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Decarbonising transport and mobility through data-driven modal shift: DeMo final report

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Summary

The DeMo project – Decarbonising transport and Mobility through data-driven modal shift – explored how digital services, mobility data, transport modelling and public-private collaboration can make sustainable mobility more attractive, accessible, and effective. The project examined how these enablers can accelerate the transition towards low-carbon mobility and create new ecosystem-based business opportunities. Implemented by VTT and Tampere University, the project combined literature reviews, user surveys, co-creation workshops, concept design, technical development, pilots and business-model analysis in the urban contexts of Helsinki and Tampere. This report presents results of VTT's work and those made in collaboration with Tampere University and other participating organisations.

The research shows that mode choice is shaped not only by travel time, cost and reliability, but also by situational, experiential and habitual factors. Complex trip chains, weather, carrying goods, uncertainty and difficulties in the first and last mile can reinforce car use. Digital interventions should therefore provide reliable, context-sensitive and accessible support while also making sustainable journeys attractive and meaningful.

Two traveller-oriented concepts were developed and evaluated. Opastaja supports multi-stop trip planning and destination discovery through route-aware points of interest, aiming to make public transport and active travel more appealing. The Extended Trip Planner supplements conventional journey planning with visual, contextual and accessibility-sensitive guidance, reducing uncertainty on unfamiliar routes. Evaluations indicated clear value in exploration, confidence-building and last-mile navigation, while identifying needs for richer data, personalisation, multimodal flexibility and sustainable arrangements for maintaining guidance content.

The project also developed a Mobility data sandbox architecture that links heterogeneous data, governed data spaces, digital twins and AI services. Demonstrators in living-lab and operational environments showed the potential of interoperable data sharing, AI-assisted analytics, controlled agent-based monitoring and data-driven micromobility safety interventions. The work nevertheless highlighted continuing challenges in data quality, semantic interoperability, privacy, governance, participant onboarding and scalable maintenance.

Overall, sustainable modal shift requires coordinated development of user-centred services, high-quality infrastructure, interoperable data ecosystems and viable public-private collaboration models. Recommended next steps include larger real-world and longitudinal pilots, stronger integration with established journey-planning platforms, clear allocation of data and content responsibilities, governance-by-design and systematic assessment of behavioural, accessibility, emissions and business impacts.

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Preface

The DeMo project – Decarbonising transport and Mobility through data-driven modal shift – was established to explore how data-driven services, collaboration models and experimentation environments can make sustainable mobility more attractive, accessible and effective. The project was carried out by VTT Technical Research Centre of Finland and Tampere University in collaboration with cities, public transport authorities, national authorities and companies.

Helsinki and Tampere provided important urban contexts and experimentation environments for the work, including Mobility Lab Helsinki and Lyyli Living Lab. These environments enabled the project to connect research with practical challenges, test emerging approaches and assess how digital mobility solutions can support the transition towards low-carbon transport.

The project was funded by Business Finland through the Decarbonized Cities programme as a Co-Research project. We gratefully acknowledge Business Finland for making this work possible and for supporting research that contributes to broader national and European objectives for low-carbon transport, sustainable growth, transport digitalisation and interoperable mobility data ecosystems.

We would also like to express our sincere thanks to the members of the project steering group: the City of Helsinki, the City of Tampere, the Finnish Transport and Communications Agency Traficom, the Ministry of the Environment, Matkahuolto, iQ Payments, Solita, Škoda Transtech, Tieto, UDT Technologies, Voi Technology, Waltti Solutions, ITS Finland, Tampere University and VTT. Their active participation, constructive guidance and invaluable contribution strengthened the relevance, quality and practical applicability of the project throughout its implementation.

The steering group brought together extensive expertise in digital infrastructure, payment and access solutions, data analytics, emerging transport technologies, public transport, micromobility, land use, transport modelling, multimodal travel services, policymaking and regulation. The members' insights helped connect the research to operational needs, shape the project's pilots and concepts, and identify pathways for the further use and development of its results.

Finally, we thank all partner organisations, researchers, workshop participants, interviewees, pilot contributors and other stakeholders who shared their time, data, expertise and perspectives. The results presented in this report are the outcome of this broad collaboration and a shared commitment to advancing sustainable, user-centred and data-driven mobility.

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1. Introduction

1.1 Data-driven modal shift

Reducing emissions from urban transport is one of the most significant global challenges of our time. Technological development and the transition to low-emission vehicle fleets are essential, but they do not alone address the full scale of the challenge. Progress also requires a modal shift from private car use towards public transport, walking, cycling and shared mobility services, particularly in urban areas where cities can influence transport demand, service provision, land use and the allocation of public space. Such a shift can reduce greenhouse-gas emissions and energy use while contributing to safer, more accessible and more liveable cities.

Transport policy commonly combines push measures that discourage unsustainable travel with pull measures that improve the attractiveness of sustainable alternatives. The DeMo project focused primarily on the latter: understanding users' needs and motivations and developing data-driven services, service concepts, collaboration models and experimentation environments that make sustainable travel easier, more reliable, more accessible and more appealing.

1.2 DeMo project context and motivation

The DeMo project – Decarbonising transport and Mobility through data-driven modal shift – was established to identify practical means and tools for accelerating sustainable modal shift in urban transport. Its starting point was that existing public transport and Mobility-as-a-Service solutions had not yet become sufficiently attractive alternatives to private car use, and that fragmented data, limited interoperability and unresolved public-private collaboration arrangements continued to hinder integrated mobility services. DeMo therefore examined modal shift as a systemic challenge involving user experience, digital services, data governance, transport modelling, business models and public-private partnership practices.

The project was carried out by VTT Technical Research Centre of Finland and Tampere University in collaboration with cities, public transport authorities, national authorities and companies. Helsinki and Tampere provided important urban contexts and experimentation environments, including Mobility Lab Helsinki and Lyyli Living Lab. The steering group members – City of Helsinki, City of Tampere, Finnish transport and communications agency Traficom, Ministry of Environment, Matkahuolto, iQ Payments, Solita, Škoda Transtech, Tieto, UDT Technologies, Voi Technology, Waltti Solutions, and ITS Finland – contributed valuable expertise in digital infrastructure, payment and access solutions, data analytics, emerging transport technologies, public transport, micromobility, land use, transport modelling, multimodal travel services, policy-making and regulation. The project was funded through Business Finland's Decarbonized Cities programme as a Co-Research project and supported broader national and European objectives related to low-carbon transport, sustainable growth, transport digitalisation and interoperable mobility data ecosystems.

1.3 Objectives and research questions

The overall objective of DeMo was to develop knowledge, methods and tools that help cities and mobility stakeholders promote sustainable modal shift while balancing environmental, economic and social sustainability. Environmentally, the project sought to reduce urban transport emissions and improve energy efficiency. Economically, it aimed to identify cost-effective and commercially viable solutions, strengthen public-private collaboration, and create scalable reference cases for

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Finnish companies. Socially, it addressed accessibility, service availability and the reduction of transport poverty by considering different user groups and mobility needs.

The work was guided by four research questions:

- How can data-intensive solutions be leveraged to develop sustainable mobility services that are attractive and accessible to all user groups, and how do these solutions enhance accessibility and inclusivity?
- What kinds of future public-private partnership (PPP) models can promote the development and adoption of commercially viable, sustainable mobility services and cross-sectoral Beyond MaaS services?
- What are the means to improve data quality and interoperability, what opportunities are offered by AI-based data processing, and how can data-related regulation (including GDPR) and data sharing be facilitated?
- How can transport services and other services integrated with them be incorporated into regional transport models, and what is the emissions reduction potential of mobility services in urban regions?

In addition to producing research-based knowledge, the project aimed to develop and evaluate practical service concepts, proofs of concept and pilots in real urban environments. The final report assesses how these objectives evolved during implementation and synthesises the results, lessons learned and implications for further research, policy and commercial exploitation.

1.4 Work plan and report structure

The project was organised into seven mutually supporting work packages. WP1 investigated attitudes, motivations and user needs related to modal shift. WP2 developed regional transport modelling approaches for assessing changes in mode share and emissions. WP3 designed and tested a development environment – a Mobility data sandbox – for data-intensive and AI-enabled mobility services. WP4 implemented and evaluated pilots, demonstrations and related studies. WP5 examined collaboration, public-private partnerships and business models for low-carbon mobility services. WP6 coordinated dissemination and communication, while WP7 ensured project management and coordination.

The structure of this report follows the project's progression from understanding the drivers of mode choice to designing, implementing and evaluating solutions. The following sections present the behavioural evidence base, concept-development process, proof-of-concepts and pilots, the Mobility data sandbox, collaboration and business-model results, and the project's overall conclusions and recommendations.

1.5 Collaboration networks

DeMo was implemented through a broad collaboration network that combined research, public-sector and business perspectives. Nationally, the project engaged cities and public transport authorities, national ministries and agencies, companies developing mobility, data and digital-service solutions, and relevant transport-sector networks. Stakeholder participation through the steering group, workshops, interviews and living-lab activities helped align the research with operational needs and supported the validation and exploitation of results.

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International collaboration complemented the Finnish activities through research exchanges, benchmarking, joint workshops and links to related projects and conferences. Collaboration with partners in Australia, Spain, the Nordic countries, and elsewhere provided comparative perspectives on Beyond MaaS, public-private collaboration, digital passenger information, AI, and emerging mobility technologies. These networks also supported the transferability of the project's results and created pathways for subsequent European and international research and innovation initiatives.

2. Towards sustainable modal shift

2.1 Factors influencing mode choices

Based on the assumption that individuals have agency over choosing between different modes of mobility, a growing body of research has examined the factors that affect individual mode choices. However, these studies come from diverse disciplines and research traditions, while deploying a wide variety of different methodologies. Although existing cognitive and motivational theories have been applied (see e.g., Allen et al. (2019) for Maslow's hierarchy of needs, Timmer et al. (2023) for Theory of Planned Behavior and Goal-framing theory, Kang et al. (2019) for Theory of interpersonal behavior), and new models proposed to explain how people make decisions regarding travel mode choices (Bösehans & Walker, 2020; Schneider, 2013; Timmer et al., 2023), the complexity of the topic, diversity of existing literature, and contradictory results being commonplace within the corpus prevents a comprehensive synthesis of the factors that drive mode choice (Charreire et al., 2021; Timmer et al., 2023).

Below, an overview of some of the motivational factors that either encourage or hinder individuals when choosing a specific mode of mobility is provided. Although these factors emerge relative to the user perceptions and the characteristics of the mobility system, due to the diversity of existing literature on the topic, these factors differ qualitatively as well as in their level of abstraction. While some of the mapped factors can be considered affordances - i.e., features of mobility that allow certain types of interactions and behaviours (e.g., road safety conditions, reliability) - some can be rather understood as outcomes of these affordances (e.g., relaxation). Borrowing from prior research on environmental psychology and service research (Hamari et al., 2016; Lindenberg & Steg, 2007; Tolppanen & Kang, 2021), these factors are categorized into utilitarian, hedonic-experiential and altruistic. While the primary purpose of mobility is to efficiently move from one place to another (utility), it encompasses a broader spectrum of experiences and sensations associated with being on the move (experiential & hedonic) that affect individual mobility choices and behaviours (Bösehans & Walker, 2020). Moreover, as the wider environmental, social, and economic implications of mobility have taken centre stage in discourses around the topic and risen to public awareness, they have become factors that increasingly shape individual mobility behaviours, tapping into the individual willingness to do good and 'act appropriately' (altruistic) (Hunecke et al., 2001; Lindenberg & Steg, 2007). The analysis focuses on prior research related to public transport, active transport (i.e., walking and cycling), and private cars. It is, however, noteworthy that in the context of day-to-day life, mobility behaviours can become habitual, rather than based on deliberation, leading to a tendency to choose a certain mode over others (Fujii & Kitamura, 2003; Schwanen et al., 2012). Additionally, due to habituation, these factors can become suppressed as individuals adapt to extant mobility circumstances (Novaco & Gonzalez, 2009).

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2.1.1 Public transport

Much of prior research assumes that mode choice is driven by the pursuit of maximizing utility while minimizing disutility, and accordingly a wide variety of **utilitarian factors** that encourage or hinder the use of public transport have been identified. These relate to individual perceptions of public transport costs and benefits, whether related to time, money, or effort. The *availability and accessibility* of transportation facilities and well-connected routes near one's location is an important driver for public transport use, and prior research indicates that the likelihood of using public transport decreases rapidly when the distance from a household to public transport exceeds 400 meters (Buehler, 2011; Charreire et al., 2021; Fu & Juan, 2017; Saif et al., 2019). For some user groups, the *accessibility issues associated with public transport facilities and vehicles*, such as difficulties in boarding or navigating in stations may become a barrier for choosing this option (Musselwhite & Roberts, 2021). Moreover, the *time* needed to make the intended journey using public transport, as well as the price of public transport tickets in comparison to alternatives have been recognized to discourage or encourage choosing public transport (Altieri et al., 2020; Charreire et al., 2021). To become an attractive alternative to private vehicles, public transport also needs to be perceived as *reliable* in terms of vehicles running on schedule (Burian et al., 2018; van Exel et al., 2011). In addition to the costs and benefits related to the journey itself, providing the users with sufficient *information* about public transport routes and interchanges along the journeys to enable trip planning and public transport use in an *easy* and efficient manner has been identified as a factor that drives public transport use (Charreire et al., 2021; Fu & Juan, 2017; Redman et al., 2013). An additional characteristic of public transport adding to its appeal is that it does not commonly require active user involvement while on the move (i.e., controlling the vehicle), thus affording a possibility to spend travel time doing something useful, such as working or reading (Bouscasse et al., 2018; Charreire et al., 2021; van Exel et al., 2011).

