the AV. The AV shuttle ISEAUTO propulsion engine DT is already used for performance prediction and prognosis, as presented in [36]. ISEAUTO is proposed as an integral unit of the Industry 4.0 environment [37]. Extending the synchronized digitalization to other AV systems and integrating them in an XR interface would support the operator in assessing the state of the shuttle with a more precise visualization and facilitate the decision-making process. Advanced interaction methods enable the operator to interact virtually with the real AV shuttle while in a remote location. Using the same simulation in AR would support the potential local operator with remote guidance and instructions.

7. Conclusions

This paper studied the new challenges of the emerging topic of the so-called language of driving (LoD) in connection to transportation systems in smart cities. The study was conducted through field interviews at Tallinn University of Technology campus using our custom ISEAUTO autonomous driving shuttle. This research integrates interviews involving 53 riders and 176 road users interacting with the AV shuttle as well as an expert focus group to build a joint base of needs and requirements for AVs in public spaces. According to the questionnaire results, people feel safe onboard but are still interested in knowing whether the bus is remotely operated or fully automated. Furthermore, the signaling (communication) from the bus to other road users was perceived as comprehensible, though with some limitations involving the position of the signals on the bus and the specific type of signals shown. Signal appearance, function, and position can be developed more efficiently using VR technology before adoptions in AVs.

The adoption of an XR-based experimental setup offers many advantages, which can support the faster definition of an inclusive and standard LoD for AVs. The adoption of advanced visualization and interaction technologies grants extended testing on a wider range of users and in a larger number of use cases. Simulated scenarios allow the easier assessment of usability and acceptance of the system by providing valuable solutions for real-world user experiments, criticalities, and issues.

Future works will integrate the available hardware technologies in a multi-scenario application developed for AR/VR testing and assessment, while recruiting users of different ages and with diverse abilities.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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Paper 3

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Enhancing Mobility as a Service with Autonomous Last-mile Shuttles and Data Exchange Layer for Public Transport

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Abstract. More and more people are moving to the cities, and thus the pollution indicators are going up. While the cities keep on growing, so do the rural areas around them, and the public transport lines connecting these areas with the focal points inside the city become more vital. Integrating autonomous vehicles (AV) - self-driving shuttles running on electricity into the overall chain of public transport will have a green effect compared to private cars. As AVs are still in the development phase for safety reasons, they are forced into shorter distances and outside from heavy traffic areas. Having already introduced to open roads as street-legal vehicles, this will make them perfect for rural areas, where the traffic is not hectic and servicing traditional public transport with shorter distances - being the first or last leg of the whole transport chain, making the public transport more conveniently accessible for any person - both those, who at the moment choose their private cars to commute, but also for the elderly, children and handicapped, who do not own the drivers' licence, but also need assistance to get to the local bus stops etc. With Mobility as a Service smart phone application, AV shuttles can be ordered on demand to a predefined stopping area (even to the closest location of the person who placed the order) and also to use several other transport related services. The paper covers extensive market research on MaaS components and services, focusing on the demand basis implementations and current issues. Giving the overview of the existing MaaS services available on the market, as well as explaining MaaS XT - an open-source middleware for future transport management - its functionality to integrate different transport-related services, pointing out its appealing potential for the end users engagement into using public transport more for their commuting needs. The initial results of implementing the MaaS XT solution to the test environment are analysed, and future implementations are proposed.

Keywords: Smart City, Autonomous Vehicles, Public transport, Mobility as a Service

INTRODUCTION

During the past 5 years in Estonia and all over the world, there is a new concept called MaaS (Mobility as a Service) gathering more and more popularity. Uber and Bolt need no introduction, but in short it is possible to order on demand a vehicle through a mobile phone application to wherever you need it (while being located in the service area). But what if the ondemand area would be initiated outside the city areas and offer the services also in suburban and especially in low density areas, where it is even more crucial to get more conveniently connected to any public transport services? Using for example self-driving shuttles, electric scooters to efficiently get people from their homes to public transport stops. This is exactly the ecosystem that Finest Twins Future Mobility project is tackling.

Before starting such a service, there lies a question, what kind of MaaS services are available and what can be used for a self-initiated middleware platform called MaaS XT. The goal of current research is to find out the most efficient approach for Finest Twins mobility project. To reach this goal, 3 research questions have been put forward:

1. Which *white label* MaaS solutions are available in Europe?
2. Which MaaS solutions could suit the FinEst Twins project?
3. What EU strategies and research should be considered when setting up MaaS services?

Also interviews with mobility service providers are used to find out the answers.

This article is built under three main paragraphs. The first one will handle MaaS concept's different definitions, research its characteristics and levels. Second part will introduce the solution created on the basis of the studies. And in the third part there will be a conclusion of the research with the analysis that will also answer the aforementioned research questions.

MOBILITY AS A SERVICE (MAAS)

Mobility as a Service (MaaS) is a comparatively new mobility concept. It can be taken as a concept (new idea to plan mobility), phenomenon (has emerged together with new technologies and new behaviours) or as a new transport solution (which combines different available ways of transportation and mobility services) [1]. The first *Mobility as a Service* (MaaS) definition was offered in 2014 in Sonja Heikkilä's Master's thesis "*Mobility as a Service – A Proposal for Action for the Public Administration, Case Helsinki"* [2]. According to one (very often in literature used) definition for MaaS was given by MaaS Alliance – integrating different forms of transport services into one on demand mobility service [3]. While in the USA they use TaaS - *Transport as a Service* [4] as a synonym to MaaS. MaaS platforms offer access to different ways of transportation – car and bicycle common use, taxis; trains and buses – offering the users a broad list of alternative services from trip planning to ticketing. MaaS platforms act as centralised market places for different modes of transportation as well as for different service providers, offering optimization on individual level, combining transportation offers with the user/client/consumer's transport preferences. In addition to making transport more efficient, the importance for environmental and society benefits, MaaS can also make daily commuting more convenient, which is considered in today's standards one of the less enjoyable daily activities of people [5]. Different authors have defined MaaS as follows – here is a selection:

- MaaS relies on a digital platform, which integrates from beginning to end the trip planning, booking, electronic ticket sales and payment services in all public sector and private sector modes of transport [6].
- MaaS is broadly considered as the next big change of paradigm in transport. The expectations of service providers is to offer passengers easy, flexible, trustworthy, price worthy and sustainable daily commuting, including public transport, car sharing, car leasing and road usage as well as more efficient ways of sending and delivering goods [7].
- Mobility as a service (MaaS) concept has received great attention in many conferences and forums. The MaaS concept is quite simple: bringing together different public and private sector vehicles to one easily used package for a client. The service will be provided through mobile phone applications. Despite the great interest and attention to MaaS, the actual MaaS business models and large-scale pilots are still waiting ahead of us [8].
- The goal of MaaS is to cross the gap between public and private sector transportation companies on city, intercity and state levels and to plan the integration of fragmented applications that a passenger needs for his/her trip (planning, booking, access to real time information, payments and ticketing). Mobility as a service is a user-centric and smart mobility sharing model, where all mobility service providers' offers are combined together by one MaaS operator, whose digital medium is used to forward all needed data to users [9].
- MaaS is a term that is used to describe digital services, quite commonly through a smart phone application, through which people get access to different public, shared and private sector transportation, using a system that integrates trip planning, booking and paying [10].
- MaaS offers personalised access to several travelling services according to the needs of a client [11].

Thinking about the commuting needs of people – work, school, shopping, travelling, visiting etc, as to why the MaaS concept has emerged, then it has been made possible by the last 10 years' technical developments. People wish to have one common medium, where it could be possible to meet all their mobility service needs [9].

The MaaS model can be divided into 4 level categories according to the characteristics. Here is one way [12]:

- **MaaS level 0** – The solution is missing integrations and separate services, for example Hertz car rental, public transport etc.
- **MaaS level 1** (planning) - solution has integrated information, where one can plan the trips in different means of transport, see, how much do separate transport services cost, for example Google maps, Moovit. The business model for company who deal with MaaS level 1 are mainly interested in getting their service accessible by as many users as possible, selling the data collected from the users to the city governments.
- **MaaS level 2** (planning + paying for the tickets) **-** solution includes additionally to the planning functionality - easier access to services. Which means that a user can find a suitable mean of transport, make a booking or pay, with the help of the same application. The service can also consist of several different kinds of transport means, although integrating them together on one mutual platform can be difficult. When the service/platform is run by any governmental or municipal institution, for example state's transport authority, then it has to be open and accessible to all companies offering transport services or go through an extensive time and effort consuming procurement process. The key (income) of the business model of such a company, who offers this kind of service, comes from agent fees, exchange fees and/or users' fixed membership fees. For example, this kind of service is offered by Bolt and Uber.
- **MaaS level 3** (planning + payment for the tickets + different transport packages) **-** the solution includes the functionalities of MaaS level 2, to what has been added several different transport opportunities, that enable for the user to combine and buy suitable transportation packages from one single application or web page - for one day, one week or one month. Such packages are offered for example by Whim and Ubigo. Maas level 3 conception is an alternative to owning a private car, concentrating on covering completely all mobility needs of a customer seven days a week and on all seasons. The business model on this solution concentrates on selling mobility packages to people. All mobility packages are covered with contracts that allow MaaS operators to offer users a broad spectrum of different kinds of transport: rental cars, e-scooters, public transport and taxis.
- **MaaS level 4** (MaaS 3 + society's interest) - includes everything, that is in Maas level 3, but there are also society's needs and interests integrated into - different policies, initiatives, incentives etc. Additionally, the better exchange of data between MaaS operators and public sector is crucial to create more efficient mobility solutions for all parties. At the same time, the public sector sets goals for MaaS operators and subsidises the mobility of people to decrease private car usage by offering MaaS solutions as alternatives.

We would like to stress that when utilising complicated integrations, those who offer transport service should agree upon mutual standards that enhance the successful data flow without any barriers. One such example can be TOMP - API, that enables as a common data exchange language to service all four MaaS levels' interests (TOMP - API, 2020). I addition to aforementioned prerequisites, when MaaS level 2 is the standard, then for the MaaS concept to work, it is necessary to implement driver view operators' application (for taking in orders and filling them), operators' view (for existing orders acceptance and following) and main user view (to determine new demand based areas, reports configurations, appointing price policies, etc.). MaaS level 3 and 4, where several transport operators are integrated, is undoubtedly elementary for the previous levels to be fulfilled by the operators for the full mobility ecosystem to function as a whole.

INTRODUCING MAAS XT PLATFORM - MOBILITY ECOSYSTEM FOR MULTIMODAL TRANSPORT MANAGEMENT

The main goal of the MaaS XT platform approach is to provide an architecture and open service that can deliver mobility solutions requests asynchronously. The following figure demonstrates the MaaS XT platform architecture:

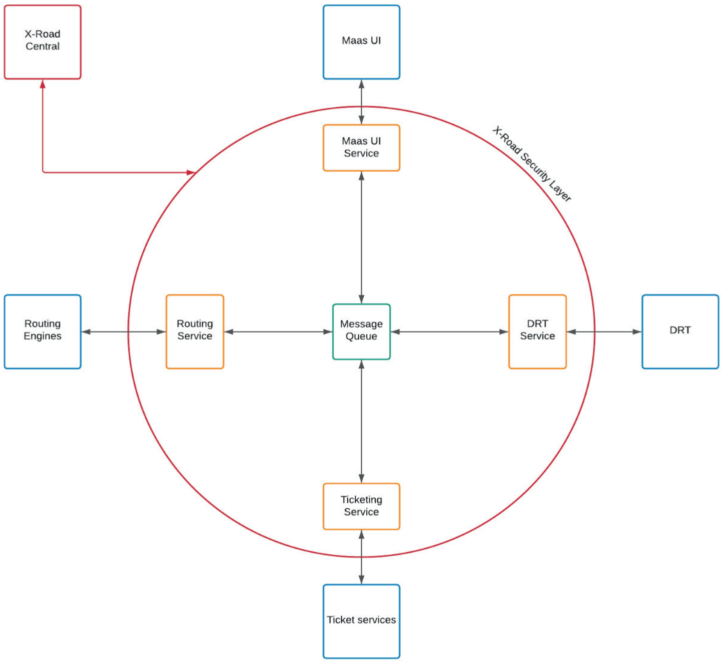

FIGURE 1. MaaS XT platform architecture

The experimental solution includes the following interconnected external services available on the platform: MaaS UI Provider, Routing Engine #1 (supports multi-modal service), Routing Engine #2, DRT Provider #1, DRT Provider #2 and Ticketing platform. The prototype of the MaaS XT platform is designed and developed relying on the X-Road security infrastructure, known from the Estonian X-road success story. The solution has a multilayer concept, enabling the interconnection of external services.

1. Platform services - These components are MaaS XT specific services. Each of these services acts as a gate into the MaaS XT platform for the external components. Platform services are separate for each type of service provider (e.g. MaaS UI services, DRT services, ticketing services and routing services).
2. Platform communication - This component is the message queue implementation. Its purpose is to facilitate communication between platform service components. With this asynchronous communication and message, redundancy is achieved.
3. Security services - These components are X-Road specific services to provide a layer of security to the platform. Each external service is required to authenticate via X-Road to communicate with MaaS XT components, given that they have the correct permissions.

This kind of an approach leaves the future developments open, to add new functionalities. It also enables the preservation of transparency of complicated systems and reliability. UI has been developed as a browser-application that is optimised for smartphone adaptation.

To clarify even more, in the server there is an open source coded OTP (*Open Trip Planner)* service that searches suitable transport suggestions for the user. The data is renewed each morning according to the public transport schedules released by authorities. For ticket sales, an integration (for example in Estonia a company called Ridango) with who is responsible for public transport ticket sales platform management and enables to also validate the tickets later on public transport vehicles.

This solution is implemented as a prototype in Estonia connected to TalTech self-driving vehicle shuttle iseAuto pilot under Finest Twins challenge initiative in the spring of 2023 in the City of Tallinn and the sub-urban areas close to Tallinn by interconnecting classical public transport services with self-driving shuttles. The pilot corridor is from the passenger's home in the suburban area of Tallinn to Tallinn harbour and beyond to Helsinki.

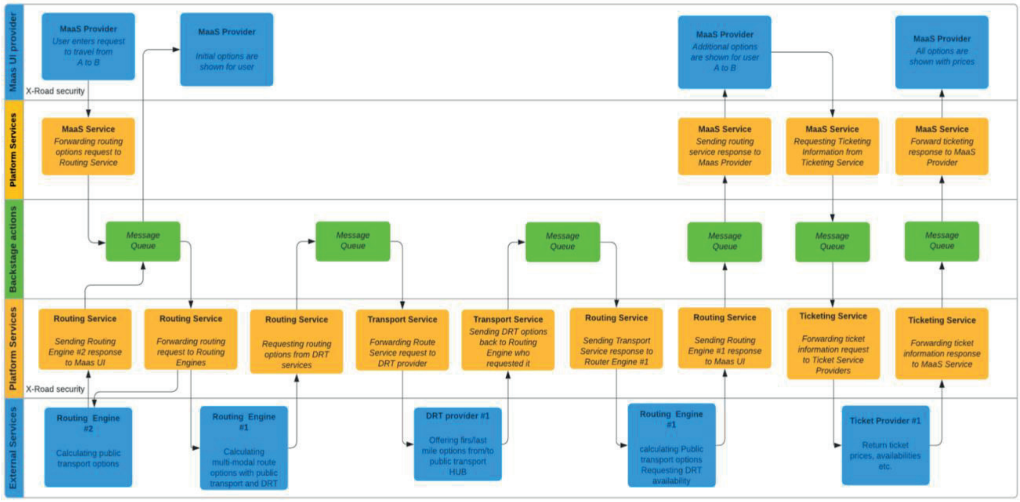

FIGURE 2. Architectural diagram - clarifying the different services within the MaaS XT platform

The process of what happens, when a user makes a request from MaaS UI to plan a trip from point A to B, for first Maas UI connects to Maas-XT Maas UI service to request routing between A and B. Meanwhile the requests are made in the backend, Maas UI shows a loading screen to the user. Maas UI service sends a request to the Message Queue for Routing Service to get possible routes from A to B. Routing Service reads this message from Message Queue and sends requests to all of its known and available Routing engines. Routing engine #1 maps a route from A to B. It also sends requests back to the Routing Service to get possible DRT solutions for the route. These requests are relayed as messages to the Message Queue for Scheduled Transport Service. The Scheduled Transport Service reads these messages and sends them to its known and available DRT providers. Each DRT provider sends back responses to the Scheduled Transport Service, which
in turn sends them back to the Routing Service via the Message Queue. Meanwhile Routing engine #2 already sends its possible routes to the Maas UI Service via Routing Service and Message Queue. Maas UI receives these responses and can start showing them to the user while waiting for other responses. Routing Engine #1 has finished its routing and is sending a response to Maas UI Service via Routing service and Message Queue. Maas UI receives these responses and shows them to the user and then makes a request to the Ticketing platform via Maas UI Service and Message Queue to receive ticket prices (note that routing engine provides either a price or information on who sells tickets).

CONCLUSION

The aim of this study was to research and analyse existing MaaS solutions and software, by examining 7 MaaS solution providers and 3 DRT solution providers, whose conditions meet or fit the needed concept.

The formula for seamless mobility is to organise transport in a way so that people's journeys are organised as smoothly as possible without having to search or wait for suitable transport. The mobility of people should not require a deep search for a suitable transport to get to the desired destination. Instead, the transport should depend on the passengers' needs and be available on-demand. Using a well-functioning public transport infrastructure: city buses, electric scooters and self-driving demand-driven transport, the MaaS solution integrated into the public transport system can offer a significant additional opportunity to better fill the gap between both - for the first/last mile and for people who live in sparsely populated areas. In addition, the solution offers a viable alternative to private cars and is also significantly more environmentally friendly, reducing the load of vehicles on tourist sites, on the very few parking spaces in city centres and has the environmentally friendly effect in general.

Based on the results of the study, the answers to three research questions were found:

1. **What are the white label MaaS solutions available in Europe?** In Europe, MaaS solutions are used in more than 40 cities, by 50 different applications, divided into MaaS level 1 to MaaS level 3 categories. MaaS level 3 solutions, such as Whim, Trafi, Siemens-Hacon, etc., are functional, allowing different types of transport operators to be connected and providing payment solutions for a multimodal journey in a single payment, but a major disadvantage of the solutions is the lack of a single open standards interface system. TOMP-API tries to cover this hole with its own open standards approach to all MaaS functionality, which Whim for example has joined.
2. **Which MaaS solutions could be suitable for the FinEst Twins project?** From the existing concepts of MaaS solutions, these could be suitable for FinEst Twins:
   a. MaaS white label solutions with DRT - MaaS level 3 solution providers that offer a complete solution with DRT.
   b. MaaS white label solution and DRT solution separately - 2 different providers, one of which offers a MaaS solution and the other a project-specific DRT solution.
   c. Further development of the MaaS XT concept - Within the MaaS XT, there is a prototype to which all transport operators who are ready to join the open standards could be connected.

   With both a, b and c options, involving the public sector initiative to enhance, stimulate and subsidise mobility, it is possible to scale the MaaS concept to level 4 in MaaS.
3. **What are the EU's strategies, studies and projects for MaaS?** In Europe, MaaS is used in more than 40 cities and EU projects towards MaaS are rather modest. MaaS operators offer their solutions directly to cities and urban transport operators. In larger cities, it is common to use solutions from several MaaS operators. EU projects have a rather modest focus on MaaS, projects focus on piloting the implementation of the MaaS concept and testing the performance of various MaaS schemes. Writing scientific journal papers also goes hand in hand with MaaS piloting and case studies. Since 2016, scientific journal papers' releases have grown year by year. The most important of the EU strategies related to MaaS is Directive 2010/40 / EU, where all EU Member States must open their national access points, which must also be described by appropriate metadata and interoperable with the data exchange format and protocols.

The study identified three approaches that would contribute to a better overview of MaaS solutions discussed in the study. Based on this, we propose:

1. **Prepare the initial task of the project (duration, services, etc. requirements) and take initial offers considering the possibility to use the piloted software even after the end of testing**. All MaaS level 3 white label solutions covered in the study: Whim, Trafi, Siemens-Hacon, ReachNow, IOMOB are able to offer more than one mobility operator interface. Preference should be given to providers that adopt or lead the development of general data standards like: Whim and Iomob.
2. **Further investigate the conditions under which the MaaS XT prototype is suitable for the FinEst Twins project to bring together transport operators**. Today, there is a prototype solution with a passenger application that allows the integration of different transport operators on the principle of open standards. It is wise to explore the possibility of additional moments of cooperation with the Estonian Transport Department and peatus.ee to use their travel planner.
3. **If a MaaS solution provider should emerge in Tallinn, which is willing to interface with all transport operators that wish to join, it is worth exploring the places of cooperation.** If a MaaS operator were to come to Tallinn, which, based on the principles of the FinEst Twins project, is willing to make its platform open and accessible to transport operators and would be ready to further scale the solution on the same principle, it would definitely be worth thinking about this approach.

The authors believe that the objectives set in this study have been met and the findings and results can be successfully used by FinEst Twins to further implement the MaaS concept and to further explore the MaaS together with autonomous vehicles.

ACKNOWLEDGMENTS

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Paper 4

Udal, A., Sell, R., **Kalda, K.**, & Antov, D. (2024). A predictive compact model of effective travel time considering the implementation of first-mile autonomous mini-buses in smart suburbs. Smart Cities, 7(6), 3914–3935.

smart cities

Article

A Predictive Compact Model of Effective Travel Time Considering the Implementation of First-Mile Autonomous Mini-Buses in Smart Suburbs

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Highlights:

What are the main findings?

- A general mathematical methodology and calculation model have been proposed, which allow taking into account most of the important factors that determine the impact of the introduction of first-mile autonomous vehicles on the daily time use of suburban residents.
- Following the compact modelling approach, an easily understandable and definable set of source data with a minimum volume has been proposed, which allows to reach the desired result.

What is the implication of the main finding?

- A practical tool for shaping transport solutions and local government decisions: Thanks to the transparency of the model and the easy-to-understand input data, the transport planners and local governments can perform estimation calculations without long and complex scientific studies.
- Predictive capability of the model: a minimalistic and easy-to-understand input data set enables preliminary assessments of the implementation of autonomous vehicles for various local governments and suburbs located near metropolitan centres.

Abstract: An important development task for the suburbs of smart cities is the transition from rigid and economically inefficient public transport to the flexible order-based service with autonomous vehicles. The article proposes a compact model with a minimal input data set to estimate the effective daily travel time (EDTT) of an average resident of a suburban area considering the availability of the first-mile autonomous vehicles (AVs). Our example case is the Järveküla residential area beyond the Tallinn city border. In the model, the transport times of the whole day are estimated on the basis of the forenoon outbound trips. The one-dimensional distance-based spatial model with 5 residential origin zones and 6 destination districts in the city is applied. A crucial simplification is the 3-parameter sub-model of the distribution of distances on the basis of the real mobility statistics. Effective travel times, optionally completed with psycho-physiological stress factors and psychologically perceived financial costs, are calculated for all distances and transportation modes using the characteristic speeds of each mode of transport. A sub-model of switching from 5 traditional transport modes to two AV-assisted modes is defined by an aggregated AV acceptance parameter 'a' based on resident surveys. The main output of the model is the EDTT, dependent on the value of the parameter a. Thanks to the compact and easily adjustable set of input data, the main values of the presented model are its generalizability, predictive ability, and transferability to other similar suburban use cases.

Keywords: autonomous vehicle acceptance; autonomous shuttle vehicle; compact model; distance distribution function; effective travel time; first-mile transport; psycho-physiological stress factor; smart city suburb; travel time model

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1. Introduction

Transportation planning is an engineering field with a very long history [1]. In the past 10–15 years, autonomous vehicles (AVs) have acquired a game-changing role in the visions of future transport development [2–6]. Figure 1 illustrates the rapid growth in the number of scientific publications that discuss the application of AVs in solving future transportation issues.

To solve the ever-increasing environmental problems and parking problems in city centers, privately owned electric AVs can provide solutions for both the car owners and the cities. However, real high-value win-win solutions to complex socio-economic tasks are still expected from shared AVs and especially from autonomous shuttle (AS) minibuses [7–9]. To achieve the biggest positive effect for both the residents and the municipalities, the AS buses are brought into service to solve the first-mile and last-mile transport tasks in sparsely populated suburban areas where the maintenance of public transport bus lines is not economically feasible [7,9,10]. In this paper, we construct a model and estimate numerically the impact of the implementation of autonomous first/last-mile minibuses on the time usage of the average resident of a suburban area who has to make both local trips and longer trips to the adjacent city every day.