However, in addition to those related to utility, prior research has identified **experiential and hedonic,** or **non-utilitarian,** characteristics of public transport that impede or encourage usage. As opposed to factors that are extrinsic to the act of getting from one place to another, such as the effort needed for trip planning, or costs in terms of time and money, these factors are intricately connected to the journey itself and the experiences that are embedded in the act of traveling. More precisely, hedonic, and experiential factors relate to how an individual feels in the short term within the mobility context, affecting mode choice through the avoidance of negative feelings while seeking positive ones (Lindenberg, 2022). As an example, Redman et al. (2013) identified *comfort* of the vehicle in terms of seat access, noise, driver handling, air conditioning, and cleanliness as a factor that affects individual decision to use public transport. Some studies have even argued that the aesthetics of the public transport vehicles and waiting areas (Redman et al., 2013) encourage the use of public transport, and, due to the lack of involvement required from the user as previously described, the journey may become a place of relaxation, posing another reason to choose public transport instead of private vehicles (Sandberg et al., 2023; van Exel et al., 2011). Co-passengers are a central characteristic of most public modalities, and prior research has indicated that vehicle and station crowdedness and being forced to be in proximity with others may hinder the travel experience, driving some individuals to use other modalities (Kent, 2014; Musselwhite & Roberts, 2021; Sandberg et al., 2023; van Exel et al., 2011). Sharing space with strangers in the vehicle and in waiting areas, however, is not only a hindrance to comfort but can affect the perception of personal security and safety, thus becoming a potential barrier to public transport use (van Exel et al., 2011).

Literature has also identified **altruistic** motives for choosing public transport over private modes. Instead of focusing directly on individual-level benefits or experiences, these factors relate to long-term, collective goals of ensuring the prosperity of communities and ecosystems. It has become widely known that private cars are environmentally unsustainable but also pose challenges to cities in terms of liveability and the use of public space. Accordingly, the reasons for favouring public transport may relate to the pursuit of reducing one's environmental footprint (Egset & Nordfjærn,

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2019; Sandberg et al., 2023; van Exel et al., 2011), or mitigating the concerns related to the occupation of public space by private vehicles (Bouscasse et al., 2018; Höysniemi & Salonen, 2019). Table 1 summarises the utilitarian, hedonic/experiential and altruistic factors affecting public transport usage.

Table 1. Factors affecting public transport usage.

Utilitarian	**Hedonic/experiential**	**Altruistic**
Availability and accessibility (Charreire et al., 2021) Accessibility issues of stations and vehicles (Musselwhite & Roberts, 2021) Information (Redman et al., 2013) Price (van Exel et al., 2011) Ease of planning and travel (Fu & Juan, 2017; Redman et al., 2013) Dependency on routes and schedules (van Exel et al., 2011) Reliability (Burian et al., 2018; van Exel et al., 2011) Utilisation of travel time (Bouscasse et al., 2018; Charreire et al., 2021; van Exel et al., 2011)	Possibility to relax (Sandberg et al., 2023; van Exel et al., 2011) Aesthetics of waiting areas & vehicles (Redman et al., 2013) Crowdedness of the vehicle, forced proximity of others (Kent, 2014; Musselwhite & Roberts, 2021; Sandberg et al., 2023; van Exel et al., 2011) Perceived safety (van Exel et al., 2011) Perceived security Comfort (e.g., seat access, noise, driver handling, air conditioning, vehicle cleanliness) (Redman et al., 2013)	Environmental concerns (Egset & Nordfjærn, 2019; Sandberg et al., 2023; van Exel et al., 2011) Occupation of space concerns (in comparison to private cars) (Bouscasse et al., 2018; Höysniemi & Salonen, 2019)

2.1.2 Active mobility

Like public transport options, active mobility (i.e., walking, cycling) is associated with a wide range of **utilitarian** factors that encourage or discourage individuals from choosing this modality. These factors mostly revolve around the notions of physicality, the flexible, yet a close connection with one's surroundings and infrastructure, and that these modes are essentially cost-free. Being

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physically active and the associated health benefits serve as strong motivators for individuals to choose active modes of transportation such as walking or cycling (Bhandal & Noonan, 2022; Charreire et al., 2021; Egset & Nordfjærn, 2019). However, a hurdle of using active travel on certain occasions is the need to carry packages that causes inconvenience for walking or cycling (Schneider, 2013). Low costs, both in terms of transportation expenses and potential savings on parking fees, as well as the flexibility of parking in the case of cycling make active transport an attractive option in comparison to both public transport and private cars (Bhandal & Noonan, 2022; Jones & Ogilvie, 2012; Simons et al., 2014). Additionally, the reasons for choosing forms of active travel include potential time savings in comparison to the alternatives, especially on short routes, and the possibility to take shortcuts unavailable to other options (Bhandal & Noonan, 2022; Jones & Ogilvie, 2012; Simons et al., 2014). However, concerns related to the availability of proper infrastructure as well as road safety conditions, and personal security concerns associated with walking or cycling in certain areas can have a negative impact on active transport use (Bhandal & Noonan, 2022).

Choosing active modes of mobility is also influenced by various **experiential and hedonic** motivational factors that relate to the characteristics of the surroundings and the environment, in addition to the attributes directly connected to active modalities. A pleasant environment, such as those characterized by the presence of greenery, can enhance the appeal of walking or cycling (Charreire et al., 2021; Grigoletto et al., 2022). Moreover, in relation to the surroundings, the perceived safety of the environment has been recognized as a factor that can hamper or enhance the travel experience of cycling or walking, along with weather conditions, road conditions for cyclists, and the availability of proper lighting, that play a significant role in shaping the experience of active mobility (Bhandal & Noonan, 2022; Charreire et al., 2021; Simons et al., 2014). Active transport, especially cycling, can also become a form of socializing, and the presence of other cyclists and the opportunity to cycle together contribute to a sense of connectedness and add to the appeal of active travel (Bhandal & Noonan, 2022; Simons et al., 2014). Moreover, the sense of freedom and independence, along with the exposure to the outdoors, can be invigorating and relaxing, further motivating individuals to choose active forms of transport (Bhandal & Noonan, 2022; Sandberg et al., 2023). In addition to experiential and hedonic factors, active forms of travel are widely known to be an environmentally sustainable option in comparison to private car use and therefore driven by similar **altruistic** motives as the use of public transport (Bhandal & Noonan, 2022; Charreire et al., 2021; Höysniemi & Salonen, 2019). Table 2 summarises the utilitarian, hedonic/experiential and altruistic factors affecting active mobility usage.

Table 2. Factors affecting active mobility usage.

Utilitarian	**Hedonic/experiential**	**Altruistic**
Being physically active, health (Bhandal & Noonan, 2022; Charreire et al., 2021; Egset & Nordfjærn, 2019)	Pleasant environment (Charreire et al., 2021), greenery (Grigoletto et al., 2022)	Environmental concerns, perceived sustainability (Bhandal & Noonan, 2022; Charreire et al., 2021; Höysniemi & Salonen, 2019)
Ease and convenience (Charreire et al., 2021)	Perceived safety of the environment (Charreire et al., 2021; Simons et al., 2014)	
Public transport and/or parking within walking/cycling distance	Weather conditions (Bhandal & Noonan, 2022; Simons et al., 2014)	

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of employment sites (Jones & Ogilvie, 2012) Low costs (Jones & Ogilvie, 2012) Speed (Jones & Ogilvie, 2012; Simons et al., 2014) Bicycle theft (Bhandal & Noonan, 2022) Proper infrastructure (Bhandal & Noonan, 2022) Road safety conditions (Bhandal & Noonan, 2022) Possibility for shortcuts (Bhandal & Noonan, 2022) Flexibility in parking (cycling) (Bhandal & Noonan, 2022) Fear of tyre punctures (Bhandal & Noonan, 2022) Difficulties when having to carry packages (Schneider, 2013)	Road conditions (cycling) (Bhandal & Noonan, 2022; Simons et al., 2014) Darkness impedes cycling experience, lack of lighting (Bhandal & Noonan, 2022; Schneider, 2013) Sociality, presence of other cyclists, cycling together (Bhandal & Noonan, 2022; Simons et al., 2014) Freedom, independence (Bhandal & Noonan, 2022) Outdoors exposure (Bhandal & Noonan, 2022) Invigoration (Bhandal & Noonan, 2022) Relaxation (Bhandal & Noonan, 2022; Sandberg et al., 2023)	

2.1.3 Private car use

To identify ways to increase the appeal of sustainable mobility options, it is also necessary to understand the unique motivations behind private car use. First, the decision to choose a private car is driven by a variety of **utilitarian** motivational factors. Most notably, private cars are characterized by the perception of close to non-restricted accessibility to different locations, as well as that of flexible means of transport that is not bound to fixed schedules or routes, being always available, while allowing the carriage of goods with little effort, therefore reducing the need to plan one's journeys ahead and overall travel time in many cases (Charreire et al., 2021; Hiscock et al., 2002; Kent, 2014; van Exel et al., 2011). Moreover, due to providing an enclosed environment, car

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driving provides protection from security incidents stemming from the presence of others (Hiscock et al., 2002).

Additionally, car use is driven by **hedonic and experiential** motives. Resonating with the flexibility previously mentioned, car use affords a sense of freedom, autonomy, and control to the user (Hiscock et al., 2002; Kent, 2014; Simons et al., 2014; Steg, 2005). When using a private car, users can choose their routes spontaneously, while maintaining control of the vehicle speed, adding to its allure. Moreover, driving a car affords a sense of action and satisfaction associated with the uninterrupted movement (Kent, 2014). Unlike public and active modes, the car presents a secluded and enclosed environment – 'a cocoon' (Kent, 2014)- where the user can have freedom from the world outside, providing a place of privacy as well as one of personalisation and of selective socializing as one can choose who to travel with while being protected from undesired social events (Hiscock et al., 2002; Simons et al., 2014). Resonating with the personalisation possibilities, the sense of psychological ownership, i.e., the feeling that the vehicle is 'theirs' adds to the appeal of using private cars (Paundra et al., 2017). Cars also afford a level of comfort that is not easily achievable by other modalities. For example, using a car provides protection from the weather as it reduces the need to walk outside in comparison to public transport or active travel (Hiscock et al., 2002).

Table 3 summarises the utilitarian, hedonic/experiential and altruistic factors affecting private car usage.

Table 3. Factors affecting private car usage.

Utilitarian	**Hedonic/experiential**	**Altruistic**
Accessibility (Charreire et al., 2021; Kent, 2014; van Exel et al., 2011) Flexibility (Charreire et al., 2021; Kent, 2014; van Exel et al., 2011) Availability (Charreire et al., 2021; Kent, 2014; van Exel et al., 2011) Security (Hiscock et al., 2002)	Perceived control (Kent, 2014) Sense of autonomy and freedom (Kent, 2014; Simons et al., 2014) Cocoon-like environment (Kent, 2014) Sense of action and uninterrupted movement (Kent, 2014) Form of selective socializing (Simons et al., 2014) Personalisation, sense of ownership (Hiscock et al., 2002; Paundra et al., 2017)	Environmental concerns in the case of e-cars

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	Protection from undesired social events (Hiscock et al., 2002) Protection from weather (Hiscock et al., 2002)	

2.2 Harnessing ICT to support sustainable mode choice

ICT has become a pervasive part of mobility systems (Gössling, 2018). Most notably, mobility is becoming increasingly datafied due to technologies such as the Internet of Things, apps and artificial intelligence which are transforming transportation systems (Laakko et al., 2020; Pihlajamaa et al., 2020; Sourbati & Behrendt, 2021; Tuominen & Ahlqvist, 2010). Sensors embedded in vehicles and mobility infrastructure, along with mobile devices generate masses of data of how we move (Gössling, 2018). These new ways in which mobility is becoming increasingly datafied and ICT-embedded provide tools for directly addressing the motivational factors that drive mode choice (Andersson et al., 2018). Notably, the developments in ICT generate novel opportunities to increase the appeal of sustainable mobility by allowing new ways of informing and persuading users, as well as through the provision of new types of integrated services (Andersson et al., 2018). In addition, advances in areas such as virtual (i.e., using technology to create immersive simulated experiences) and augmented (i.e., experiences that combine real-world and digital content) reality allow new ways to present information to the user as well as provide novel types of experiences while on the move. In the subsections below, we provide an overview of some of the most prominent ICT approaches that have the potential to encourage the adoption of sustainable mobility options by tapping into the utilitarian, experiential and altruistic factors that affect modal choice previously outlined. We concentrate on ICT approaches that augment the existing modes of mobility and provide user interaction, therefore excluding developments such as shared micro mobility that introduce altogether new forms of mobility and data-based tools for mobility planners and organisers.

2.2.1 Utilitarian mobility ICT

Advances in ICT allow many ways of improving the convenience of sustainable mobility options, encouraging their use through utilitarian motives. Below, these approaches are described under five broad thematic areas: *Providing information for easy and accessible trips*, *Easing the journey execution through integration*, *Enabling access and improving availability*, *Persuasion based on individual benefits*, and *Enabling the utilisation of travel time* that comprise different technologies and types of designs used at different phases of the journey, from planning (i.e., pre-trip), to execution (i.e., during trip) to post-trip.

Providing information for easy and accessible trips. Many of the most common ICT solutions within mobility are designed to provide the user with information regarding mobility, thus easing the planning and execution of the journey using public or active modes of mobility. These solutions leverage different data that is collected from the mobility infrastructure, vehicles, and the users. *Trip planners*, such as Google Maps, are widely used to increase user awareness of different sustainable mobility options. Trip planners ease the planning of journeys by providing location-specific and (near) real-time information of sustainable mobility and allow comparing different travel options in terms of time, distance, and price. Moreover, these solutions can offer specific information to mobility-impaired people, such as the existence of steps and gradients in stations and platforms, and seat access inside vehicles, and suggest accessible routes based on the special needs of the user (Hounsell et al., 2016; Mirri et al., 2014). In the case of active travel, such as cycling, trip planners can also incorporate information of the route infrastructure and traffic conditions to alleviate the associated safety concerns (Gössling, 2018). For example, the free-to-

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use tool Bikemaps.org uses crowdsourcing to gather information related to bicycle collisions, near misses, hazards, and thefts. It presents this information to users in the form of a map, along with specific dates and times when these incidents are more likely to occur, allowing users to proactively avoid and prepare for potentially dangerous areas when planning their cycling routes (BikeMaps, n.d.). The developments in AI have further potential to provide route recommendations based on user preferences and characteristics, as exemplified by Aydin & Telceken (2015) where the authors proposed a recommender system that provides tourists with routes that optimize the time spent at points of interest, while minimizing the time spent travelling. In addition to AI, another emerging technology that has become prevalent in trip planner apps is *augmented reality* which has been used to improve trip planners and the accessibility of sustainable mobility options by embedding computer generated informational content onto the non-digital reality. For example, the Bus Times London app by Mapway displays information augmented to real-world view, such as digital paths to transport facilities and real-time information of arrival and departure times, easing and making the navigation process more accessible while using public transport (Mapway, n.d.). These augmentations can also be based on haptic or auditory feedback to improve the accessibility of visually impaired users (e.g., mobile phone or a wearable that vibrates when a bus arrives at the stop) (Jacob et al., 2011; Hersh, 2022).

Easing the journey execution through integration. On top of trip planning, ICT allows higher level of integration between different modes of transportation, based on data sharing and transactional partnerships between private and public service providers, having further potential to promote sustainable modal choices by making the multimodal journey more fluent (Shaheen & Cohen, 2019). Payment technologies are increasingly enabling applications that integrate the information regarding different modes with the possibility to pay for the entire journey within the application – a concept often referred to as *mobility-as-a-service* (MaaS) (Kamargianni et al., 2016). MaaS typically integrates public transport options with additional services, such as taxis or rental vehicles, and the service is offered to the user using a single interface, potentially attracting users to adopt sustainable mobility by further simplifying the journey planning process and saving the trouble of obtaining transport tickets from various providers, lowering the cognitive effort that is required from the user (Lyons et al., 2019). In addition to integrating different modes of mobility, MaaS approaches can also integrate other services depending on the purpose of the travel, such as events, healthcare services, or retail – a concept sometimes referred to as Beyond MaaS (Pihlajamaa et al., 2022). For example, in Denmark, the collaboration scheme DOT provides event tickets that can be purchased for cheaper journeys to and from various events, while covering the use of buses, train and metro (Din Offentlige Transport, n.d.). A further development in the domain of service integration is the emergence of 'super apps' that provide various services, including mobility, under a single umbrella application. These applications are becoming widespread particularly in South Asia, where apps, such as WeChat and Gojek provide access to, for example, mobility, food delivery, medical services, and various well-being services (Pelikh, n.d.).

Enabling access and improving availability. To tackle the accessibility, availability and flexibility issues associated with sustainable mobility options, ICT has enabled new ways of complementing the existing public transportation modalities with first and last mile solutions that are in many cases integrated to MaaS as well as trip planner approaches. These approaches mainly rely on data sharing between mobility organisers (e.g., private and public service providers), as well as individual and vehicle mobility data. Notably, mobility services based on collaborative consumption, such as bike-sharing, shared e-scooters, and ride-sharing services that are operational through apps, have emerged as a solution to first and last-mile mobility, being particularly relevant for neighbourhoods with limited access to public transport options (Canales et al., n.d.; Gössling, 2018). These systems utilise ICT platforms for payment, user identification, navigation, availability information as well as gathering of user data to optimize the locations of the shared devices (Canales et al., n.d.; Gössling, 2018).

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Persuasion based on individual benefits. Besides informing and aiding in effective journey planning and execution, ICT can be utilised to inform users of the personal benefits of choosing sustainable mobility options. This approach is prevalent in applications that track individual mobility patterns and encourage active transportation by providing the users with feedback and insights on these patterns along with health-related information, such as burnt calories or activity levels therefore nudging towards these options as opposed to private cars (Jariyasunant et al., 2012). In addition to informing of the benefits, these *self-tracking* applications often incorporate persuasive and gameful design elements such as personal goalsetting, challenges, or competition to further encourage active and sustainable mobility (Marquart & Schuppan, 2022). For example, the application provided by the city of Tampere tracks user active mobility patterns and provides the user with information of how they affect their mortality risk, while awarding the user with medals based on the amount of active travel each day. Moreover, based on the assumption that the use of sustainable mobility options such as active travel or public transport is cheaper than the use of private cars, some self-tracking apps also inform the user of the monetary savings accumulated over time to further encourage sustainable mobility, while they can also incorporate monetary rewards for sustainable mobility (Jariyasunant et al., 2012; Marquart & Schuppan, 2022).

Enabling the utilisation of the travel time. Technological advances have opened new ways for the utilisation of travel time itself, having the potential to increase the appeal of public transportation options. Unlike other approaches for utilitarian mobility ICT described previously in this section, this approach does not revolve around mobility data utilisation. While mobile devices such as laptops and smartphones allow using the otherwise wasted travel time productively (Cohen-Blankshtain & Rotem-Mindali, 2016), emerging technologies enable ample opportunities for further downplaying the perceptions of disutility. For example, augmented and virtual reality solutions that complement the physical reality with virtual objects, or outright replace the physical reality, have been proposed as an advancement that can further transform the otherwise idle travel time into one of productivity, overcoming some of the issues associated with conventional mobile devices. The utilisation of these technologies is based on the notion that they can provide a full-fledged virtual workspace within the confined transit space, providing an ergonomic and private option to personal devices, such as mobile phones and laptops (Medeiros et al., 2022). In addition, ICT-based solutions can specifically tackle the idle time that is spent waiting at the public transit stops. An instance of such a solution was implemented in Singapore, where smart bus stops allow users to access and browse the e-book collection of the national library, facilitating the utilisation of the waiting time (Kirk, 2017).

2.2.2 Hedonic-experiential mobility ICT

Although the existing solutions predominantly focus on the utilitarian aspects of mobility, ICT also plays a key role in improving the travel experience, thus encouraging adoption, and continued use of sustainable mobility options. These approaches are mapped under four broad thematic areas: *Experiential route planning, Turning mobility into a site of enjoyment, Overcoming the limitations of physical space, Enabling personalisation and ownership.* On the one hand, some of these approaches leverage the fact that the characteristics of the environment have an impact on the journey experience and can be affected in the journey planning phase (i.e., pre-trip). On the other hand, it is noteworthy ICT also has the potential to provide augmentations to improve the overall experience of the journey, even if the route itself remains unchanged (i.e., during trip).

Experiential route planning. ICT provides opportunities to support sustainable modal shift by enabling the user to plan their journeys based on the experiences that the route is likely to afford instead of maximizing utility. For example, the Green Paths application that is operational in Helsinki region provides the user with route recommendations based on user preferences for greenery, quietness, and air quality, improving the experience of cycling and walking (University of Helsinki, n.d.). Similar approaches have been proposed to improve the experience of using public transport by directing users to less crowded transportation options and routes, thus overcoming the

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discomfort of being in proximity with others, or providing other information related to travel comfort, such as seat availability or the driving style of the driver (Drabicki et al., 2023; Hadas et al., 2022; Meng et al., 2018). However, instead of trying to mitigate them, ICT can also provide social experiences by affecting route choice. The application Strava, which focuses on cycling and other forms of active travel, allows users to create routes that others can utilise, but also has the option to create events and group activities, tapping into the social factors that increase the appeal of active travel for some users (Strava support, n.d.). Such approaches based on social mobility have additionally been proposed for public transport, as the use of GPS data on user and vehicle locations allows deploying systems that increase the likelihood of friends, colleagues or other peers traveling together in the same vehicle (Foth & Schroeter, 2010).

Turning mobility into a site of enjoyment and voluntary socializing. Along with personal mobile devices becoming a pervasive part of everyday life, including mobility, novel opportunities have emerged for enhancing the experiential and hedonic qualities of being on the move. Especially phenomena such as *location-based gaming* and *gamification* have the potential to turn mobility into a site of play and enjoyment, as well as one of voluntary socializing. For example, Zhang et al. (2015) proposed a mobile-based multiplayer game where users can engage in gaming with fellow commuters, attempting to mitigate the boredom of traveling in a public vehicle by enabling playful social interaction. A similar approach was adopted in Camacho et al. (2015), that introduced an application that allowed users to chat with a randomly assigned co-passenger during train commuting. More recently, the potential to leverage gamefulness to support sustainable mobility was revealed by the wide uptake of the location-based augmented reality game Pokémon Go. The smartphone-based game embedded virtual objects in real-world locations to facilitate playful and gameful interactions while on the move, simultaneously increasing the likelihood of using non-motorized and public transport among some of the user groups (Guo et al., 2022). Many other location-based games also integrate mobility as a key characteristic of gameplay, such as the widely popular Ingress in which players join one of the two factions that battle over areas located in real-world public spaces, therefore having potential to affect individual mobility patterns and mode choices (Karpashevich et al., 2016).

Overcoming the limitations of physical space. Advances in ICT, especially in *immersive virtual reality*, provide opportunities for overcoming the limitations of physical space within mobility, enhancing the experiences of using sustainable modes of mobility. The use of Virtual Reality has been investigated to enhance travel comfort in public transportation vehicles as it allows disconnecting the user from their surroundings, creating spaces for relaxation and other positive experiences. More specifically, VR can afford escapism in the form of personal and private experiences, thus alleviating the discomfort of being forced to proximity with other commuters, creating a cocoon-like environment resembling that of a private car (Bajorunaite et al., 2021, 2023; Kent, 2014; Medeiros et al., 2022).

Enabling personalisation and ownership. In relation to overcoming the limitations of physical space, augmented reality solutions additionally offer users the ability to digitally customize and personalise the space around them and objects in their surroundings. This approach holds the potential to extend the personalisation capabilities commonly associated with private vehicles to public transportation options. This can also entail the ‘leaving of marks’ or ‘digital graffiti’ that are also visible to other users, thus providing a form of interaction to tap into the sense of community as well as potentially creating a sense of ownership by allowing customizing one’s surroundings – appropriating one of the main qualities that add to the appeal of private cars into public modalities (Foth & Schroeter, 2010).

2.2.3 Altruistic mobility ICT

Finally, ICT can tap into the individual willingness to do good, supporting sustainable modal shift through altruistic motives. These approaches are described through three thematic areas: *Nudging*

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through altruistic motives, Integrating collective benefits to journey planning and *Enabling tangible acts of altruism through mobility,* representing applications for all phases of the journey (i.e., pre-, during, post-trip).

Nudging through altruistic motives. ICT applications have additionally introduced new ways of bringing the altruistic motives for choosing sustainable mobility options to the forefront. These applications can focus on informing the user of the sustainability impacts of their mobility patterns, while using various persuasion strategies to encourage the use of more sustainable means for mobility. As an example, the City of Tampere incorporates a carbon footprint calculator in its mobile application, allowing the user to track the CO2 emissions resulting from their journeys, and see their ranking in comparison to other users (Tampere, n.d.). Experimental research suggests that social nudges based on altruistic values have a greater impact than financial nudges on mobility behaviour, while mixing both types might in fact decrease their impact (Riggs, 2017).