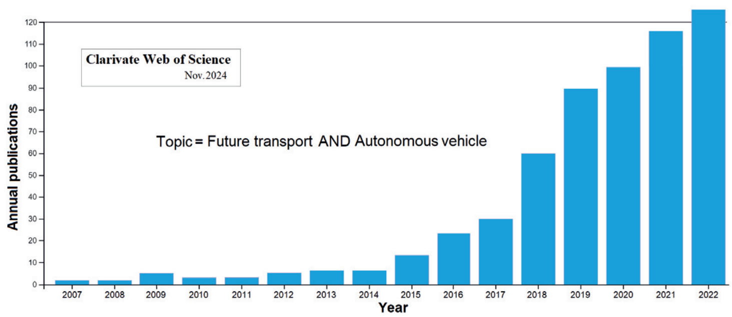

Figure 1. Growth of annual number of publications dedicated to application of autonomous vehicles in future transportation.

Transport analysis and planning is a complex multidisciplinary socio-techno-economical problem [11–13]. For example, the psychological pre-setting of people to switch to new modes of transport is an essential key factor to be considered [14–16]. The corresponding computational models tend to become very multi-dimensional and multi-level, with several feedback loops and thereby with a very large amount of heterogeneous input data. The latter fact often makes it difficult to obtain practically usable computational tools to solve actual transport planning tasks.

To provide a solid framework for versatile transport tasks, the concepts of travel time savings (TTS) and multi-functional value of travel times savings (VTTS) have been introduced and widely applied, e.g., [17–19], In recent years, a significant amount of research has addressed the potential of AVs to reduce travel time with the implementation either in the form of private AVs or shared AVs [17–20]. However, most of these studies consider the potential applications of AVs for longer trips than just suburban regions, e.g., [21–23]. Although time savings from the application of AVs in suburban first/last-mile transportation problems have also been touched on in a few works, e.g., [3,8,20,24]. Following the central idea of transport tasks that travel time in some form should be used as the summarizing complex output parameter, in the present study, the effective daily travel time (EDTT) of an average suburban resident is introduced. As the advanced feature of the proposed EDTT formulation, we have here accounted within EDTT the psycho-physiological travel stress φ-factors and the financial cost perception ψ-factors that account for extra time saved by the travelers using the faster travel modes like car or taxi.

One general problem in transport research is large volumes of input data, which makes the models less transparent and tied to specific cases, thus reducing the generalizability and predictive ability of the models. In this study, in contrast, we have created a maximally compact EDTT model with a minimalist input data set that still describes all the important mechanisms that determine the positive and negative effects of implementing AVs. In other words, in this work we have tried to follow Einstein's principle of simplicity—make the model or theory as simple as possible, but not simpler. It is expected that by keeping the set of initial data minimal and easy to understand, but at the same time reserving the possibility to detail several sub-models (e.g., sub-models for AV waiting times and for people's readiness to switch from traditional transport modalities to AV-enabled modes), it is possible to propose a practical and sufficiently universal calculation model that allows proactively evaluating the beneficial effect of minibus AVs for different suburbs.

In summary, the advanced features of the proposed travel time model include:

- Reasonably wide set of considered transportation modes (5 traditional and 2 AV-assisted);
- Definition of a simplified but rather general one-dimensional spatial layout (5 residential zones and 6 city destination zones);
- Using relatively well-defined statistics of pre-lunch outbound trips to forecast the daily trips;
- Introduction of an aggregated AV acceptance parameter α as the key input variable of the model;
- Introduction of a practical 3-parameter distribution function for trip distances;
- Introduction of a 2-stage trip scheme (local and city), allowing for the description of the different combined modes of transport;
- Introduction of a minimalistic 2-parameter AV wait time model including dependence on the number of AVs in the service area;
- Expressing the main output of the model via easily understandable and testable daily travel time of the average resident;
- Expanding the concept of travel times with additional perceived extra time terms to take into account psycho-physiological stress and financial costs.

In the voluminous transport research literature, a partly similar approach to effective time components of main transport modes is discussed in [22,25,26]. People's attitudes towards AVs (which we describe with one aggregated parameter) have been studied in great detail in many works, e.g., [6,14–16,23,27]. The important special question of AV waiting times that we describe in present research with a minimalistic 2-parameter model has been studied with a high degree of detail (for example, by the means of agent-based modeling) in several works [4,9].

2. Description of the Model

2.1. Concept, Sub-Models and Approximations

To arrive at an estimate of average daily transport time, it is necessary to look at a sufficiently adequate set of trip length options with statistical weighting for each option. In doing so, it is mandatory to add a weighted summation across modes of transport. In addition, if sufficient data are available, it would be desirable to add weighted averaging across population groups. With this, we arrive at the estimate that the imaginable 4-dimensional matrix of variants (trip origin zones, trip destination districts, mode of transport, population groups) has the size order of a thousand cells, all of which require input data. This is even if we apply averaging over hours (i.e., omit the 5th dimension of hours). The conclusion is that many simplifications are needed for a practically usable transport time model. And especially for preliminary assessments, when there is still little data from measurements and surveys.

In order to arrive at a practically usable calculation model for predictive estimates with a reasonably compact set of initial data, in this study the following simplifications have been introduced:

- Detailed distribution over daily hours is omitted. An exception is the preparation of the distribution functions of travel distances for pre-lunch and all-day outbound trips based on the actual time-dependent statistics of the movement of the Tallinn city residents. In the final formulation of the EDTT model, all-day trips are calculated using pre-lunch outbound trips (6:00–12:00) with an empirical factor.
- The spatial situation is reduced to a one-dimensional distance-based spatial model. The travel times are calculated by using estimated average speeds of different transport modes that add only a few input parameters to the model.
- The differentiation by population groups is only implicit in order to avoid an additional dimension in the summation scheme. The calculation of groups of residents is indirectly included in the factor of non-moving residents N and in the weight parameter of local trips D_0 (mainly students in local schools).
- To model the transition from traditional transport modes to AV-assisted modes, an aggregated single parameter of AV acceptance α, based on the population survey summary, is introduced. If necessary, the relevant sub-model can be refined with additional studies that take into account the attitudes of residents using different modes of transport in more detail.
- In order to estimate the waiting time for ordering AVs, a simple 2-parameter empirical sub-model with minimal complexity that accounts for the number of available AVs is used in the present study. With additional measurements in a real-world situation and with agent-based modeling, this sub-model can be relatively easily refined.

On the other hand, the task of assessment of AV-supported local transport has also required the introduction of several complexities, such as:

- Formal framework of summation of trip times should be presented not on the basis of traditional two-dimensional Origin-Destination matrices but based on three-dimensional Modality-Origin-Destination (MOD) matrix, the size of which in the present study is $7 \times 5 \times 6$. A relatively wide set of transportation modes (5 traditional and 2 AV-supported) has been necessary to assess the impact of AVs.
- Introduction of 2 stages of outbound trips—local and remote. This is necessary complexity to account for residential use of AVs in combination with public transport (PT). Transfer occurs in origin zone $Z0$ containing the transportation artery, along which the PT stops are located (see Figure 2 below).
- Optional psycho-physiological stress φ-factors to account for the increase in perceived travel time due to stress of private car driving during rush hours, bicycling in bad weather, walking difficulties, and walking with heavy hand luggage (AV using reasons indicated by residents in the surveys).
- Adding waiting times to driving times for all modes of transport and for both stages of trips.
- Accounting for optional financial cost terms for private cars, taxis, and PT E_{car}, E_{taxi}. E_{bus} converted to travel time on the basis of the national average hourly wage A_h. In general, the cost of using AVs should be taken into account as well (currently zero in the case of the discussed pilot project in Rae municipality).
- Accounting for optional perceived time saving ψ-factors that take into account the time gains when using the faster modes of transport (private car and taxi).

Figure 2 summarizes the general structure of the proposed computational model and indicates the numbers of sections of the paper text that describe the construction of different sub-models.

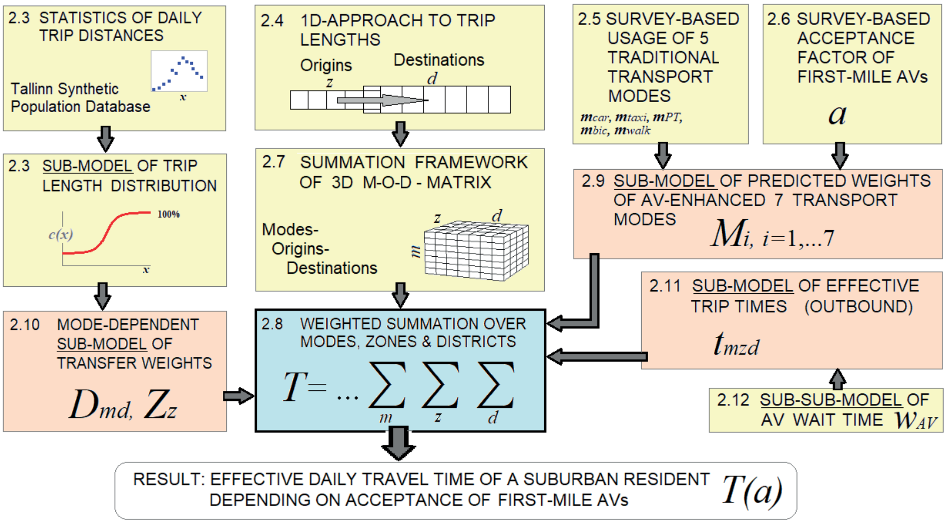

Figure 2. General structure of the calculation model. The upper corner numbers of the blocks correspond to the subsections in the paper text.

2.2. Example Use Case

In 2022, a pilot project of future transport was initiated by the Finest Centre of Smart Cities at Tallinn University of Technology [28–31] in order to test the applicability of ISEAUTO autonomous minibuses on the first-/last-mile section connecting the suburban residential region Järveküla with Tallinn Harbour (see Figure 3a below). The real spatial situation of the task and initial version of the developed autonomous minibuses are illustrated in Figure 3 below.

Figure 3. Explanation of example suburban transport task: (**a**) Location of Järveküla residential area (purple rectangle) in Rae municipality beyond the southern border of Tallinn city (red line). The blue line marks the major public transportation bus line 132 to Tallinn center; (**b**) Current development stage of Järveküla residential area of approx. 200 houses; (**c**) Pilot AV shuttle minibus designed for first-mile transport service in residential area.

The problem of the recently established suburban area of private houses (approximately 200 houses and 1000 inhabitants per half square kilometer will be expanded) is the excessive use of private cars (over 80%). Although the district is closer to the center of Tallinn than some old suburbs, the residents do not want to give up private cars due to the excessive travel times spent, especially on the first kilometers of trips. At the same time, the local government and bus companies, in turn, cannot tighten the bus connection because of too much car use and because of too sparse a population. The application goal of the model is to investigate how much the local self-driving shuttle buses can save the time spent on transportation by residents.

2.3. Sub-Model of Trip Distance Distribution

In order to perform weighted averaging of transport times over journey lengths, it is necessary to know the statistical distribution of daily journeys over distances [32–35]. In the case of a very detailed analysis, it would also be necessary to know these distributions for different modes of transport and population groups. Considering the need to minimize the amount of input data, in our use case, we proceed from the assumption that the same distance distribution function applies to all groups of residents and to all modes of transport oriented to longer distances (private car, taxi, public transport bus).

Due to the lack of detailed trip length data for the suburban residential area of Järveküla, in this study, we have applied the hypothesis of the similarity of the trip length distribution functions with the remote private housing districts within Tallinn city borders. Reliable distribution functions can be constructed on the basis of the available detailed database of the daily movements of the Tallinn synthetic population database [36]. Figure 4 presents the two depicted example areas within Tallinn city limits (Mõigu and Kakumäe-Tiskre), which could be similar to the residential area of Järveküla (red rectangle in Figure 4) in terms of percentage of private housing and residents' movement profiles.

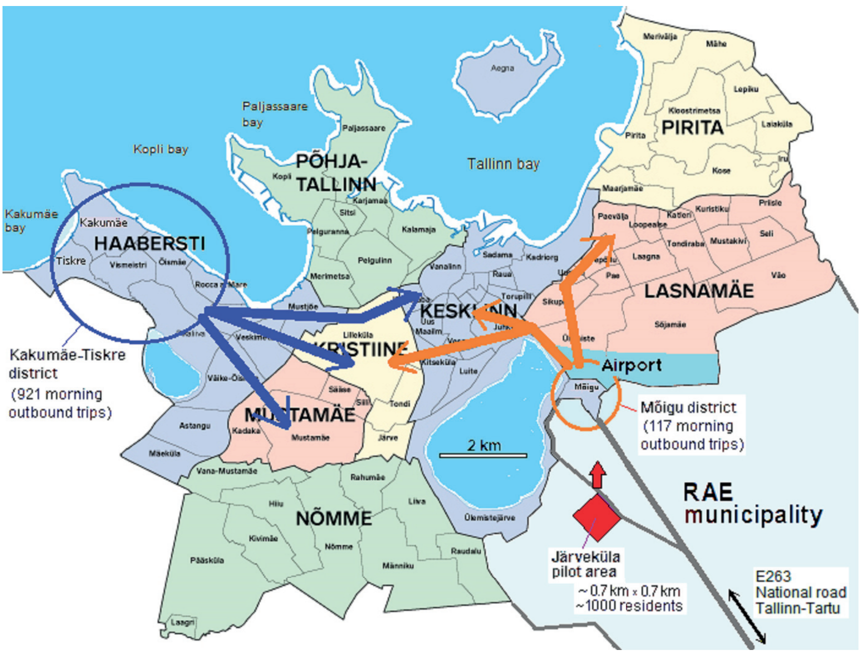

Figure 4. Selection of two reference areas within the city limits of Tallinn (Mõigu and Kakumäe-Tiskre), for which the trip length distribution functions were found.