Integrating collective benefits to journey planning. In addition to altruistic nudges that make the environmental impacts of one's mobility behaviours graspable post-hoc, similar approaches have been proposed for the trip planning phase. For example, journey planners can present different travel options which are not only described in terms of time and costs, but also their environmental impacts (e.g., CO2-emissions) (Kırdar & Ardıç, 2020). An instance of such a planner is described in (Su et al., 2010), where the authors develop a (cycling) planner that optimizes the routes based on user preferences for aspects, such as travel time, elevations gains, air quality, route vegetation, safety, and calories to be burnt, while providing information of CO2-emissions avoided for the given route in comparison to a private car.

Enabling tangible acts of altruism through mobility. On top of merely using information-based persuasion, some applications also offer opportunities for tangible acts of altruism by choosing sustainable mobility options. For example, the app Charity Miles allows users to choose a charity for which the sponsors involved donate money based on the distance that the user travels by bicycle or on foot (Charity Miles, n.d.). Some other apps, such as Evidation, offer the user the option to either redeem points acquired by engaging in active mobility, as well as other healthy behaviours, either in the form of personal monetary incentives or by donations to charity. A distinct approach to tangible altruistic acts in mobility was presented by Kuramoto et al. (2013), where the authors described the implementation of a role-playing type of game 'Stand UP, Heroes!'. In the game, the users could develop and compare their game characters by frequently standing in public transport vehicles to give seats to those that need them, at the same time improving the comfort of public transport in terms of seat access (Kuramoto et al., 2013).

Further information on the topic can be found in the publication: Wallius, E., Lamuela Orta, C., Lusikka, T., Pihlajamaa, O., & Hautala, R. (2025). Decarbonizing urban mobility through data-driven services: How to achieve modal shift? In *McNally, C., Carroll, P., Martinez-Pastor, B., Ghosh, B., Efthymiou, M., Valantasis-Kanellos, N. (eds) Transport Transitions: Advancing Sustainable and Inclusive Mobility. TRA conference 2024. Lecture Notes in Mobility.* Springer, Cham. pp. 576–581. https://doi.org/10.1007/978-3-031-85578-8_77

2.3 Survey study on factors affecting mode choices in different travel contexts

As a backdrop for concept design towards sustainable mode choices, a survey study was conducted to elicit how individuals make mode choice decisions across different mobility contexts. The study adopted the trip-chaining view of human mobility, where the assumption is that, instead of simple point-to-point travel, individuals often tend to conduct multiple activities within a single trip

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across various destinations. In such cases, mode choices are likely influenced by the entirety of the trip chain, not being limited to the proximate trip leg.

The survey was administered among participants in Helsinki and Tampere regions in June 2024, with participants recruited through a commercial service provider. The participants were required to be over 18 years of age and possess a driving licence. In addition to background information and questions on general mobility behaviour, as well as factors that shape mobility choices, the survey included a section where the participants were asked to think about their last private car trip chain they could recall well and evaluate items pertaining to various situational factors that affected the specific mode choice. The situational factors involved both utilitarian (i.e., travel time, ease of planning, reliability, ease of carrying objects, avoiding transfers, saving money, travel time utilisation), and non-utilitarian hedonic and experiential (freedom, protection from weather, avoiding crowded spaces, relaxation, enjoying surroundings or scenery) factors. A similar section was provided for the last public transport trip. Altogether, the survey yielded 1123 responses.

How do trip chain characteristics influence the situational factors behind private car mode choices?

Considering the goal of promoting sustainable mode choices, the main focus of the analysis was on the private car trip chains reported by the respondents (altogether 731 valid responses, after non-engaged respondents were removed).

Based on the results, all the examined trip chain characteristics (i.e., complexity, length, purposes) impact on the prevalence of different utilitarian and non-utilitarian situational factors affecting private car decisions.

First, previous research suggests that people choose cars for complex trip chains mainly for practical reasons like saving time and ease of planning. The findings confirm these utilitarian motives, yet they also surprisingly reveal that as trip chains become more complex, the prevalence of non-utilitarian factors such as relaxation, freedom, enjoying scenery, and avoiding crowds also increases. A possible explanation is that complex journeys may feel stressful, leading individuals to compensate for the mental burden by choosing a mode that maximizes positive experiences.

Second, the results indicate that trip chain length is positively associated with nearly all situational factors influencing car use, suggesting that the perceived benefits and experiential characteristics of private cars become increasingly salient as trip length grows. As exceptions, travel time utilisation, ease of carrying objects, and weather protection did not show significant associations with trip length.

Third, the analysis revealed significant associations between specific travel purposes within a trip chain and situational factors influencing private car mode choices, when controlling for trip distance and complexity. Commuting was linked to travel time utilisation and weather protection, suggesting that individuals value opportunities for tasks such as reflection or phone calls during commuting and seek shelter from adverse conditions, as commuting typically occurs routinely regardless of weather. Errands were associated with ease of carrying objects which is unsurprising as errands often involve transporting goods. However, errands were, somewhat surprisingly, also associated with freedom of mobility, possibly due to ad-hoc decisions during errand trips, when for example, items or services are not available in the chosen destination. Additionally, compared to e.g., commuting, errands tend to be less predictable in terms of destinations and timing, which may make individuals more inclined to maintain flexibility and avoid the fixed schedules of public transport that they may not be familiar with. Leisure trips were associated with relaxation and enjoying the scenery, aligning with prior research that emphasizes the affective and experiential dimensions of leisure travel, where the journey itself is expected to contribute to well-being rather than being purely derived demand.

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The findings also show that habituation (i.e., not considering alternative modes) was positively associated with errands, likely because carrying goods creates a barrier to alternatives like cycling or public transport, and negatively associated with escort trips, which are likely less routine-like, especially during the holiday season when regular school or daycare trips are less common. Habituation was not associated with either trip chain complexity or length.

Overall, the findings have implications for the development of passenger information systems. While state-of-the-art route planners have increasingly begun to incorporate contextual factors such as elevation, safety, air quality, and public transport crowdedness, they primarily focus on point-to-point travel. Our results suggest that these systems should also support planning for complex journey chains, tailoring route suggestions to the characteristics of multi-stop trips. Both utilitarian factors, such as reliability, as well as non-utilitarian factors, such as weather protection and crowd avoidance, become more significant as trip complexity increases. To enhance the attractiveness of sustainable modes, route planners could integrate features like shelter availability at stops and real-time predictions of vehicle and station crowdedness, combined with journey complexity, length and purposes to provide context-sensitive travel recommendations.

Full details of the analysis of situational factors impacting mode choices across different trip types can be found in the publication: *Wallius, E., Kaipainen, K., & Pihlajamaa, O. (2026). Trip chain characteristics and situational factors influencing private car mode choices – A survey study in two Finnish urban areas. Transportation Research Interdisciplinary Perspectives, 36, 101821. https://doi.org/10.1016/j.trip.2025.101821*

How do temporary external and internal conditions influence mode choices across demographics?

In addition to contextual factors shaped by the characteristics of the trip chain, the study analysed how temporary internal and external hurdles impact the likelihood of individuals choosing a private car instead of public transport.

The mean values and standard deviations of the conditions are presented in the table below, showing that having to carry objects stands out as a factor increasing the likelihood of private car use, while all the examined factors have an impact on the likelihood of private car usage.

Table 4. The mean values and standard deviations of the conditions impacting the likelihood of individuals choosing a private car instead of public transport.

Temporary condition	Measurement item	Mean	Standard deviation
Carrying objects	I am more likely to leave home using a private car than public transport if… *…I have objects to carry*	4.38	0.929
Illness	*…I am ill*	3.75	1.290
Rain	*…it rains*	3.69	1.277
Other than daytime	*…I'm traveling in other than daytime*	3.62	1.267
Nauseous	*…I'm feeling nauseous.*	3.52	1.301
Cold	*…the weather is cold*	3.49	1.281
Heat	*…It is a heatwave outside*	3.25	1.278
Slippery	*…it is slippery outside*	3.24	1.314
Dark	*…it is dark outside*	3.20	1.313

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Tired	*…I am tired*	3.20	1.295
Stressed	*…I am stressed*	3.11	1.288

Differences between demographics were also examined. In relation to gender, being a woman was associated with agreeing to be more likely to use private car instead of public transport when carrying goods, the weather is cold, being ill, or feeling nauseous. To examine the effect of age, the participants were divided into three age groups: <29 years of age, 29-65 years of age and >65 years of age. Being <29 years of age was associated with agreeing to be more likely to use private car instead of public transport when being ill, stressed or nauseous, and being 29-65 years with the increased likelihood of using a private car when the weather is cold, when traveling in other than daytime, or being ill, stressed, tired or nauseous when compared to those >65 years of age.

Overall, the findings suggest that women and younger people are especially influenced by temporary internal factors, like illness or tiredness, when deciding between public transport and private cars. Women's heightened sensitivity to these conditions reflects their tendency to prioritise comfort and safety, while men focus more on travel time and cost. As a result, women are more likely to choose private cars when facing discomfort or the need to carry items. Additionally, both women and younger individuals have less entrenched car habits, making their travel choices more flexible and responsive to changing circumstances.

The findings suggest ways to make public transport more appealing for people facing temporary barriers to mobility. Enhancing information about external factors, such as integrating weather data and routing to minimize exposure, can encourage PT use. Personalised route recommendations, based on user profiles and real-time mental or physical states, may further encourage public transport use. It is also important to investigate how factors like stress or tiredness affect travel comfort and to reflect these insights in infrastructure design. Targeted, context-specific interventions should address the unique needs of different demographic groups, especially women and younger users, who are more affected by temporary conditions. Gender-specific preferences should be considered to increase inclusivity, while strategies for men and older adults, who have stronger car habits, should focus on reshaping attitudes and promoting public transport as a valued alternative to reshape the mental image of PT.

Full details can be found in the publication: Wallius, E., Kaipainen, K. & Pihlajamaa, O. (2026, *in press*): Temporary external and internal conditions affecting mode choices: Results from a survey study in Finland. Transport Research Arena 2026, 18-21 May 2026, Budapest, Hungary.

3. Concept designs for sustainable mobility behaviour

3.1 Introduction

The DeMo project set out to understand how digital mobility services could meaningfully support a shift toward more sustainable travel behaviour. The project focused on identifying the barriers that prevent people from choosing low-carbon modes and exploring how digital solutions could reduce these barriers, build confidence, and make sustainable travel more attractive. This work culminated in the development of two concepts – Extended Trip Planner and Opastaja – whose purpose is to address key behavioural and informational gaps that influence modal choice.

Developing these concepts required a careful and multidisciplinary process. The team drew together insights from behavioural literature, empirical data gathered through a user questionnaire,

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and the rich, collaborative discussions that took place in three DeMo workshops. These activities produced an initial longlist of ideas that was gradually refined through synthesis, feasibility assessment, and behavioural impact analysis. Ultimately, two concepts stood out as the most promising for supporting sustainable mobility in a user-oriented and technically feasible manner.

This section describes the process and presents the rationale for selecting the two concepts developed further in the project.

3.2 Methods

The concept development followed a mixed-methods process combining theoretical, empirical, and participatory approaches. First, a targeted literature review was conducted to identify behavioural mechanisms relevant to sustainable mobility, including factors such as uncertainty, cognitive load, trust in public transport, and the motivational role of exploration and meaningful travel experiences. This review helped establish the behavioural framing used throughout the project.

Second, an online user questionnaire was administered to collect empirical insights on people's mobility habits, perceived barriers to using sustainable modes, and preferences for digital support features. The survey captured both behavioural patterns and attitudinal responses, providing a quantitative complement to the literature review and helping to validate the relevance of different behavioural factors.

Third, three co-creation workshops were organised with project partners and stakeholders. These workshops served to interpret the findings from the earlier research steps, generate a wide range of concept ideas, and evaluate their potential from behavioural, experiential, and technical perspectives. Participants collaboratively formulated, refined, and assessed concept proposals, contributing practical viewpoints and domain expertise.

Finally, the project team conducted an integrative synthesis of the literature insights, survey findings and workshop output. This synthesis allowed the concepts to be compared on the basis of behavioural impact potential, user desirability, feasibility, and suitability for demonstration within the project. Through this iterative process, the longlist of ideas was reduced to the two concepts to be developed further into demo applications.

3.2.1 Literature review

The project started with an extensive literature review, drawing on a wide array of sources (over 140 references) from transport studies, environmental psychology, service research, and ICT innovation. The references chosen for the literature review reflect a deliberate, interdisciplinary, and methodologically diverse approach. The literature review included the following types of sources:

1. **Foundational Theories and Frameworks**
   Classic behavioural and psychological theories (e.g., Maslow, Theory of Planned Behavior) are used to explain motivations behind mode choice and structure the analysis of utilitarian, hedonic, and altruistic factors.