Figure 5 summarizes the daily outbound trip statistics for the mentioned two example districts within Tallinn limits. In relation to the given statistics, it can be noted that the mobility statistics of the Mõigu region are based on an overly small number of trips, which is reflected in large fluctuations in the differential distribution. In turn, in the case of Kakumäe-Tiskre, there may be a noticeable difference observed in the behavior of the residents in the morning and throughout the day. For both regions, a general conclusion can be made that the integral distribution functions are relatively smooth and similar and can be sufficiently well described by some basic parameters such as the median path length and the characteristic path length of the decline in the share of longer trips.

Results in Figure 5 demonstrate that while the differential distributions are very uneven, the normalized integral curves that grow from 0 to 100 percent demonstrate similar smooth behavior of morning movement from two depicted example areas. This kind of smooth step curve may be approximated mathematically by sigmoid curves, for example, by the logistic function [37]:

$$c(x) = \frac{1}{1 + \exp(-\frac{x - x_c}{L_t})} \quad (1)$$

where x_c is the median distance and L_{tail} is the tail abruptness parameter that represents the characteristic length of exponential approaching of the final 100% level.

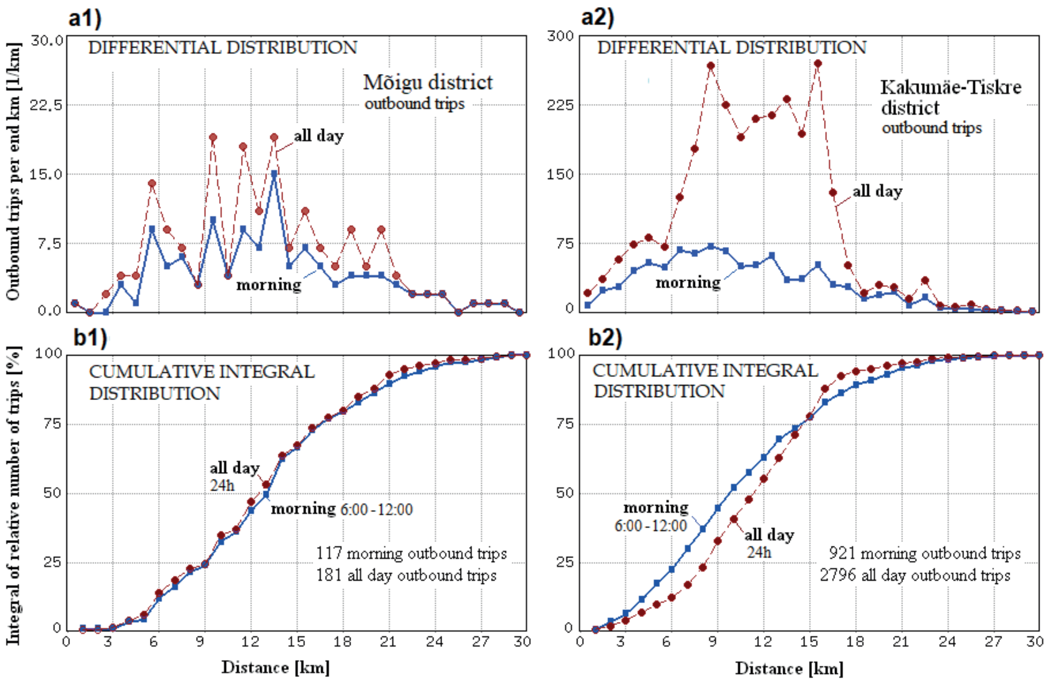

Figure 5. Summary of trip distance statistics of daily outbound trips for two example residential areas of Tallinn city on basis of the synthetic population database of Tallinn: (**a1**) Differential distributions with 1 km step for Mõigu area; (**b1**) The integrated cumulative distributions for Mõigu area; (**a2**) Differential distributions with 1 km step for Kakumäe-Tiskre area; (**b2**) The integrated cumulative distributions for Kakumäe-Tiskre area.

Figure 6 shows the result of RMS (Root Mean Square) fitting of statistics of morning outbound trips of Figure 5 by the 2-parameter sigmoid curves (1) for districts of Mõigu and Kakumäe-Tiskre. The results show that the median path length of established morning journeys for Tallinn residents is between 10 and 13 km, and the willingness to choose more distant places of work and study decreases exponentially with a characteristic path length of 3.4 km. The greater median distance x_c for the Mõigu district may be explained by the airport, which separates the settlement of Mõigu further from schools, shopping centers and workplaces.

However, it must be mentioned that the analysis of the two-parameter sigmoid Model (1) shows that the description of short distances is not adequate. The special feature of the Järveküla sample area is that it has a young population and two nearby schools within a 2–3 km radius, where many pupils (estimated 20% of the population) move every morning. Thus, from a modeling point of view, it makes sense to add a third adjustable empirical parameter that describes the morning movement of residents to local schools and institutions. A modified 3-parameter sigmoid model that includes a contribution factor of local trips D_0 and subsequent growth from level D_0 to 1 by the smooth sigmoid step may be specified by the following equations:

$$c(x) = C_0 + \frac{1 - C_0}{1 + \exp(-\frac{x - x_c}{L_t})} \tag{2}$$

and

$$C_0 = D_0 + \frac{1 - D_0}{1 + \exp(\frac{x_c}{L_t})}. \tag{3}$$

Figure 7 summarizes the constructed 3-parameter distribution function used below in the present study to describe both the contribution of local trips and the distribution of lengthier trips over longer distances provided by private cars, taxis, and public transport buses.

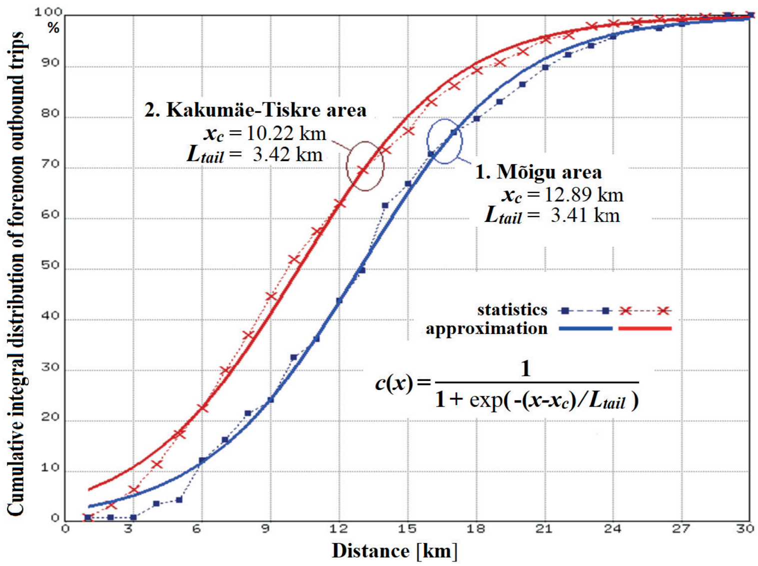

Figure 6. Results of RMS-fitting of the statistics of forenoon outbound trips by the 2-parameter sigmoid curves for Kakumäe-Tiskre and Mõigu districts.

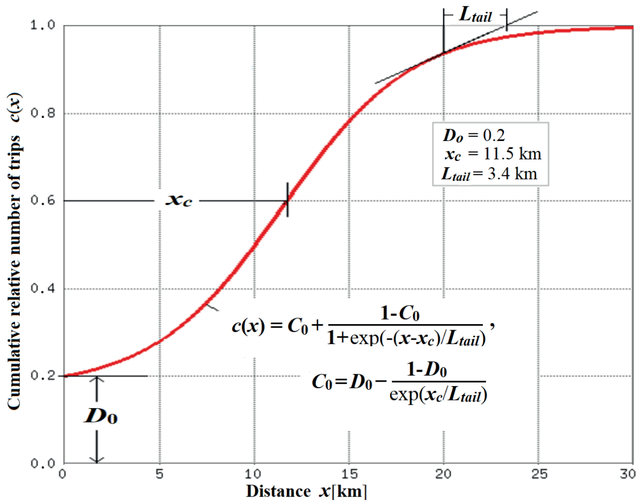

Figure 7. The constructed 3-parameter model of distribution of trip distances combining the initial short-distance contribution and the smooth sigmoid step for lengthier distances. Parameter values are estimated to represent the Järveküla example area.

2.4. One-Dimensional Spatial Situation Model

In order to model the potential positive impact of AVs on the time use of suburban residents, it is most important to consider those remote neighborhoods that are located more than 1 km away from transport arteries. Secondly, in order to adequately take into account the transport times of moving to different parts of a larger city, the city must also be divided into regions by distance. In addition to this, if a generalizable model is the goal, the scheme of source zones and destination districts should be left one-dimensional to allow calculation of transport times from distances and estimated speeds. Figure 8 describes the constructed one-dimensional spatial situation model for calculation of morning outbound trips from 5 origin zones in residential areas to 6 destination districts, both in the local municipality and in the larger city area.

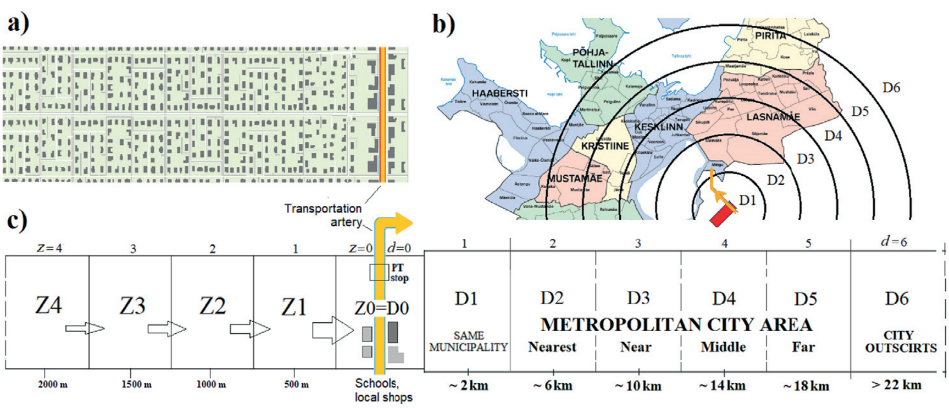

Figure 8. One-dimensional distances-based spatial model of transportation task: (**a**) an abstract map of residential area housing with local institutions, transport artery, and public transport stops on one edge; (**b**) distances-based concept of destination districts in metropolitan areas; (**c**) the simplified one-dimensional spatial scheme of origin zones and destination districts.

2.5. Initial Usage of Transportation Modes

In connection with the pilot project for the implementation of AVs in the municipality of Rae [30], a survey was conducted in 2021 [38], in which 819 residents gave answers about their present usage of different transport modalities in winter and in summer. The summary results of this survey, as well as the deduced input parameters for the model of the present work, are explained in Table 1 below.

Table 1. Actual usage of transportation modes in Rae municipality by 2021 survey and the deduced parameters for modeling example of the present study. Answers from 819 residents.

2021 Survey in Rae Municipality				Adopted Model Parameters		
Transportation Mode	**Winter**	**Summer**	**Average**	**Parameter**	**Value**	**Symbol**
1. Passenger car	80.5%	72.9%	76.7%	1. Private car	69.0%	m_{car}
				2. Taxi *	7.7%	m_{taxi}
2. Pyblic transport (walk+bus)	15.1%	11.1%	13.1%	3. Public transport (walk+bus)	13.1%	m_{PT}
3. Bicycle	0.7%	7.7%	4.2%	4. Bicycle	4.2%	m_{bic}
4. Walking	2.8%	7.4%	5.1%	5. Walking	5.1%	m_{walk}

* Estimated 10% of passenger cars.