2. **Empirical Studies on Mode Choice**
   Empirical research – both qualitative and quantitative – examines factors influencing choices between private cars, public transport, and active mobility across diverse contexts and populations.

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3. **Transport Policy and Sustainability Transitions**
   Literature on sociotechnical transitions and transport policy highlights systemic change, innovation, and the importance of multi-stakeholder collaboration for sustainable mobility.

4. **ICT and Mobility**
   Recent studies focus on ICT's role in mobility, covering trip planners, MaaS, AR/VR, gamification, self-tracking, and data-driven solutions, including critical perspectives on unintended effects.

5. **Data Sharing and Multi-Stakeholder Partnerships**
   References address public-private partnerships, data sharing, and collaborative governance, exploring organisational, regulatory, and technical integration challenges.

6. **Contextual and Demographic Analyses**
   National and regional mobility surveys and demographic studies inform how age, gender, income, and family status affect mode choice.

7. **Well-being, Urbanism, and Social Innovation**
   Literature links mobility to well-being, urban design (smart/tactical urbanism), and social innovation, supporting a holistic view of sustainable modal shift.

The literature review, summarised in Sections 2.1 and 2.2, provided a solid theoretical foundation for understanding why people choose certain modes over others and how digital interventions might support more sustainable decisions. Research repeatedly shows that uncertainty plays a central role in mobility choices: people often avoid public transport not because of objective service quality but because of fears of getting lost, misinterpreting instructions, or being unable to navigate complex environments. This uncertainty is especially pronounced among infrequent users, travellers in unfamiliar areas, elderly users, and newcomers.

The review also highlighted the importance of pre-trip familiarisation for reducing perceived risk. Clear explanations, contextual cues such as photos of landmarks, and transparent descriptions of walking segments can greatly increase confidence. Similarly, behavioural literature emphasized that users are more likely to engage in sustainable mobility if the experience is not only convenient but also meaningful or enjoyable. This insight provided the foundation for exploration-oriented concepts.

Altogether, the literature demonstrated that digital tools are well positioned to address both cognitive and motivational drivers of mobility behaviour, either by lowering uncertainty or by enriching multimodal travel.

3.2.2 User questionnaire

The questionnaire was developed as part of a survey study conducted in June 2024 among residents of the Helsinki and Tampere metropolitan regions in Finland. Participants were recruited through a commercial service provider and were required to be at least 18 years old, possess a driver's license, and have used both private cars and public transport within the past 12 months. The survey, administered in Finnish, included demographic questions, items on weekly travel frequency by mode, and a series of questions specifically designed to assess the influence of various temporary internal (e.g., feeling ill, tired, or stressed) and external (e.g., weather conditions, time of day) conditions on mode choice. Both closed and open-ended questions were used to capture a comprehensive view of respondents' experiences. Out of 1123 initial respondents, a subset of 811 who met the criteria of having used both private car and public transport was selected, and after data cleaning, 731 valid responses were retained for analysis.

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The final sample included adults aged 19 to 84 years (mean age 50.1, SD 14.6), with a gender distribution of 53.8% women.

The questionnaire comprehensively covered demographics, weekly mobility patterns, detailed recall of recent trips by car and public transport, motivational and situational factors influencing mode choice, and information needs. Both quantitative (multiple choice, Likert scales) and qualitative (open-ended) questions were included to capture a holistic view of respondents' travel behaviour and preferences.

The results of the user questionnaire, summarized in Section 2.3, offered empirical evidence on current travel habits and user perceptions. Respondents frequently described navigation-related anxiety as a barrier to using public transport. This was not limited to the public transport journey itself but also included fear of misinterpreting walking instructions, confusion about station layouts, and uncertainty about how to transfer between modes.

At the same time, many participants expressed a desire to explore new places and were enthusiastic about features that might enrich their journeys. Users showed interest in discovering points of interest along their route and in planning leisure-oriented trips. Importantly, the questionnaire revealed that while users value digital assistance, they prefer tools that remain simple, intuitive and low in cognitive burden.

The questionnaire thus confirmed two major behavioural needs: reducing uncertainty and supporting exploratory, motivating travel.

3.2.3 DeMo workshops

Three key workshops were organised for the concept development phase of the DeMo project: on 23 November 2023, 10 December 2024, and 22 January 2025 (the latter in conjunction with a steering group meeting). The purpose of these workshops was to refine and concretize ideas and themes emerging from the project's literature review and user survey (last two workshops) into actionable pilot initiatives and service concepts. The workshops followed a phased approach: first, the main motivational factors and knowledge gaps identified in the literature and survey were discussed, after which participants worked in small groups to develop and evaluate various solution options.

Systematic workshop templates were used in planning and execution, ensuring that each concept idea was reviewed through questions such as: What? How? Why? For whom? What could the pilot include? What could each organisation contribute? In addition, the impact (CO_2 reduction, business value, novelty), feasibility (technical, business, regulatory challenges), and benchmarking against existing solutions were assessed.

The workshops were closely linked to the literature review and user survey: findings from the user survey (e.g., the importance of reliability, safety, and freedom of movement for different user groups) and development needs identified in the literature (e.g., data and technology utilisation, service accessibility, user-centricity) were actively brought into the workshop discussions.

The workshops resulted in a set of concrete development themes and pilot ideas, grounded in both user research and literature findings. These included:

- **Reliability and Safety:** Improving the reliability of route planning and travel chains (e.g., congestion, weather, health information), integrating safety and health data into services, and emphasizing freedom of movement (e.g., return options, flexibility during the journey).

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- **Sociality and Community:** Concepts such as everyday cycling communities, “Carpool 2.0,” and a social route planner (KAVERI-SOPPA), aiming to increase the attractiveness of sustainable modes through peer support and social pressure.
- **Goods Transport and Logistics:** Utilising shared vehicles for goods transport, developing multimodal mobility hubs, and enhancing service chains (e.g., service tickets, loyalty programs).
- **Guidance and Journey Planning:** Context-aware route planners, integrating health data into journey planning, safety nudges for the elderly, and advanced passenger information (e.g., vehicle occupancy, real-time conditions).
- **On-board and On-stop Experience:** Services provided during the journey and at stops, such as using vehicle data for information services and enriching travel chains with additional services.

The workshops made a significant contribution to concept development: they enabled the identification, prioritisation, and further development of user-driven and multidisciplinary solutions. The results of the workshops guided the focus areas for DeMo project pilots and further development, and provided a foundation for concrete pilots and service concepts that address both user needs and sustainable mobility objectives.

3.2.4 Synthesis across sources

The synthesis phase brought together evidence from all earlier steps. The literature established the behavioural logic, the questionnaire validated user needs, and the workshops generated a wealth of creative directions grounded in real-world constraints. The project team then evaluated the concepts on their behavioural impact, user desirability, technical feasibility and readiness for demonstration. Furthermore, the planned outcomes of the ongoing and near-future projects were reviewed to avoid overlapping work.

Through this synthesis, two concept families emerged as the strongest matches to user needs and behavioural insights. The first was a set of concepts focused on reducing uncertainty through enhanced navigation support – ideas that would eventually form the *Extended Trip Planner*. The second centred on enabling rich, enjoyable, exploratory travel through multi-stop planning and POI discovery – laying the foundation for *Opastaja*.

3.3 Concepts

3.3.1 Opastaja application

The Opastaja application is a multi-stop exploration planner designed to help users build personalised itineraries using points of interest (POIs) along or near transit routes. Its mobile-first, map-centric interface allows users to:

- Explore and filter POIs (e.g., food, culture, nature) on an interactive map,
- Plan multi-stop trips, dynamically rearrange visit order, and adjust stop durations,
- Choose between various transportation modes (public transport, walking, cycling, driving),

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- Receive route-aware POI recommendations to enrich journeys and make sustainable modes more attractive,
- Save and share trip plans, supporting both detailed planning and spontaneous travel.

Opastaja's core value is in making sustainable travel more appealing and accessible by integrating destination inspiration and practical planning into a single, user-friendly tool. The application is being further developed in the SmartRail#3 project, where it will evolve into a "Destination Guide" with even richer destination information and tailored travel program support.

3.3.2 Extended trip planner

The Extended trip planner (XTP) enhances traditional journey planning by adding rich, contextual, visual navigation support. Key features include:

- Integration of photos, annotated images, and visual cues into routes,
- Pre-trip familiarization via browsable guidance media,
- Geofenced cues for walking segments,
- Optional accessibility-sensitive routing and alternate routes (e.g., to avoid roadworks),
- Step-by-step media cues for real-time, on-trip guidance.

The XTP is designed to address uncertainty and lack of trust in unfamiliar environments, especially for infrequent or vulnerable users. It supports both pre-trip confidence-building and real-time navigation, ensuring travellers are well-prepared and supported throughout their journey. The architecture allows for easy integration with existing trip planners (e.g., Digitransit) and was validated in early user testing.

3.4 Evaluation of concepts

3.4.1 Opastaja

Literature review:
Opastaja addresses a key gap identified in the literature: the need to make sustainable travel modes more attractive by integrating destination inspiration and practical planning. Studies highlight that providing users with relevant points of interest (POIs) and enabling flexible, multi-stop planning can increase the appeal of public transport and active modes, especially for leisure and non-routine trips.

User questionnaire:
Survey respondents expressed a desire for tools that help them discover interesting destinations and plan multi-stop journeys efficiently. The need for route-aware POI recommendations and the ability to adjust trip plans dynamically were frequently mentioned as ways to make sustainable travel more engaging and convenient.

Workshops:
In the DeMo workshops, Opastaja was prioritised because it directly responded to user-identified needs for inspiration, flexibility, and ease of use in trip planning. The concept was also seen as highly feasible for prototyping and demonstration, and it aligned well with ongoing development in

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related projects (e.g., SmartRail#3), ensuring that DeMo's work would complement rather than duplicate existing efforts.

3.4.2 Extended trip planner

Literature review:
The XTP concept is grounded in research showing that uncertainty, lack of trust, and cognitive barriers are major obstacles to adopting sustainable modes, particularly for new or infrequent users. Visual and contextual guidance, such as annotated images and real-world cues, have been shown to increase user confidence and reduce anxiety about unfamiliar routes.

User questionnaire:
Respondents highlighted the importance of pre-trip familiarization, visual cues, and real-world landmarks for building confidence in using public transport and active modes. Many users reported that they would be more likely to choose sustainable options if they had access to step-by-step, visually rich guidance – especially for complex or unfamiliar journeys.

Workshops:
During the workshops, XTP stood out as a solution that could be rapidly developed and tested, with clear benefits for vulnerable and infrequent users. Its modular architecture allows for integration with existing trip planners, and early user feedback confirmed its value in addressing trust and usability barriers.

3.4.3 Coordination with other projects

Both concepts were selected with careful consideration of ongoing work in related projects (e.g., SmartRail#3, OptiPEx, NEMU). Furthermore, several discussions were held with Helsinki Region Transport, Waltti and Fintraffic with respect to ongoing and planned work for Digitransit, that is the primary platform for national trip planners in Finland. In this way, it was ensured that DeMo's contributions are complementary and that resources are used efficiently, avoiding unnecessary duplication.

4. Proof-of-concepts, pilots, and studies

4.1 The Opastaja demo application

4.1.1 Introduction of the concept

The Opastaja demo application, developed and evaluated as part of Lassi Timoskainen's master's thesis (Timoskainen, 2025), is a web-based trip-planning application whose explicit intent is to encourage sustainable mobility during the pre-decisional planning phase when mode choices are still malleable. Instead of points or badges, the concept applies a limited, ethical set of persuasive techniques so that intent remains transparent (clearly communicated to the user) and the UI stays uncluttered. In this context, transparent intent means the system openly signals that it aims to make public transport, walking and cycling attractive by design (not by covert manipulation).

The main design principles for the application were established through a combination of literature review and a pre-design user study. The initial concept combined (1) trip planning, (2) sustainability

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nudges, and (3) a light social layer (save/share trips; later, shareable recommendation profiles). It intentionally prioritised mobile-first clarity and user freedom, while focusing persuasion on route-enrichment instead of rewards. This sharply scoped concept informed the UX goals: Sustainability, Freedom, Discovery, Clarity.

The user study, conducted with 123 participants (primarily young adults from Tampere), provided practical insights into users' mobility habits, trip planning practices, tool preferences, attitudes toward sustainability, and social influences. Survey findings led to several key design implications for the trip planning application:

1. **Integrated multi-modal support:** Users prefer walking and public transport but want the flexibility to choose any mode. The application should make switching between transportation modes seamless, encourage sustainable options, and provide accurate, context-aware information (e.g., live data, weather).

2. **Flexible planning:** The system should allow users to easily modify their plans, balancing structure with spontaneity – such as enabling buffer times between stops.