2.6. Acceptance of Autonomous Vehicles

User adoption of AVs has been the subject of numerous in-depth studies, e.g., [6,14–16,19,27,28,39]. For the modeling task discussed in this work, it is important to construct a sub-model with a reasonable level of complexity that describes the transition of residents from five conventional modes of transport (see Table 1) to new AV-supported modes of transport. For the construction of the mentioned sub-model, Table 2 summarizes the residents' responses regarding the possible use of AVs. The answers of 819 residents are collected from the Supplementary Materials [38].

Table 2. Formulation of the aggregated autonomous vehicle acceptance factor on the basis of Rae municipality 2021 survey (answers from 819 residents).

Question/Parameter	Positive Answers
Should AV become a part of public transport?	72.8%
Would you use AV for everyday needs?	63.0% *
Would you use AV in case of on-site travel assistant?	48.8%
Would you use AV in case of remote travel assistant?	49.9%
Would you use fully automatic AV?	35.2%
Allow children to use AV in case of on-site travel assistant?	62.3%
Allow children to use AV in case of remote travel assistant?	38.8%
Allow children to use fully automatic AV?	23.1%
Consider AV safe on the street?	63.6%
Could AV replace your travelling with car?	45.5%
Aggregated average acceptance of AVs α	50.3% **

* 'Yes' answers and half of 'May be' answers summarized. ** Estimated maximal value of parameter α in present study.

The data in the table confirm the high readiness of nearly 50% of the population to use AVs. In order to realize a maximally compact calculation model for pre-assessment of the impact of AVs, here is proposed a single aggregated parameter α to account for the transition of people to AVs. With the addition of more detailed statistical data, it is possible to refine the treatment of this sub-model of AV acceptance.

2.7. Framework of Three-Dimensional Modality-Origin-Destination Matrix

The application of two-dimensional origin-destination (OD) matrices is a well-known methodology in transportation research; see, for example, [40]. In the present study, it is necessary to add a third dimension of transport modality to account for changes in proportions between transport modes due to the availability of AVs. The formal three-dimensional framework of the modality-origin-destination matrix is explained by Figure 9 below.

In the proposed MOD matrix, the following denotation of cell indexes may be agreed upon:

m—index of transportation mode (1–7);
z—index of zone of origin (0–4);
d—index of destination district (0–6).

In the MOD matrix framework, the next central issue of the EDTT model is to calculate the effective travel times t_{mzd} for all cells of the MOD matrix. As already commented in Section 2.1, the possible fourth dimension of the general task associated with population groups was here excluded to keep the model compact. If desired, the consideration of population groups can be added to the calculation of t_{mzd} values for matrix cells with a higher weight. Such are, for example, the cells corresponding to the use of a private car at medium distances (m = 1 and d = 3 or 4).

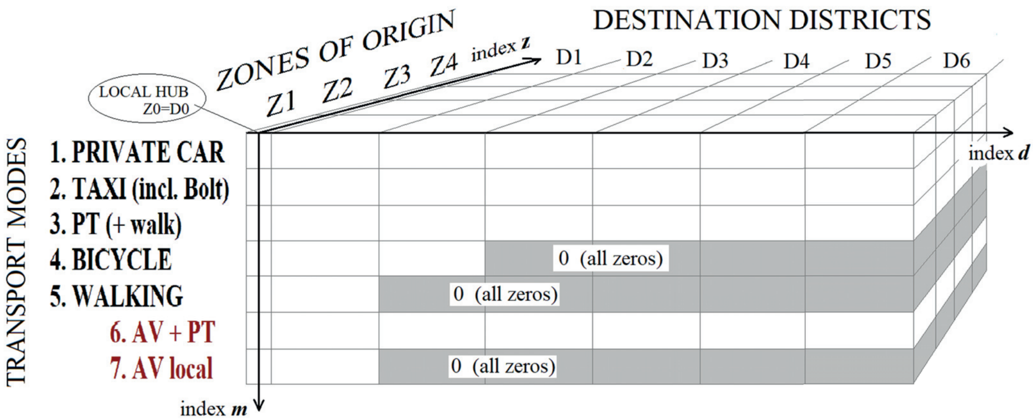

Figure 9. Explanation of concept of three-dimensional modality-origin-destination matrix used to sum up the daily transport times. Matrix defines 5 origin zones, 6 destinations districts, and 5 + 2 transportation modes. Each cell of MOD matrix is characterized by transport time with optional psych-physiological and economical extra terms and weight factors of distance and transport mode.

2.8. Central Summation Formula over Modes, Zones and Districts

In the three-dimensional mode-origin-destination framework of the transport times task, the central summation formula may be written in the following form:

$$T = (1 - N)HR \sum_{m=1}^{7} M_m \sum_{z=0}^{n_z} Z_z \sum_{d=0}^{n_d} D_{md} t_{mzd} \quad (4)$$

where

T is the average daily travel time of an average resident,
N is the fraction of non-moving residents before noon (e.g., small children),
H is the ratio of full-day outbound trips to forenoon outbound trips (≈1.6, see Figure 5),
R is the ratio of all sections of outbound and return trips together to outbound trips (≈2),
m is the index of the transportation mode (values 1–7, see Figure 9),
M_m is the statistical weight of the transport mode m (see Section 2.9 below),

z is the index of the zone of the origin (values 0–4, see Figure 9),
n_z is the maximal index of the zone of the origin (4 in present study, see Figure 8c),
Z_z is the statistical weight of the zone of the origin ($1/(n_z + 1) = 0.2$ in present study),
d is the index of the district of the destination (values 0–6, see Figure 9),
n_d is the maximal index of the district of the destination (6 in present study, see Figure 8c),
D_{md} is the (mode) m-dependent statistical weight of district d (see Section 2.10 below), and
t_{mzd} is the effective trip time for mode m, zone z, and district d (see section 2.11 below).

It should be noted that several simplifying assumptions have been used in Formulation (4), such as the assumption that the statistical weight of transport modes is independent of the origin zone and destination district. The practical value of the Model (4) is that it explicitly provides the average daily transportation time of an average municipality resident, and the dependence on the number of residents is only indirect (first of all via sub-model of AV waiting times).

2.9. Sub-Model of Transportation Mode Weights

In Figure 9, the concept of transportation modes was presented—a set of 5 conventional modes completed with 2 local AV-assisted modes to support the first-mile mobility of residents. An AV-dependent sub-model of transport mode weights M_m is needed to describe the transition from the conventional usage proportions described in Table 1 to the expected AV-supported proportions. Very detailed models can be found in the literature that examine the readiness to switch to AVs by population groups, gender, and other indicators (for example, [41]). Here, in order to arrive at reasonable preliminary estimates in a situation of limited information, a practical compact modeling approach could be to link the transition with the aggregated parameter α of AV acceptance (see Table 2). Considering this, a simple approach to describing the expected decrease in weights of conventional transport modes may be approximated by the following formulas:

$$M_1 = (1 - \alpha)m_{car}, \tag{5}$$

$$M_2 = (1 - \alpha)m_{taxi}, \tag{6}$$

$$M_3 = (1 - \alpha)m_{PT}, \tag{7}$$

$$M_4 = (1 - \alpha)m_{bic}, \tag{8}$$

$$M_5 = (1 - \alpha)m_{walk} \tag{9}$$

where weights of conventional modes $m_{car}, m_{taxi}, m_{PT}, m_{bic}, m_{walk}$ are defined and evaluated in Table 1.

Formulas (5)–(9) are based on the assumptions that all 5 traditional transport modes lose users equally according to the parameter α. Here, of course, the dominant mode of transport is the private car, the users of which showed 45.5% interest in the use of AVs in the survey (see Table 2), which justifies linking the mode change with the general parameter α. Formulas (10) and (11) describe the transfer of residents from the five traditional modes of transport to AV-supported modes 6 and 7.

Modeling the growth in the use of new AV-enabled transport modes 6 and 7 requires an assessment of the proportion between the local AV transport (mode 7) and combined mode of AV with urban buses (mode 6). The simplest modeling approach could assume 50:50 division, but a more realistic proportion could be stated on the basis of weight parameter D_0 of local trips of the trip distance Models (2) and (3):

$$M_6 = (1 - D_0)\alpha(m_{car} + m_{taxi} + m_{PT} + m_{bic} + m_{walk}), \tag{10}$$

$$M_7 = D_0\alpha(m_{car} + m_{taxi} + m_{PT} + m_{bic} + m_{walk}). \tag{11}$$

The constructed sub-model (5)–(11) is based on strong simplifying assumptions that are justified to obtain preliminary estimates. More focused questionnaires and the collection of real-world usage data by AVs after their introduction will enable significant refinement of this sub-model. It should be noted that the approach proposed here is based on the conservative assumptions that the total volume of trips and the profile of distances will remain the same after the introduction of AVs. Taking into account the corresponding changes is possible with an additional feedback loop in model when additional data on changes in people's behavioral profiles become available.

2.10. Sub-Model of Weight of Distances

Assuming an even population distribution in the residential area, it is possible to determine the statistical weight coefficients of the origin zones Z_z in the main summation Formula (4) simply as the inverse of the number of zones $n_z + 1$.

$$Z_z = 1/(n_z + 1). \tag{12}$$

The sub-model of statistical weights of destination districts D_{md} in Formula (4) may be specified on the basis of the distribution function of trip lengths (2) for the transport modes that cover larger distances in the city by private car, taxi, or PT buses. Local transport modes (bicycle, walking, local AV), whose final regions are $d = 0, 1$ or 2 (see Figure 9), can be described in a simpler way without applying a distribution function. With this sub-model, it has been assumed that there is no dependence on the origin zone z, as the zone lengths L_z are remarkably smaller than distances to destination districts in city dL_d.

In summary, the weight coefficients D_{md} of the destination districts in cases of long-range transport modes $m = 1, 2, 3, 6$ may be calculated on the basis of distribution function (2) by the following formulas:

$$D_{md} = c(dL_d) - c((d-1)L_d) \quad \text{for } 0 < d < n_z, \tag{13}$$

$$D_{md} = 1 - c((d-1)L_d) \quad \text{for } d = n_z, \tag{14}$$

$$D_{md} = D_0 \quad \text{for } d = 0, \tag{15}$$

In cases of short-range bicycle mode m = 4, the equal weight of close districts $d = 0, 1$ and 2 may be assumed:

$$D_{md} = 1/3 \quad \text{for } d \leq 2, \tag{16}$$

$$D_{md} = 0 \quad \text{for } d > 2. \tag{17}$$

In the case of short-range walking mode m = 5 and local AV mode m = 7, the equal weight of the remaining two local districts $d = 0$ and 1 in the same municipality may be assumed:

$$D_{md} = 1/2 \quad \text{for } d \leq 1, \tag{18}$$

$$D_{md} = 0 \quad \text{for } d > 1. \tag{19}$$

It can be noted that since the use of bicycles and walking has a small share (4.2% and 5.1%, respectively, see Table 1), the accuracy of modeling these modes of movement is not critical in the present use case.

2.11. Sub-Model of Transport Times

In addition to the formulation of sub-models for weight factors for modes M_m, zones Z_z, and districts D_{md} in the general summation Formula (4), the key question of modeling is the estimation of travel times t_{mzd} for every transportation mode m, origin zone z and destination district d. An important aspect that follows from the logic of transportation modes that rely on public transport is that the modeling of trips is reasonable to divide into two stages: stage 1 for local movement towards local transportation artery zone $Z_0 = D_0$ and stage 2 for later movement to destination districts D_0–D_6. This formal scheme includes a special case of local destination district d = 0 that corresponds to zero distance of stage 2.

A significant reduction of the amount of input data can be achieved via the calculation of travel times on the basis of average speed estimates for cars (private and taxi), public transport buses, AVs, bicycles, and human walking. Figure 10 explains the 2-stage concept and the introduced set of waiting and driving time parameters with optional psycho-physiological [42] and economical additional parameters for the calculation of effective transport time costs.

Based on the one-dimensional spatial structure of the task in Figure 8c, the trip lengths for stages 1 and 2 are calculated as follows:

$$l_1 = zL_z + l_{endwalk} \quad , \tag{20}$$

$$l_2 = (d - 1/2)L_d \quad \text{for } d > 1, \tag{21}$$

$$l_2 = 0 \quad\quad \text{for } d = 0 \tag{22}$$

where L_z and L_d denote the size of origin zones and destination districts, respectively, and the nonzero $l_{endwalk}$ term describes the walk from the PT end stop to the destination in the case of modes 3 and 6, which include public transportation.