3. **Social features:** Users value collaborative planning and sharing. The application should support sharing trip plans and integrating recommendations from friends or trusted sources.

4. **Unified information and discovery:** To address fragmented information, the app should centralize destination details, offer recommendations, enable filtering, and highlight lesser-known or local favourites to support discovery.

These findings complemented the theoretical framework and directly informed the design decisions, ensuring the application addressed real user needs and challenges.

4.1.2 Functionality of the Opastaja demo application

The user interface of the Opastaja application (Figure 1) is designed with a mobile-first, map-centric approach that emphasizes clarity, adaptability, and ease of use. Users interact with an intuitive map view to explore, filter, and select Points of Interest (POIs), plan multi-stop trips, and choose between various transportation modes such as walking, cycling, public transport, or driving. The interface dynamically adapts to different screen sizes, ensuring a seamless experience on both mobile devices and desktops. Key features include interactive route visualization, adjustable

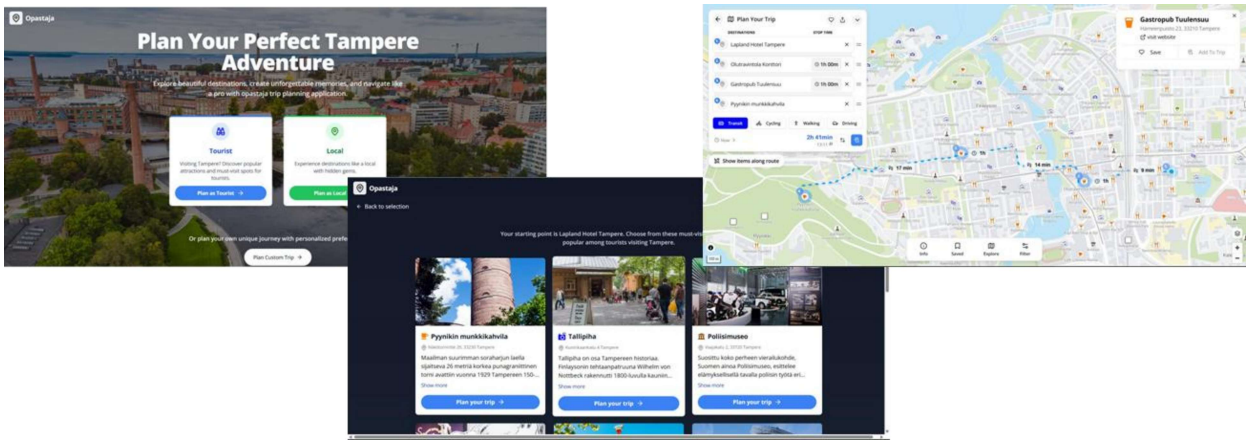


Figure 1. User interface of the Opastaja application.

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trip schedules, and integrated tools for saving and sharing trip plans, all presented within a visually appealing and uncluttered layout that supports both detailed planning and spontaneous travel adjustments.

The core functionalities of the application include:

- **Interactive map exploration**: Users can browse a map of the Tampere area, view categorized points of interest (POIs), and filter/search for destinations.
- **Multi-stop trip planning**: Users can create itineraries with multiple destinations, choosing the order and adjusting the duration of each stop.
- **Multi-modal routing**: The app supports various transportation modes – public transport, walking, cycling, and driving. Users can switch modes, and the app recalculates routes and schedules accordingly.
- **Route-aware POI recommendations**: The system suggests interesting destinations along the planned route, making sustainable options (like public transport or cycling) more appealing by enriching the journey.
- **Scheduling**: Users set a departure time and specify how long they wish to spend at each stop. The app then generates a detailed schedule, including total travel time and estimated arrival times.
- **Trip saving and sharing**: Users can save their trip plans and share them with others, supporting collaborative planning and social discovery.
- **Responsive UI**: The interface adapts to both mobile and desktop devices, ensuring usability across platforms.

Figure 2 depicts the operation of the application. The typical user workflow of the Opastaja application proceeds as follows:

1. **Start planning:**
   - The user opens the application and selects whether to plan as a tourist or local, or starts a custom trip.
2. **Explore and select destinations:**
   - On the map, the user browses POIs, uses filters or search, and selects destinations of interest.
   - The user can view details for each POI (name, address, category, and, where available, images or opening hours).
3. **Build an itinerary:**
   - The user adds one or more destinations to the trip plan.
   - The order of destinations can be adjusted (drag-and-drop).
   - The app automatically calculates the route between stops.
4. **Choose transportation mode:**
   - The user selects a preferred mode (public transport, walking, cycling, or driving).
   - The app visually distinguishes routes by mode and updates travel times and schedules accordingly.
   - Users can switch modes at any time; the system recalculates the route and timing.

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5. **Adjust schedule:**
   - The user sets a departure time and specifies how long to spend at each stop.
   - The app generates a complete schedule, showing leg-by-leg travel times and overall trip duration.
6. **Discover along-route recommendations:**
   - The app suggests additional POIs along the planned route, which the user can add to the itinerary to enrich the journey.
7. **Save and share:**
   - Once satisfied, the user can save the trip plan for later use.
   - The plan can be shared with others, supporting collaborative planning or recommendations.
8. **Review and edit:**
   - The user can revisit saved trips, make changes, or share them again.

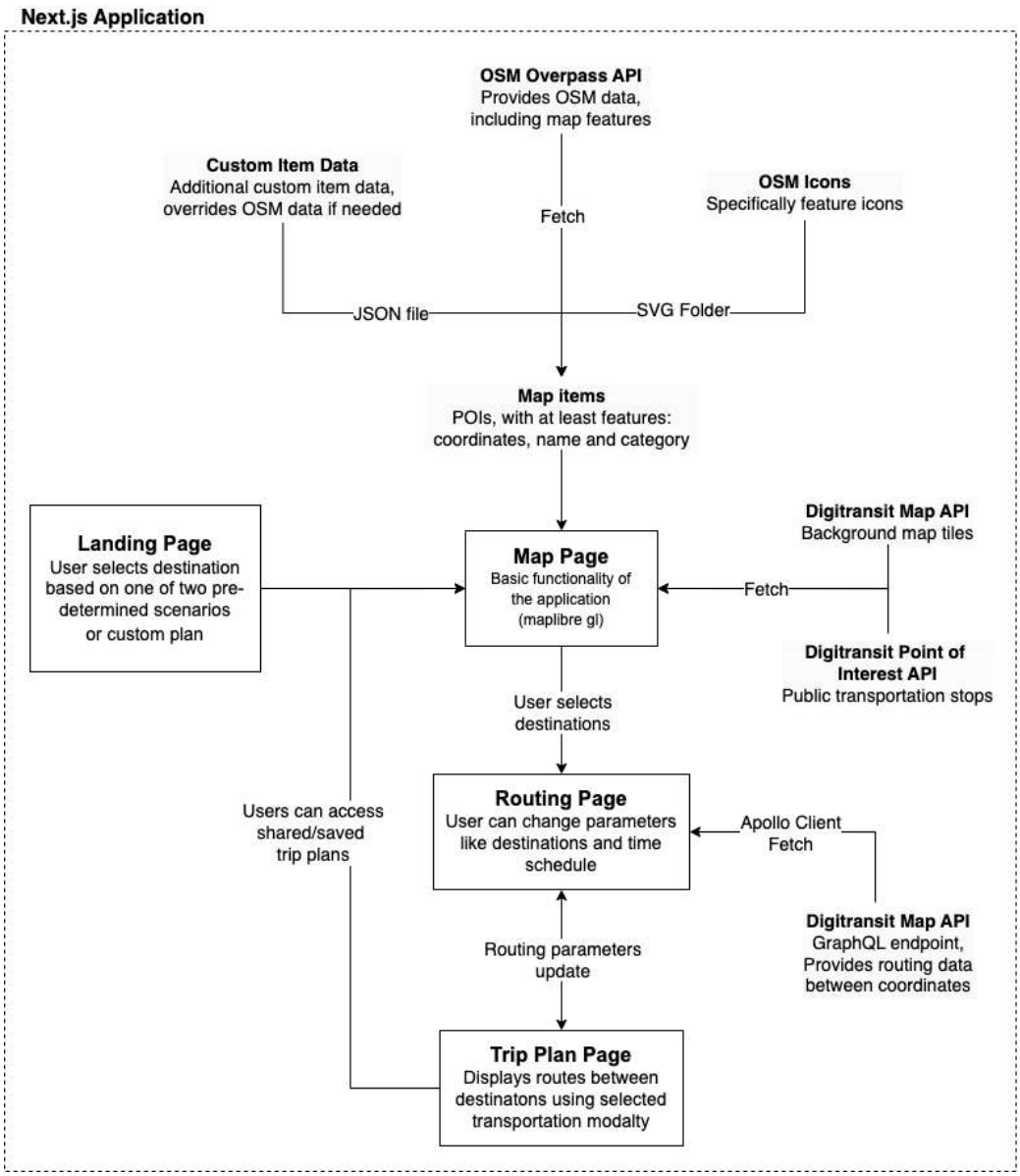


Figure 2. Operation of the Opastaja application.

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4.1.3 Technical implementation

The technical implementation of the Opastaja application is grounded in a modern web architecture that prioritises cross-platform accessibility, robust data integration, and a responsive user experience. The application is developed using the Next.js framework, which enables efficient server-side rendering and seamless operation across both desktop and mobile devices. This choice supports the mobile-first design philosophy, ensuring that the interface remains intuitive and functional regardless of the user's device or context. The architecture of the Opastaja application is depicted in Figure 3.

Central to Opastaja's operation is its integration with external APIs for both mapping and routing functionalities. Points of Interest (POI) data are sourced from the Open Street Map (OSM) Overpass API. While OSM provides a comprehensive foundation, the application supplements this with custom POI entries to address gaps in coverage and enrich the user experience with more detailed and relevant destination information. For map visualization and routing, the application leverages the Digitransit APIs. These APIs supply not only the background map tiles and public transportation stop data but also the routing logic that underpins the application's multi-modal and multi-stop trip planning features. Routing requests are dynamically constructed based on user input, including coordinates, departure times, and selected transportation modes such as walking, cycling, public transport, or driving. The system's ability to handle user-defined visit durations at each stop is particularly significant, as it enables the generation of feasible and realistic schedules – especially for public transport routes, which are often a challenge for conventional trip planners.

All core logic for data integration and user interaction is handled on the client side, with real-time requests to the external APIs ensuring that map and routing information is always current. The application's architecture is designed to minimize latency and maximize responsiveness, with asynchronous data fetching and state management ensuring a smooth user experience even as users modify their plans or switch between devices. The user interface, prototyped in Figma and implemented with a focus on clarity and adaptability, provides interactive elements for searching and filtering POIs, visualizing routes, and adjusting trip parameters. The UI adapts responsively to different screen sizes and input methods, supporting both detailed planning and spontaneous adjustments during travel.

In addition to its core mapping and routing features, Opastaja incorporates mechanisms for sharing trip plans and recommendation profiles. These social and collaborative features are implemented within the same web-based architecture, allowing users to easily distribute their plans or preferences without the need for additional software or complex authentication flows. Throughout the implementation, technical considerations such as data privacy, efficient API usage, and extensibility have been prioritised. The application avoids collecting unnecessary user data by relying on predefined recommendation profiles and only requesting essential information from external services. This approach not only enhances privacy and security but also simplifies compliance with data protection standards.