The presented 2-stage concept of trip distances makes it possible to construct a universal sub-model for effective transport times with the inclusion of optional terms of psycho-physiological stress factors and psychologically perceived financial costs:

$$t_{mzd} = w_1 + \frac{l_1(1 + \varphi_1)}{v_1} + \frac{E_1 l_1 \psi_1}{A_h} + w_2 + \frac{l_2(1 + \varphi_2)}{v_2} + \frac{E_2 l_2 \psi_2}{A_h} \tag{23}$$

where

w_1, w_2 are the transport waiting times for stages 1 and 2,
l_1, l_2 are the travel distances for stages 1 and 2,
v_1, v_2 are the estimated travel speeds for stages 1 and 2,
φ_1, φ_2 are the psycho-physiological stress factors for stages 1 and 2,
E_1, E_2 are the financial costs per distance unit for stages 1 and 2,
ψ_1, ψ_2 are the psychological factors of perception of the financial costs for stages 1 and 2,
A_h is the national average hourly wage.

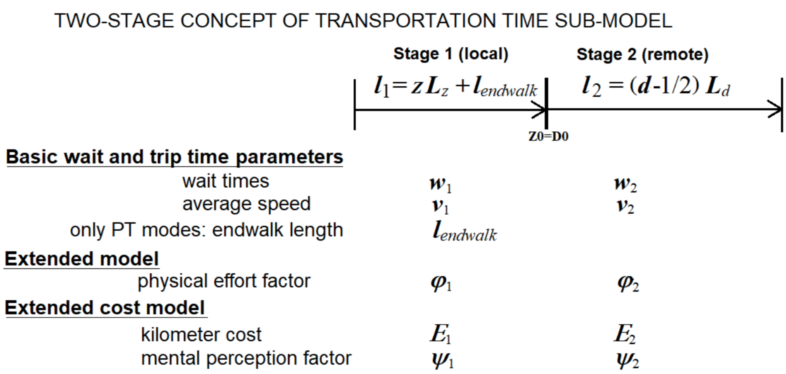

Figure 10. Explanation of the two-stage concept of outbound trips and input parameter set for calculation of effective transportation time costs.

Figure 11 illustrates the 2-stage effective trip time concept with actual values of parameters for the present use case. Denotations have the following meanings: φ—psycho-physiological stress factor; ψE—financial cost with psychological perception factor of time usage; n_{AV}—number of AV shuttles in residential service area.

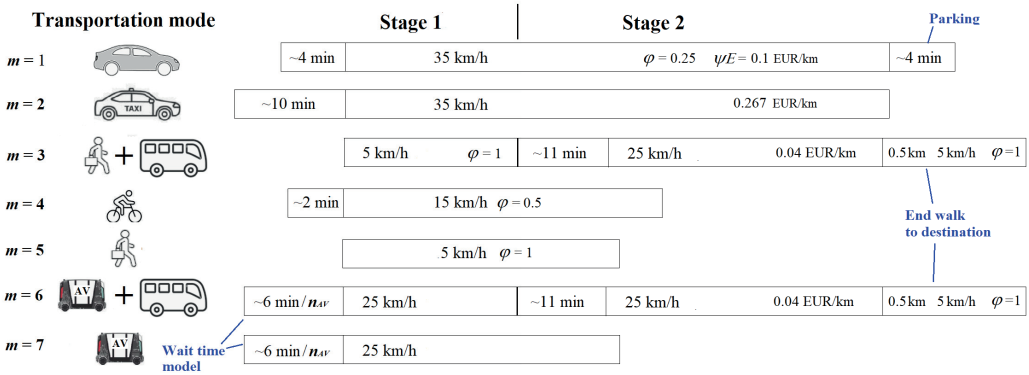

Figure 11. Explanation of 2-stage effective trip times methodology with actual numerical values of input parameters.

2.12. Sub-Model of AV Waiting Time

When implementing AVs as first-mile vehicles in a residential area, the waiting time w_1 can become the key efficiency parameter. This parameter primarily depends on the number of AVs in the service area $n_A V$ and on the spatial extent of the service area, as well as on the number of residents who want to use AVs simultaneously in the morning hours, the number of seats in AV shuttles, the quality of the online system of ordering AVs etc. It is possible to develop detailed, sophisticated models to investigate this problem, e.g., [4,9]. In conditions where input data is not yet sufficient or the goal is to obtain preliminary estimates for the impact of AVs, it is practical to use the methodology of a compact empirical model based on a minimum number of easily estimated input parameters in the present study. In the sample task of this work, we have used a maximally simplified 2-parameter model, which still contains a significant dependence on the number of AVs:

$$w_{AV} = \frac{w_{AV1}}{n_{AV}} \tag{24}$$

where

w_{AV1} is the average AV waiting time in the case of one AV in service area,
n_{AV} is the number of AVs in the service area.

A possible estimate for the parameter w_{AV1} is 6 min, which corresponds to the arrival of an AV from a distance of 2 km at a speed of 20 km/h.

3. Summary of Input Data

Transport studies usually deal with large amounts of data, due to which the studies become tied to a specific case, and the models are not easily transferable to other cases. In this study, the goal has been to create the most compact model possible, which would be able to describe the effect of introducing AVs in solving first-mile transport problems, not only in one sample case but also more generally. In doing so, it is important to design such a set of input data that would be easy to understand and easily specified. The complete list of primary input data.

The complete list of input parameters of the compact model proposed in this study is summarized below in Table 3. The following Table 4 presents the cross-use of these input parameters for trip stages 1 and 2 in the case of all 7 modes of transport.

Table 3. The complete list of input parameters of the compact model of effective transport time.

Parameter Description	Denotation	Value	Comment
Fraction of non-moving residents	N	0.1	Residents staying at home before noon
Ratio of all-day 24 h and morning 6–12 a.m. outbound trips	H	1.6	Used statistics of Mõigu area, see Figure 4
Return trips accounting factor	R	2.0	One return trip for every outbound trip
Farthest origin zone number	n_z	4	Zones 0–4 accounted for residential area
Size of origin zone	L_z	0.5 km	Up to 2 km if 4 zones
Number of destination districts	n_d	6	District 1 in local municipality
Size of destination district	L_d	4 km	Last district assumed large (up to 30 km)
Empirical parameter of fraction of local morning trips for 3-parameter distance distribution model	D_0	0.20	Local before-noon trips, e.g., children to local schools, see Model (2)
Median distance of city trips for 3-parameter distance distribution Model (2)	x_c	11.5 km	Average from the Mõigu and Kakumäe-Tiskre statistics, see Figure 5
Tail decay parameter for 3-parameter distance distribution Model (2)	L_{tail}	3.4 km	Fitting result of Mõigu and Kakumäe-Tiskre statistics, see Figure 5
Private car usage (before implementation of AVs)	m_{car}	69.0%	On the basis of 2021 survey, assumed 90% of passenger cars, see Table 1
Taxi usage (before implementation of AVs)	m_{taxi}	7.7%	10 % of passenger cars assumed to be taxis in 2021 survey, see Table 1
Public transport usage (before implementation of AVs)	m_{PT}	13.1%	Winter and summer average, includes walk to local transport artery, see Table 1
Bicycle usage (before implementation of AVs)	m_{bic}	4.2%	Winter and summer average, see Table 1
Walking percentage (before implementation of AVs)	m_{walk}	5.1%	Winter and summer average, see Table 1
Aggregated acceptance of AVs	α	0–0.5	Main input variable of model, maximum 50.3% from 2021 survey, see Table 2
Average speed of passenger cars	v_{car}	35 km/h	Same for private cars and taxi, averaged estimation from 'Google Maps directions'
Average effective speed of PT busses	v_{bus}	25 km/h	Data from before noon timetables of Tallinn city (e.g., bus line 132)
Average estimated speed of bicycle	v_{bic}	15 km/h	Local mobility until district D_2 (8 km)
Average estimated speed of walking	v_{walk}	5 km/h	Local mobility until district D_1
Average speed of AVs	v_{AV}	25 km/h	Local mobility until district D_1
Average waiting time of private car	w_{car}	8 min	Car initial warming (and end location parking)
Average waiting time of taxi	w_{taxi}	10 min	Estimate for arrival of Bolt system taxis
Average preparation (waiting) time of bicycle	w_{bic}	2 min	Estimated preparation time of bicycle
Average waiting time of PT buses	w_{bus}	11 min	Half-interval towards city in morning 6:00–12:00 (from Tallinn city and Harju county timetables)
Estimated AV waiting time (single AV case)	w_{AV1}	6 min	Empirical parameter, depends on size of service area, see Model (24)
Number of AVs in local service area	n_{AV}	2	Planned 2 AVs in present use case, see Model (24)
Average walk length from end PT stop to destination	$l_{endwalk}$	0.5 km	Important addition to realistic transport situation, see Figure 10
Psycho-physiological stress factor of private car driving	φ_{car}	0.25	Accounts for driving stress in rush hours, see Model (23)
Psycho-physiological stress factor of bicycling	φ_{bic}	0.5	Accounts for fatigue and weather stress, see Model (23)
Psycho-physiological stress factor of walking	φ_{walk}	1.0	Accounts for fatigue due to baggage, physical difficulties of elderly people etc.
Private car kilometer cost due to price for full mileage, maintenance and fuel	E_{car}	0.3 EUR/km	May be reduced due to car sharing (improvement of present model)
Taxi car kilometer cost	E_{taxi}	0.8 EUR/km	Estimated average value on basis of ordering system of Bolt
Public transportation bus kilometer cost	E_{bus}	0.04 EUR/km	Estimation based on price of typical 30-day tickets (≈1 EUR/day) and daily trip distances
Estimated hourly wage in the country	A_h	9 EUR/h	Conversion coefficient of financial costs to travel time (=0.15 EUR/min), see Model (23)

Table 3. *Cont.*

Parameter Description	Denotation	Value	Comment
Psychological cost perception coefficient of private car	ψ_{car}	0.33	Reduction factor of cost perception due to working and rest time savings, see Model (23)
Psychological cost perception coefficient of taxi	ψ_{taxi}	0.33	Reduction factor of cost perception due to working and rest time savings, see Model (23)
Psychological cost perception coefficient of PT buses	ψ_{bus}	1.0	Reduction irrelevant due to low speed of PT buses, see Model (23)

Table 4. Cross-use table of input data for 7 transport modes and 2 trip stages (local and remote) considered in transport times model (23). The referenced parameters are defined in the general input data Table 3.

Parameter of Model (23) for Stages 1 and 2		Mode 1 Private Car	Mode 2 Taxi	Mode 3 Walk + Bus	Mode 4 Bicycle	Mode 5 Walking	Mode 6 AV + Bus	Mode 7 Local AV
Waiting time, stage 1 (local)	w_1	$w_{car}/2$	w_{taxi}	0	w_{bic}	0	Model (24)	Model (24)
Waiting time, stage 2 (city)	w_2	$w_{car}/2$	0	w_{bus}	0	0	w_{bus}	0
Average speed, stage 1	v_1	v_{car}	v_{car}	v_{walk}	v_{bic}	v_{walk}	v_{AV}	v_{AV}
Average speed, stage 2	v_2	v_{car}	v_{car}	v_{bus}	v_{bic}	v_{walk}	v_{bus}	v_{AV}
Psycho-physiological stress factor, stage 1	φ_1	φ_{car}	0	φ_{walk}	φ_{bic}	φ_{walk}	0	0
Psycho-physiological stress factor, stage 2	φ_2	φ_{car}	0	0	φ_{bic}	φ_{walk}	0	0
Financial cost, stage 1	E_1	E_{car}	E_{taxi}	0	0	0	0 *	0 *
Financial cost, stage 2	E_2	E_{car}	E_{taxi}	E_{bus}	0	0	E_{bus}	0 *
Cost perception factor, stage 1	ψ_1	ψ_{car}	ψ_{car}	0	0	0	0	0
Cost perception factor, stage 2	ψ_2	ψ_{car}	ψ_{car}	ψ_{bus}	0	0	ψ_{bus}	0

* Free AV service in present use case.

4. Simulation Results

The simulation results of Models (2)–(24) with input data values listed in Tables 3 and 4 are discussed below. Figure 3 illustrates the spatial situation of the example task of the suburban area. Since the central summation Formula (4) of the model is defined using weight coefficients and transport times of MOD matrix cells, the model directly provides the average daily transport time of an average suburban resident. The defined factor α of acceptance of AVs, describing the reorientation of residents from traditional modes of transport to new AV-supported modes according to the sub-model (5)–(11), allows all results to be presented in a generalized form depending on this parameter.