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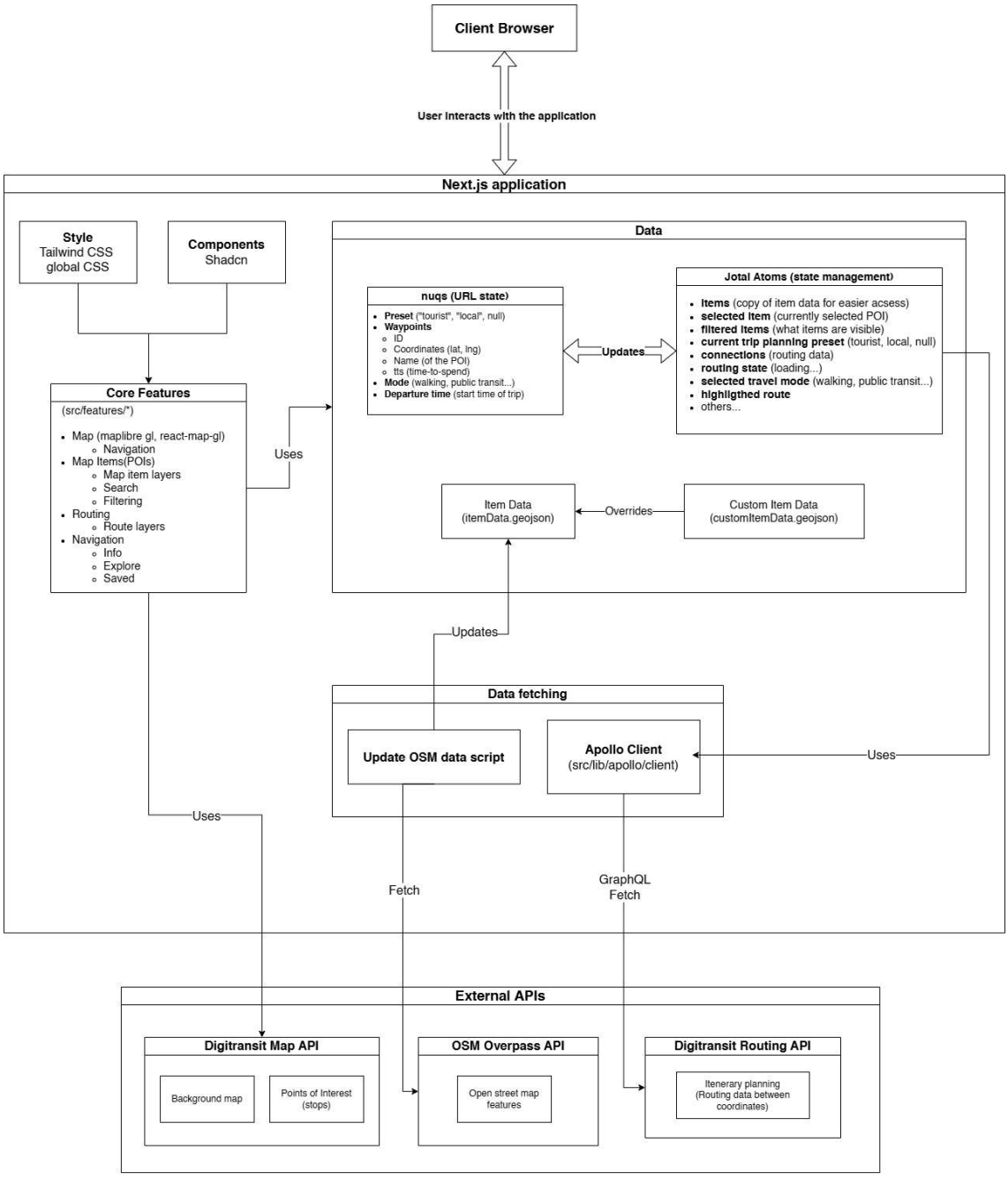


Figure 3. The architecture of the Opastaja application.

4.1.4 Evaluation of the Opastaja application

The Opastaja multi-stop tourism trip planner was evaluated in two consecutive studies: (1) expert-oriented user study as part of a master's thesis and (2) in a subsequent non-expert study made in the project. Both evaluations applied qualitative methods but differed slightly in participant profiles and focus.

In the master's thesis, the evaluation focused on a functional prototype through a qualitative expert-oriented user study. Four participants with expertise in travel, tourism, and service design

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were recruited. The evaluation sessions were conducted remotely using Microsoft Teams and followed a structured process consisting of (i) introduction and consent, (ii) task-based testing with think-aloud protocol, and (iii) a semi-structured post-interview. The test scenario asked participants to plan a day trip in Tampere using the application, including adding destinations, modifying the itinerary, and saving and sharing the plan. The sessions lasted approximately 40–60 minutes, and the collected data (observations, think-aloud comments, and interview responses) were analysed using thematic analysis.

In the latter study, the evaluation involved a broader user-focused qualitative study with five participants aged 23-33. Participants were recruited from the researchers' networks and participated in remote Microsoft Teams sessions lasting 33-46 minutes. The evaluation combined scenario-based task execution with think-aloud and follow-up interviews. Two alternative scenarios were used: planning a personal weekend itinerary or planning activities for a group of colleagues visiting Tampere. The collected data were transcribed and analysed to assess usability, perceived usefulness, travel experience, and especially the application's potential to influence mobility behaviour.

4.1.4.1 Highlights from the evaluations

Across both evaluations, the Opastaja concept was consistently perceived as intuitive and useful for multi-stop trip planning. The map-based interaction model enabled users to easily understand spatial relationships between destinations and to construct itineraries efficiently. The ability to add multiple points of interest (POIs) and dynamically update routes was seen as particularly valuable for structuring a day trip.

A central strength identified in both studies was the application's ability to support discovery. By presenting POIs along routes and visualizing them on a map, Opastaja encouraged exploratory behaviour and helped users identify destinations they would not otherwise have considered. This exploratory functionality was particularly relevant in unfamiliar destinations and contributed positively to the overall travel planning experience.

Another key outcome was the application's potential to promote sustainable mobility choices. Users perceived that the visualization of distances and accessible routes fostered a sense of compactness and ease of movement, which made walking, cycling, and public transport appear more attractive compared to private car use. Importantly, this effect was not primarily driven by detailed itinerary optimization but rather by how the application conveyed accessibility and flexibility in reaching multiple destinations.

In addition, the overall usability of the application was rated positively. Users described the interface as clear, consistent, and easy to use, with the map-based presentation supporting both overview and decision-making in itinerary planning.

4.1.4.2 Identified needs for improvement

Despite the positive overall assessment, both evaluations highlighted several areas requiring further development.

The most prominent improvement need concerns the availability and depth of information. Users indicated that the application should provide richer descriptions of POIs, including contextual information such as opening hours and additional background details. Similarly, mobility-related information was considered insufficient, particularly for public transport. Participants expressed a need for more detailed information such as stop names, departure times, and clearer indications of transport modes used for each leg of the journey.

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A second major development need relates to personalisation and flexibility. While the application allows multi-stop planning, users requested more advanced customization options. In particular, there is a clear need to support different transport modes for different segments of the trip, improved automatic ordering of POIs within the itinerary, and the ability to define free-form routes or intermediate waypoints beyond predefined POIs.

Third, both studies identified usability refinements, especially in relation to navigation and information presentation. Challenges included difficulty in locating specific POIs due to small or unclear map markers, limitations in filtering and search functionality, and insufficient visual feedback for certain user actions. Users also noted that improved clarity in route visualization would be beneficial, particularly for more complex itineraries.

Finally, the evaluations suggest that the application could more effectively support sustainable behaviour by strengthening the presentation of mobility alternatives. For example, highlighting public transport frequency and flexibility, or emphasizing constraints of private car use (such as parking availability), could further reinforce mode shift toward more sustainable options.

4.1.5 Business models and implications

A traveller-oriented digital service such as the Opastaja application depends on data from several actors across multiple industries, including tourism and hospitality, mobility, recreational services, retail and rental, and public services such as swimming halls and post offices. To provide seamless travel planning, route guidance, service recommendations, and real-time support, such a service would need access to diverse datasets, digital interfaces, and service information from transport operators, tourism service providers, destinations, public authorities, and other ecosystem actors (Lusikka & Hakkarainen, 2025).

Figure 4 represents an overall depiction of tourism mobility ecosystem that is needed to provide Opastaja-like applications. Some data is essential for enabling a functional travel service. This includes, for example, information on public transport, private mobility services, accommodation, opening hours, prices, accessibility, and service availability. Other data can improve the quality of the travel experience without being strictly necessary. Examples include real-time queue information, weather conditions, visitor flows, local recommendations, or environmental observations. These additional data sources can help travellers make better decisions and adjust their plans during the trip. (Lusikka & Hakkarainen, 2025)

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Figure 4. Overall depiction of tourism mobility data ecosystem (Adapted from: Lusikka & Hakkarainen, 2025).

In the future, such applications could also generate valuable data for the wider ecosystem if travellers consent to its use. Data on mobility patterns, preferences, interests, and service use could support more personalised recommendations and help destinations and service providers better understand traveller needs. In this way, the service would not only consume data from the ecosystem but could also contribute new insights to it (Lusikka & Hakkarainen, 2025). This reciprocal exchange could enable more sophisticated business models for various actors.

The overall depiction of tourism mobility data ecosystem (Figure 4) was used to create data and value flow map of Opastaja application seen in Figure 5. Of course, there are multiple ways to structure the data and value flows, and the required flows depend strongly on the purpose and value proposition of the service. A service designed for outdoor recreation, for example, would require different data than a service aimed at cultural tourism or business travellers (Lusikka & Hakkarainen, 2025). Therefore, a successful application should not attempt to include all possible data, but should define its target users, use cases and service scope clearly as too much information may weaken the user experience if it is not filtered and personalised effectively (Lusikka & Hakkarainen, 2025).

Opastaja in its designed form serves mainly as an information source and destination guide, which means that there are no actual services that can be booked or purchased from the application. Furthermore, Opastaja was designed to promote sustainable mobility in the destination as sustainability aspects are becoming more important for travellers and destinations. Thus, it was seen that Opastaja would benefit mainly the traveller and the destination that is interested in attracting new travellers and lengthening their stay in the area. This would also benefit the businesses in the destination's sphere of interest. Hence, the data and value flow map is based on initial idea that Destination Management Organisation (DMO) would be the host of the service and would want to offer the Opastaja application to attract travellers and provide new interesting services and experiences for them.

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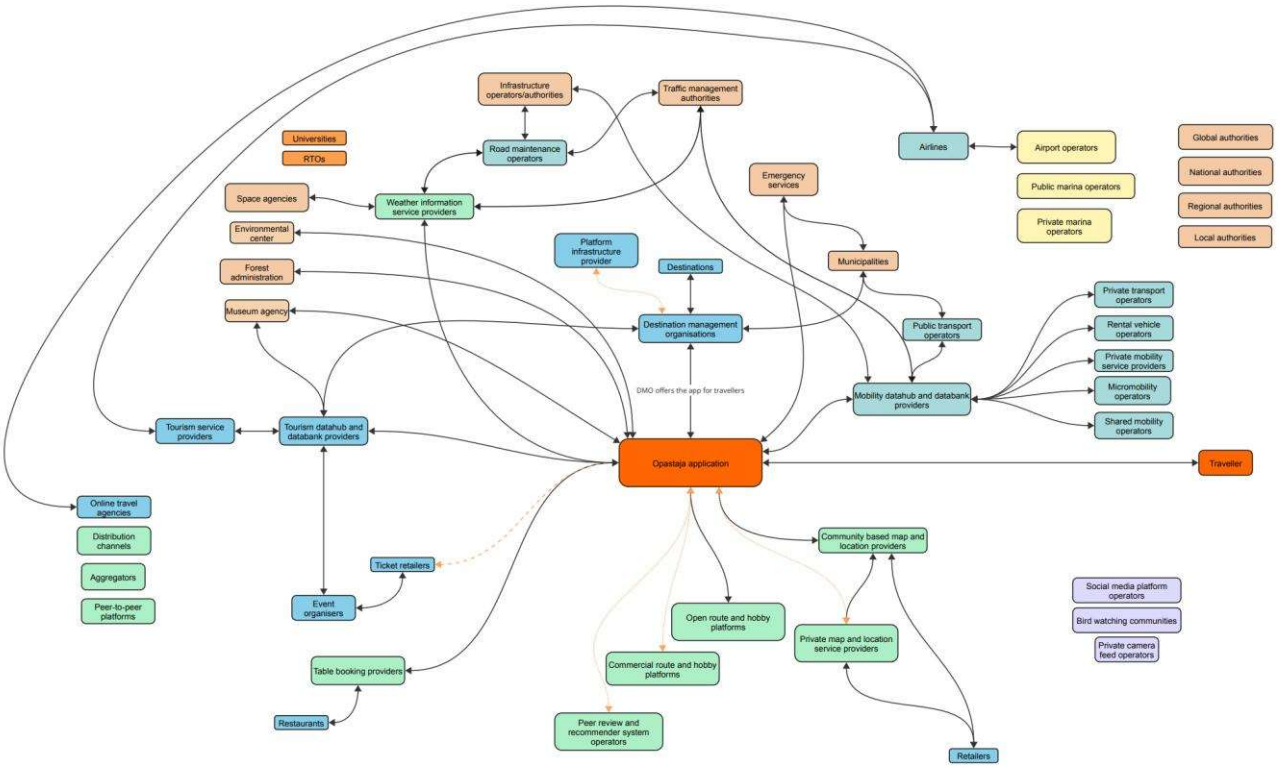


Figure 5. Data and value flows of Opastaja application ecosystem.

Most of the data sources used (and sources that could be used) in the application provide open data and thus there is no need for the DMO to pay for used data. For such data exchanges, black arrows are used to describe data and value flows in Figure 5. There are also commercial data and services available that could be incorporated in the application. This would likely mean some form of compensation (monetary or other). These flows are described with orange dotted lines in the Figure 5. Thus, in this business model the main direct cost for the DMO (if the commercial data is not included) would be the platform itself and related upkeep services that would likely be provided by external IT company (platform infrastructure provider in the figure).

The model also assumes that the service is provided free for travellers to attract new travellers to the destination by providing good quality information service about the experiences, locations and services in the area. By gaining new travellers and lengthening the stays of travellers, businesses in the destination would benefit from new income from new travellers. Furthermore, it is expected that travellers would use more services and visit more businesses if such an application would be available to plan their stay in the destination.