Below in Figure 12 are summarized the main results of the daily transport times model for 3 levels of complexity of inclusion of different transport times costs:

1. Only waiting and driving time terms of sub-model (23) are included;
2. Psycho-physiological stress φ-factors added;
3. Psycho-physiological stress factors and financial costs with perception ψ-factors added.

The results from Figure 12 show, firstly, that the obtained people's daily transport times are of the order of 50 min, which are very realistic estimates that confirm the basic adequacy of the model. The easy-to-verify model output in the form of the averaged transport time provides good opportunities for further refinements of the model when more accurate monitoring data are received. If considering only the wait and pure driving times, then the positive effect of the reduction in time consumption predicted from the implementation of AVs is only in the order of a few percent, which can be justified by the fact that the use of AVs together with public transport buses remains slow compared to private cars and taxis. However, the model opens new possibilities for municipality officials to estimate, for example, improvements from the increasing frequency of public transport buses.

Next, if psycho-physiological stress factors are included in the study, the picture changes significantly more in favor of AVs. A nearly 19% reduction effect of AVs on the effective transportation time is obtained. This is explained by the fact that the local autonomous shuttle buses can significantly reduce the needed amount of first-mile walking in the residential area. Also, using public transport buses does not cause psycho-physiological stress, but with private cars, a 25 percent increase in perceived driving time is estimated due to psycho-physiological stress (see parameter φ_{car} in Table 3). Note that it is relatively easy to obtain more accurate estimates of the impact of factors like psycho-physiological stress, financial costs and perception of time gains due to faster transportation with additional focused surveys among suburban residents after the implementation of first AVs.

Furthermore, the results from Figure 12 show that including in the calculation the ψE-terms of perceived financial cost increases the positive effect of implementing AVs, but not as much as adding the φ-terms of psycho-physiological stress to the pure waiting and driving times.

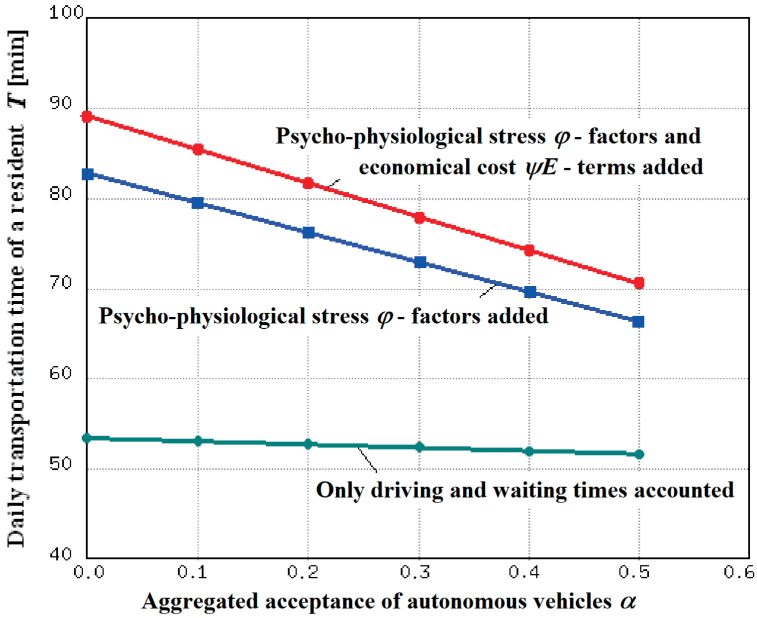

Figure 12. The main output of the model: daily effective transportation times of an average suburban resident versus the aggregated parameter of autonomous vehicle acceptance α.

Including the ψE-terms of perceived financial cost in the calculation further increases the positive effect of implementing AVs but not as much as adding the φ-terms of psycho-physiological stress to the pure wait and driving times.

5. Discussion

In this work, a practical, complete model of transport times affected by AVs is proposed, which comprehensively allows model users to reach from a set of transparently defined input data with minimal necessary volume to a concise output, which is the effective daily travel time EDTT of an average suburban resident. The model takes into account, either precisely or simplified, most of the important mechanisms that shape the impact of AVs in the role of first-mile vehicles.It should be emphasized that, following the compact modeling methodology, in order to preserve the model's predictive power and generality, the inclusion of overly detailed sub-models has been deliberately avoided, and only the most important aspects that affect EDTT have been taken into account. Thus, the paper focuses on the formulation of the mathematical computational system rather than the details of the system components (submodels), for which many high-level detailed publications are available.

The newly introduced moments, which have been used in this work to reach the desired final results, are as follows:

- Forenoon outbound trips are taken as a basis for evaluating the movements of the whole day;
- A sufficiently complete set of 5 traditional transport modes has been considered;
- An aggregated parameter α is introduced to characterize people's willingness to adopt AV;
- A simplified sub-model is proposed to describe the transition of people from 5 traditional modes of transport to the extended set of 7 modes augmented by AVs;
- For a compact description of trip lengths, a one-dimensional spatial model with origin zones and destination districts is applied;
- To describe combined movements such as local AVs combined with PT buses, a 2-stage trip description is introduced;
- A 3-parameter empirical distribution function of trip distances is constructed on the basis of real mobility statistics;
- A provisional AV wait time sub-model that includes practically important dependence on the number of AVs is proposed;
- The psycho-physiological stress factors of different transportation modes are introduced;
- A methodology for converting kilometer prices into effective transport times based on the country's average hourly wage has been proposed;
- Perception factors of financial cost are introduced to describe people's time gain in faster modes of transport.

Based on the set of the input data, the present work is partially similar to the studies [22,25,26], where characteristic parameters of transport modes have been used and people's attitudes towards different types of AVs have been studied.

Although this work has been devoted to the formulation of the mathematical calculation scheme, leaving aside the details of the sub-models, it makes sense here to comment on the applicability of the model for the analysis of some current special issues of smart city traffic management.

Positive effect of improved crowdsourcing [43]. In any case, the deployment of on-demand AVs requires a cloud-based or on-board computer system that collects and takes into account data from real traffic. Well-organized crowdsourcing can reduce the waiting time of AVs w_{AV} in the present computational model.

Impact of parking problems in city [44]. The proposed model here takes into account parking problems for private cars in at least three parameters: waiting time for private cars w_{car} (i.e., necessary extra time to park the car near the destination), psycho-physiological stress of private car driving φ_{car}, and cost per kilometer E_{car} (see Table 3).

Impact of improved walkability in suburban area [45]. Improved conditions for walking can be taken into account by increasing the weight parameter m_{walk} and decreasing the walking stress parameter φ_{walk} in the model (see Table 3).

6. Conclusions

In conclusion, this work has proposed a compact but sufficiently complete and general model of daily travel times with a minimal set of input parameters to proactively assess the impact of implementing AVs in first and last mile transportation in different suburbs.

The main output of the model is the effective daily transport time of an average suburban resident as a function of the aggregate AV adoption parameter. In addition to actual trip times, the model also provides effective travel times augmented with psycho-physiological stress and mentally perceived financial cost terms.

In order to achieve compactness and concrete numerical estimations, several sub-models of the proposed calculation scheme as model of transition from traditional transportation modes to AV-supported modes and the AV wait time model have been implemented as simply as possible. Combined with more detailed monitoring data and focused model-based surveys of a population, these sub-models can be easily refined.

The theoretical importance of the present work for transport research could be that it shows the possibility of reducing a complex multi-dimensional summation task to a three-dimensional one by means of several reasonable simplifying assumptions. At the same time, the construction of a compact computational model has made it possible to define a minimal sample set of initial data, which allows them, taking into account the most important influencing factors, to obtain realistic estimates of changes in transport times due to the introduction of AVs. The practical importance of the proposed compact calculation model lies in the fact that urban planners and local government officials have a tool at their disposal that, thanks to an easily understandable and relatively easily determined set of initial data, allows one to obtain, without long-term complex scientific studies, quick preliminary estimates of the impact of autonomous first-mile minibuses on the quality of life of suburban residents.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/smartcities7060151/s1, Rae municipality mobility analysis—Results of the mobility survey [38].

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Abbreviations

The following abbreviations are used in this manuscript:

AV	Autonomous Vehicle
EDTT	Effective Daily Travel Time
MOD	Modality-Origin-Destination (matrix)
OD	Origin-Destination (matrix)
PT	Public Transport
TTS	Travel Time Savings
VTTS	Value of Travel Time Savings

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Paper 5

Kalda, K., Koskinen, K. M., Sarv, L., & Sell, R. (2025). Situational awareness in autonomous shuttle buses. Proceedings of the Estonian Academy of Sciences.

Situational awareness in autonomous shuttle buses

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AUTONOMOUS VEHICLES

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ABSTRACT

Autonomous shuttle buses provide a promising solution for the last-mile problem in various contexts. The removal of the human driver facilitates round-the-clock operations as well as transportation in locations that might otherwise be unfeasible for buses operated by a human driver. Trials have been conducted on these buses, and several companies aim to equip their vehicles with full self-driving capabilities. However, removing the human driver introduces several challenges, particularly in handling emergency situations. The absence of the driver, therefore, calls for increased passenger situational awareness, i.e., understanding of the environmental and contextual factors impacting the operations of the bus the passenger is on. It remains unclear to what extent bus manufacturers have considered these issues or integrated them into the design. This research seeks to shed light on the matter by studying the topic both from the industry's and users' perspectives.

1. Introduction

Autonomous transportation systems are being deployed into the public transportation ecosystem. As the architecture of autonomous transport modes represents a transformation of the role of the human driver to self-driving algorithms, they already pose formidable design challenges in terms of the deployed technology. No algorithm is entirely accurate. Numerous crashes of self-driving vehicles highlight the importance of human situational awareness (SA) in reacting to unintended behaviors of autonomous vehicle (AV) algorithms (Wang et al. 2020).

While the issue of SA has attracted a fair amount of research and practitioners' interest in relation to private passenger cars (Chandrasekaran et al. 2019), the matter has received little attention in other related research domains, such as autonomous shuttle buses (ASBs). A number of trials have been conducted with ASBs in various locations, and several companies have embarked on the challenge of developing these buses and their self-driving capabilities (Herrenkind et al. 2019; Launonen et al. 2021). In the trials, there is often a human agent inside the bus, ready to take over in case something unexpected occurs or the system fails to behave as intended. However, ultimately, the objective of these buses is to operate without having any human controller on board.

This raises the question regarding the required or expected SA of the passengers. Dealing, for instance, with unexpected situations may require passengers to adopt roles and tasks that have been so far delegated to the human driver/operator. Overall, technological systems such as AVs are, in essence, socio-technical, as their functioning and acceptance rely on different technological, social, and contextual factors that interact with and impact the system's ability to meet its objectives (Wang et al. 2020). In addition to solving the technological challenges, the development of fully autonomous ASBs is also dependent on a range of human factors, some of which are linked to and impacted by the passengers on board the vehicles as well as by people within their proximity.

This paper seeks to shed light on these other issues and challenges that so far appear to have obtained limited research interest. The research questions for this study are the following: how do different stakeholders view the level of SA required from passengers of shuttle AVs, and how is passenger SA factored into the design of the shuttles?

A major challenge for ASB developers is the lack of understanding of what real users consider important in practical situations and what they require to feel safe enough to step on board unmanned ASBs. Through a live pilot and a survey with over 100 residents in the pilot area, it is possible to answer vital questions that reveal both participants' attitudes and actual feelings. Open-ended questions also provide insight into ideas and visions that scientists working daily with ASBs fail to consider or just assume logically. But logic and people in traffic do not always go hand in hand.

The main aim of this research is to contribute towards a better understanding of the role of SA of passengers and how that is currently addressed by different actors in the sector. On the basis of these findings, we also put forward a research agenda. The data for this research are collected via interviews with ASB manufacturers and other representatives from the sector as well as via a survey conducted of the likely and actual users of these buses.

The main novelty in this research is the approach to look at SA from the angle of what is most important to the actual ASB users and generally to people in traffic with autonomous shuttles, considering the ultimate goal that there is no safety operator on board.

2. Literature on situational awareness and self-driving vehicles

SA can be defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" (Endsley 1988). SA can be divided into three levels of responsiveness. Whereas the first level, perception, is seen as the basic level requiring recognition of cues in the environment, the second level, comprehension, calls for analysis and processing of different pieces of information and their interconnections to give meaning to what is being observed. The third level, projection, builds on the first two levels and refers to the person's ability to predict the future state of the environment or context that they are observing (Endsley 2019).

The different levels of responsiveness and the ability to react quickly are of particular importance in the automation of driving (Endsley 2017). Since full driving automation has not yet been achieved in open road transportation, the SA of drivers of self-driving passenger cars has received a fair amount of interest in research and industry. Car manufacturers such as Tesla have introduced so-called nags that remind the drivers to keep their hands on the steering wheel (Nordhoff et al. 2023) while also delivering contextual information to the driver. SA has been found to be impacted by human-specific characteristics such as trust towards automation, engagement and workload of the driver, and mental capacity, as well as more technology-related factors such as level of automation, technology complexity, and information salience (Endsley 2017).

The role of passenger SA has received significantly less attention. In passenger cars with self-driving capabilities, passengers have been studied, for instance, in relation to the effect passengers have on the SA of the driver (Chandrasekaran et al. 2019), how SA impacts the anxiety of passengers traveling in a self-driving vehicle (Lu et al. 2022), or how much SA is required to improve passenger trust towards automated vehicles (Chang et al. 2019). While SA may help passengers regarding certain psychological traits, such as gaining trust and relieving anxiety, they are not expected to have any direct role in maneuvering or managing the vehicle. In the context of a passenger car, this is somewhat understandable, as the main task of driving is split between the driver and the automation, assuming the vehicle has some capabilities regarding the latter.

However, in the case of ASBs, the aim is directly linked to the removal of the human operator, whose tasks are not limited to driving the bus alone but also include tasks such as dealing with unexpected situations in and outside the bus. As a result, the operations of a fully autonomous ASB are in some instances likely to depend on the passengers, which again calls for appropriate levels of SA from them. Current research on ASBs primarily focuses on the concerns and hopes that users have regarding these buses (Herrenkind et al. 2019; Launonen et al. 2021). The required level of passenger SA and its influence on ASB design remains unclear.

This is of importance as it links to other relevant questions on the role of passengers of ASBs, such as what kinds of tasks or control mechanisms might be given to them, how much information passengers should be provided, and in what format and with whom and how to interact in unexpected situations. Our research seeks to contribute to these questions by looking at ASBs concerning the SA of passengers as well as ASB users' views regarding the matter.

3. Methodology

Building on these insights, mixed methods were used in the current case study for investigating the different perceptions of SA in the context of AVs applied in real-life traffic situations and as part of public transport services (Udal et al. 2024). The descriptive case study method was applied as it is foremost concerned with questions such as "how" and "why" and permits differences between what was planned and what occurred.

A pilot test with a self-driving shuttle bus was conducted in Rae Parish (in Estonia) as an extension to the public transport system in the spring of 2023 (see Fig. 1). The AV used for the experiment was designed and manufactured in Estonia, under the iseAuto project (Sell et al. 2024; Sell, et al. 2021). The particular vehicle was a commercial version of the iseAuto. The overall project was connected to wider future transportation solutions – MaaS XT (Kalda et al. 2024), offering seamless integration of different mobility-related services, including self-driving minibuses and on-demand transportation. The aim of the survey was to assess the attitude of suburban residents towards self-driving vehicles after experiencing shared traffic situations with ASBs, as well as after using ASBs as a local last-mile service. Before conducting the survey (2022–2023), interviews with ASB manufacturers and service providers were conducted to assess

Fig. 1. Autonomous shuttle bus – iseAuto – used for the case study in Rae Parish. Photo taken by the authors.

their consideration of user experience and SA. The interviews are described in more detail at the end of this chapter and in the next one.

The online survey (https://forms.gle/tsEMxU2LSAPjihe28) was conducted among residents after the month-long ASB demo was finalized (dissemination was done in collaboration with the local government), with the main scope being to understand the perception of ASBs and SA from several angles.

A mixed-method approach was used, conducting semi-structured interviews with representatives of either self-driving vehicle technology or software developers, as well as with research centers focusing on AV development and application. The interviewees were selected mostly among Estonian and Finnish AV developers, as the interviews were analyzed in the context of the user survey. The interviews were open-ended, and guiding questions were sent beforehand.

The questions mainly focused on the design of internal communication in the ASB with passengers and the intended role of the passenger (either active and able to take over driving actions, active only in emergency situations, passive without any communicative actions, or passive with a possibility to communicate with remote operators). Additionally, there were questions regarding the amount of information provided to passengers in everyday situations and in cases of disruptions. The aim was to understand how much regard was given to communication-related potential challenges.

The main objective of the questions was to determine how much and at what level of complexity communication with passengers and SA had been considered while designing either the AV or a service using AVs. The interviews were adapted based on the interviewee to maximize their relevance.

4. Experiment results

Based on the interview answers, nine recurring topics were distinguished: transparency, universality of interpretation of gestures (cultural differences), the role of government/authorities, the form of communication used, the preference for making changes to the environment to enable AVs to function better rather than making AV design more human-centric, whether ASBs were considered the same as buses but without drivers, the passenger role as active or passive, technology readiness, and the relevance of the trust factor.

Some interviewees leaned towards providing some information but saw full transparency as counterproductive, potentially leading passengers to worry about factors that were not important. Others appeared not to have given much thought to issues linked to passengers' SA and increased responsibilities. The general assumption seemed to be that ASB passengers were comparable to those of a human-driven bus.

Another challenge that emerged was the variability of human behavior, gestures, and actions across different cultures. Some saw most human gestures and actions as universal, while others considered this a significant challenge. Points were made regarding how strictly people follow traffic rules and the differences in interpreting human signs. Similarly, it appeared that little thought had been given to the service design or business models around ASBs. Some doubts were expressed about whether last-mile transportation alone would be sufficient for a profitable business, and ideas such as using the buses for monitoring parking violations or gathering other types of data for additional purposes were mentioned.

The user survey included a multiple-choice questionnaire with some open-ended questions, totaling 35 questions. Among the 165 respondents, 53.9% had been in traffic with an AV, but significantly fewer had actually used one (only 28.7%). However, 86.5% expressed interest in using AVs in the future. Only 11% of survey participants considered AVs unsafe (see key results on survey in Fig. 2).

When asked whether they would use an ASB as their daily commute, responses were categorized as "yes", "no", and "don't know". When asked what kind of everyday mobility option they would replace with AV use, most respondents answered personal cars (65.5%), followed by public transport (41.8%) and taxis (30.9%). Only 15% of respondents considered it unsafe to be a passenger on an ASB in traffic. In an open-ended response, one participant stated:

"There is no reason to feel unsafe in an AV because I presume that AVs are technologically reliable like an elevator, and surely the manufacturers have thought it well through on how to provide help in case of malfunctions or accidents."

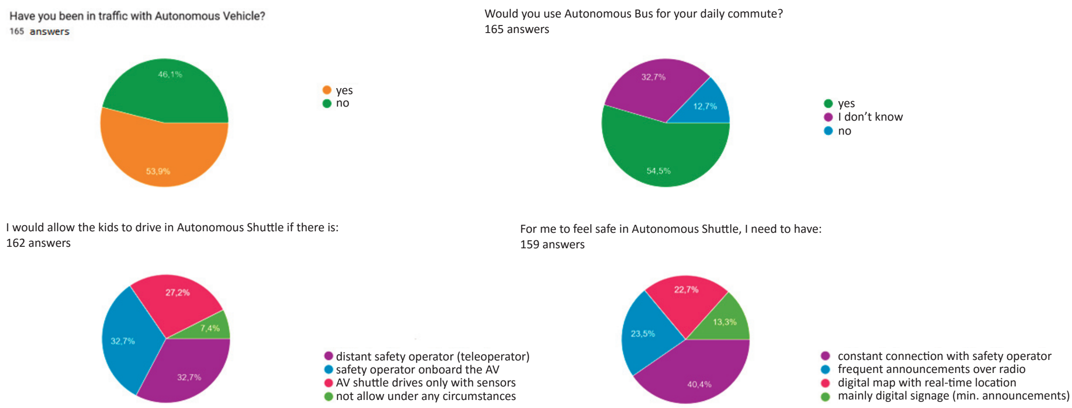

Fig. 2. Key results on survey.

Almost an equal percentage of people considered it safe for an ASB to be either remotely operated or driven only by sensors. Specifically, 20.5% considered it safe only with an operator on board, while 7% said they would not agree to use an ASB under any circumstances.

Regarding SA inside the bus, 64.8% considered it most important to have access to a digital map showing the location and movements of the ASB. Meanwhile, 37.7% preferred undisturbed rides with minimal information, except in emergencies or occasional operator interventions. A similar percentage (36.5%) stated that to feel safe, it was important to have constant communication with an operator during the ride, while 21.4% felt that a continuous flow of information was necessary to ensure safety.

5. Discussion and conclusions

The findings show that the key focus of ASB manufacturers is on solving the technological challenge of enabling fully autonomous driving of the buses. While understandable, it makes the development process of ASBs overwhelmingly technology-centric and runs the risk of ignoring human-related factors that are important for the success of ASBs. Despite technological advancements, user trust in AVs remains contingent on clear communication, and perceived safety is based on the assumption that the manufacturers and service providers have thought through how to assist passengers in case of accidents. It was quite surprising that a large number of people preferred to be minimally informed while riding with the ASB, and the most important communication measure, according to the user survey, was a real-time map showing the location of the ASB. Less important was the constant connection with the operator.

As seen from the interviews, not much consideration was given to the roles and tasks of the passengers nor to the optimal SA level of passengers or ideal communication channels to reach that level. The form of passenger communication or provided information was not based on conducted research but more on how these matters were organized in human-driven buses. This is unsurprising given the limited research on the topic. To address these differences and to establish the correct level of passenger SA of ASBs, we have identified three research areas that need to be investigated further. These areas are based on the data collected for this research and seen as of importance for the successful deployment of ASBs.

First, to establish the correct level of SA of ASB passengers, there is a need to clarify what is expected from them in different scenarios that may occur for the shuttle. Clear examples of these scenarios are accidents that an ASB might be involved in but also situations that can possibly lead to unwanted outcomes and may require passenger vigilance. These scenarios help to evaluate how active or passive the passengers are expected to be in relation to the buses' operations and set the basis for the required SA. This has also further implications for the transparency of information that is provided to the passengers on the ASB: should all available information be provided or only the bare minimum so that the passengers can fulfill the roles falling to them? Related to this, how much control of the buses' operations should passengers have, and through what kinds of channels and in which format should the information be provided?

Second, depending on location, results can vary not only geographically but also culturally, infrastructurally, and in terms of existing regulations. As a result, established passenger roles, required levels of SA, the most suitable amount of information, and preferred communication channels and formats may differ from one context to another. This calls for any research conducted on SA and ASBs to more generally consider how applicable the research findings are to other areas and cultures. Especially in situations marked by human-machine interaction, it is crucial for the machines to understand what different signs, gestures, and behavioral patterns may mean in that context. Similarly, it may well be that the best approaches to factors such as required SA evolve over time as technology develops, but also as people become more accustomed to the ASBs and their use.

Finally, as the focus is largely on solving the technological challenges of equipping the buses with fully autonomous driving capabilities, it seems that there has been less consideration of the service dimension or business model of the buses. This is linked to requirements on the level of passengers' SA. As noted above, this impacts the required trust of the passengers. Future research should expand on user expectations in different cultural and regulatory contexts, including ASB designers and manufacturers, as well as to better map the non-driving-related tasks that are currently done by the human driver. Our intention is also to continue research on the three research areas identified above to establish the requirements and contextual implications for SA of passengers inside ASBs.

Data availability statement

All data are available in the article.

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Olukorrateadlikkus autonoomsetes minibussides

Krister Kalda, Kari M. Koskinen, Lill Sarv ja Raivo Sell

Autonoomsed minibussid pakuvad lahendust viimase miili transpordiprobleemile, võimaldades ööpäevaringset teenindust ka keerukates keskkondades. Juhi puudumine tõstab aga reisijate olukorrateadlikkuse tähtsust, kuna ootamatutes situatsioonides võib vastutus langeda neile. Uuring keskendub sellele, kuidas on reisijate rolli ja teadlikkust arvesse võetud autonoomsete busside disainis ja arenduses. Intervjuud tootjate ja kasutajatega näitasid, et keskendutakse peamiselt tehnoloogiale, kuid vähem reisijate rollidele ja informeeritusele. Kasutajauuringust selgus, et paljud usaldavad autonoomseid busse, kuid eelistavad minimaalset teavet. Peamine soovitud teabeallikas oli digitaalne kaart bussi asukoha ja liikumise kohta. Uuring toob esile kolm olulist uurimisvaldkonda: reisijate ootused eri stsenaariumides, kultuurilised ja regulatiivsed erinevused ning teenuse ja ärimudeli arendamine. Edasised uuringud keskenduvad reisijate olukorrateadlikkuse optimaalsele tasemele ja sobivatele kommunikatsioonikanalitele autonoomsete busside kontekstis.

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