4.1.6 Results and further research

The results of evaluations form a coherent and mutually reinforcing picture of the Opastaja concept. The application demonstrates strong potential as a multi-stop trip planning tool that supports both exploratory and structured travel planning. Its primary added value lies in simplifying complex itinerary construction while simultaneously encouraging the discovery of destinations and the use of sustainable mobility options.

However, to reach a higher level of maturity and real-world applicability, further development is needed in three key areas: (1) richer and more context-aware information, (2) enhanced personalisation and flexibility in itinerary construction, and (3) improved user interface clarity and

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interaction support. Addressing these areas is essential for maximizing both user experience and the application's impact on travel behaviour.

The evaluations of the Opastaja multi-stop trip planning application indicate several important directions for further research, particularly in moving from prototype validation toward real-world impact. While initial user and expert evaluations suggest that such applications can encourage more sustainable mobility choices by improving perceived flexibility, accessibility, and attractiveness of alternative modes, there remains a clear need to investigate whether these effects translate into long-term behavioural change in real usage contexts. In this regard, future studies should focus on longitudinal and in-situ evaluations, examining how users interact with itinerary planning tools during actual trips and how their plans evolve over time, including the system's ability to support dynamic decision-making and adaptation.

Another key research direction concerns enhanced personalisation and adaptive itinerary planning. Both evaluations highlight the importance of tailoring both activities and mobility options to user preferences, as well as enabling flexible, user-driven planning rather than rigid scheduling. Future work should therefore explore more advanced personalisation mechanisms that incorporate contextual factors and support diverse travel styles, while maintaining usability.

In addition, the evaluations revealed limitations related to data completeness and information integration, pointing to the need for research on richer and more unified data ecosystems. Improving the quality and depth of POI and mobility information, including real-time transport data and contextual details, is essential for supporting informed decision-making and enhancing user experience. Closely related to this is the challenge of multi-modal, multi-stop journey optimization, particularly when combining public transport with uncertain activity durations. This requires further investigations of the computational models and user interaction approaches that can address this complexity.

Finally, further research is required to better understand the role of persuasive design strategies and social features in influencing travel behaviour. While current findings suggest that highlighting flexibility, accessibility, and destination discovery can encourage sustainable choices, it remains unclear which design elements are most effective across different user groups and contexts. In addition, the strong user interest in sharing and collaborative planning indicates significant potential for social mechanisms, such as shared itineraries and user-generated recommendations, to support both discovery and behavioural change.

4.2 Extended trip planner

4.2.1 Introduction of the concept and functionality

The Extended Trip Planner (XTP) concept enhances traditional public transport route planners by providing not only standard map-based navigation but also enriched, context-aware guidance for travellers. In addition to the usual route suggestions, XTP allows for the integration of rich media elements – such as photos, videos, audio, and text – at key points along a journey, making navigation clearer and more reassuring, especially for those who may struggle with map reading or orientation. Importantly, XTP also enables the creation and selection of alternate routes tailored for special needs, such as accessible paths for wheelchair users or temporary detours during roadworks. These enriched and alternative routes can be contributed by users or organisations, ensuring that guidance remains up-to-date and relevant for a variety of situations and traveller requirements. The result is a more flexible, inclusive, and user-friendly navigation experience that adapts to both individual needs and changing real-world conditions.

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For end users, the Extended Trip Planner application offers an intuitive and flexible navigation experience. Users can search for routes just as they would with a traditional trip planner but benefit from additional features such as visual or auditory guidance at key points along their journey. When planning a trip, users may see camera or media icons indicating the availability of enriched guidance – clicking these reveals photos, videos, or audio instructions that clarify complex segments or help with orientation. The application also allows users to select alternate routes, for example, those optimized for accessibility or to avoid temporary obstacles like roadworks. These features are valuable both during pre-trip planning – helping users familiarize themselves with the route and build confidence before departure – and for real-time, on-trip guidance, where step-by-step media cues support successful navigation as the journey unfolds. This dual utility ensures that travellers are well-prepared and supported throughout their entire trip.

4.2.2 Technical implementation

The technical implementation of the Extended Trip Planner (XTP) is built on a modular architecture (see Figure 6) that integrates seamlessly with existing public transport route planning platforms, such as Digitransit. At its core, XTP consists of three main components: the standard route planner, a Route Media Editor, and a Route Media Server. The Route Media Editor enables users or organisations to create enriched route guidance by associating media files – such as images, audio, or video – with specific waypoints along a route. These enriched routes, packaged with their media and metadata, are uploaded to the Route Media Server, which manages user accounts, stores route collections, and provides APIs for searching and retrieving suitable enriched routes.

The Route Media Server is implemented using a lightweight Java framework and utilises a PostgreSQL database with PostGIS extensions for efficient spatial queries and storage of geolocated media points. Media files are served via a web server, and the system supports secure, scalable deployment, including cloud environments. The application exposes RESTful APIs for both uploading new enriched routes and querying for relevant guidance based on route endpoints, addresses, or even trajectory similarity. During navigation, the client application overlays the enriched guidance onto the map interface, triggering media cues in real time as the user progresses along the route. This architecture ensures that XTP can flexibly deliver context-aware,

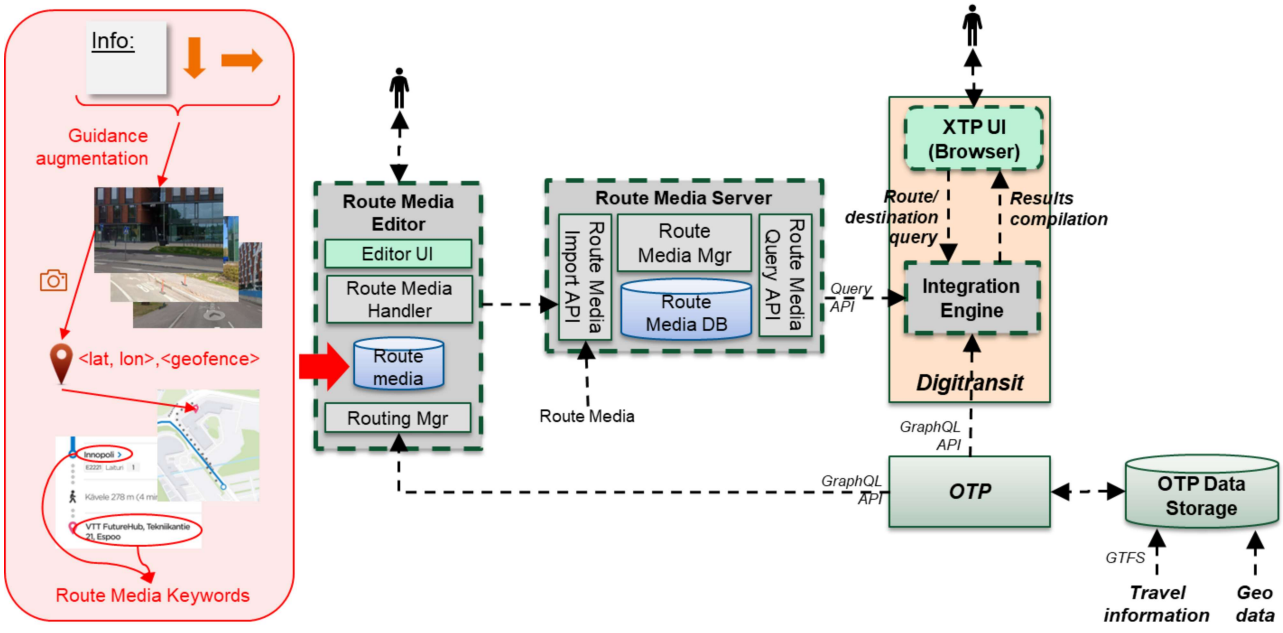


Figure 6. Overall architecture of the Extended Trip Planner system.

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media-rich, and even alternative routes – such as accessible paths or temporary detours – directly to end users, both during pre-trip planning and while on the move.

In this project the Route Media Editor was not implemented due to the limited resources. Instead the Route Media packages containing the guidance media and alternate routing were created manually and submitted to the Route Media Server using the Route Media Import API.

4.2.3 User study

The eXtended Trip Planner (XTP) was presented to journey planner experts, event organisers, facility managers and receptionists to evaluate the application. In addition, two targeted interviews were conducted with VTT personnel responsible for providing guidance to the VTT premises and events.

The evaluation indicates that both experts and potential users see clear added value in extending traditional route planning with richer contextual guidance, while also highlighting several practical challenges affecting real-world adoption. The most important strength identified is the ability of visual, location-based guidance to support user orientation, particularly in complex environments where conventional map-based navigation is inadequate. Comparing the image-based guidance with real-world surroundings was seen as particularly valuable as it reduces uncertainty and increases confidence in reaching the destination. Users and experts consistently emphasised that current journey planners rely heavily on map-reading skills, which many users find difficult, especially when transitioning from underground or dense built environments where orientation is unclear. The capability to preview routes as a sequence of images in advance was also seen as a highly valuable feature as in this way the users can form a mental image of the route before the actual navigation, and thus, increase users' confidence in finding the destination.

The interviews further highlight that last-mile navigation is a critical bottleneck in sustainable mobility chains. Users often prefer private cars not due to the overall journey but because the final segment from a public transport stop to the destination is perceived as uncertain and difficult. XTP addresses this gap by improving clarity of routes and enabling alternative guidance modalities such as visual and audio instructions, which were seen as particularly beneficial for users with diverse needs and abilities. Additionally, the possibility to integrate guidance with richer contextual information, such as points of interest, services, or organisational content, was recognised as a key opportunity to enhance user experience beyond navigation and to support discovery and engagement during the journey.

At the same time, several important areas for improvement were identified. A central challenge concerns the production, ownership, and maintenance of guidance content. The interviews reveal uncertainty regarding who should be responsible for creating and updating route-specific information, especially in environments where conditions change frequently due to construction, seasonal variation, or temporary arrangements. Maintaining up-to-date and reliable information is therefore seen as a major barrier, particularly if the process requires significant manual effort. In addition, users highlighted the need for flexibility in presentation and use, including support for different contexts (e.g. weather conditions, accessibility needs) and the possibility to integrate guidance seamlessly into existing journey planning tools rather than introducing new standalone applications. Concerns related to information overload, usability, and even security were also mentioned, particularly in relation to indoor environments and the level of detail that should be made available to users.

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4.2.4 Business model options and implications

As identified in the user study (Section 4.2.3), a central challenge for the XTP concept is determining who produces, owns and maintains the enriched guidance content. The business model must also define who operates the platform, who bears the associated costs, how quality and timeliness are assured, and which actors capture value from the service. To explore these questions, five service-organisation options were developed:

- Option A: XTP integrated into Digitransit, with destinations maintaining route content
- Option B: XTP integrated into Digitransit, with a commercial route-content provider
- Option C: a separate XTP application, with destinations maintaining route content
- Option D: a separate XTP application, with an independent commercial route-content provider
- Option E: a separate XTP application whose provider also produces and maintains route content.

These options represent the main service-organisation models identified for addressing platform operation and guidance-content production. They are illustrative rather than exhaustive, and some can coexist. For example, destinations could maintain selected routes themselves while purchasing specialist support for others. The options should therefore be assessed as alternative configurations of roles and revenue flows rather than as mutually exclusive end states.

4.2.4.1 Option A: XTP integrated into Digitransit, with destinations maintaining route content

In option A (see Figure 7), the XTP service (Route media editor, XTP media server and alternative route data) would be integrated into the existing Digitransit platform that serves as the basis for all Finnish public transport journey planners. Integration would give XTP broad reach through existing user interfaces and reduce the need to build a separate user base. Destinations would create and maintain their own enriched route content, while the Digitransit collaboration would provide the shared technical capability for storing and delivering it.

From a business perspective, the Digitransit partners (Helsinki Regional Transport Authority, Finnish traffic management company Fintraffic and Waltti Solutions) would assume responsibility for developing and operating the shared XTP capability. The resulting costs could be covered as part of the partners' existing journey-planning responsibilities, through contributions from participating destinations, or through a dedicated service fee. The appropriate mechanism depends on the public value created, expected use, maintenance burden, and willingness of destinations to pay. Before deployment, the partners should assess whether improved last-mile guidance, accessibility and service quality generate sufficient benefits to justify the shared investment.

Destinations would create enriched route content through the Route Media Editor because they have the strongest incentive and local knowledge to improve access to their premises. They should therefore remain accountable for the accuracy and timely updating of the content they publish. The operating model would nevertheless require common quality criteria, named content owners, review intervals, expiry dates and a process for reporting and correcting outdated guidance. The platform operator should retain responsibility for technical validation, availability and version management.

For passengers, XTP would be available free of charge through existing journey-planning applications. This would minimise adoption barriers and support broad access, particularly for users who benefit most from accessible and confidence-building guidance.

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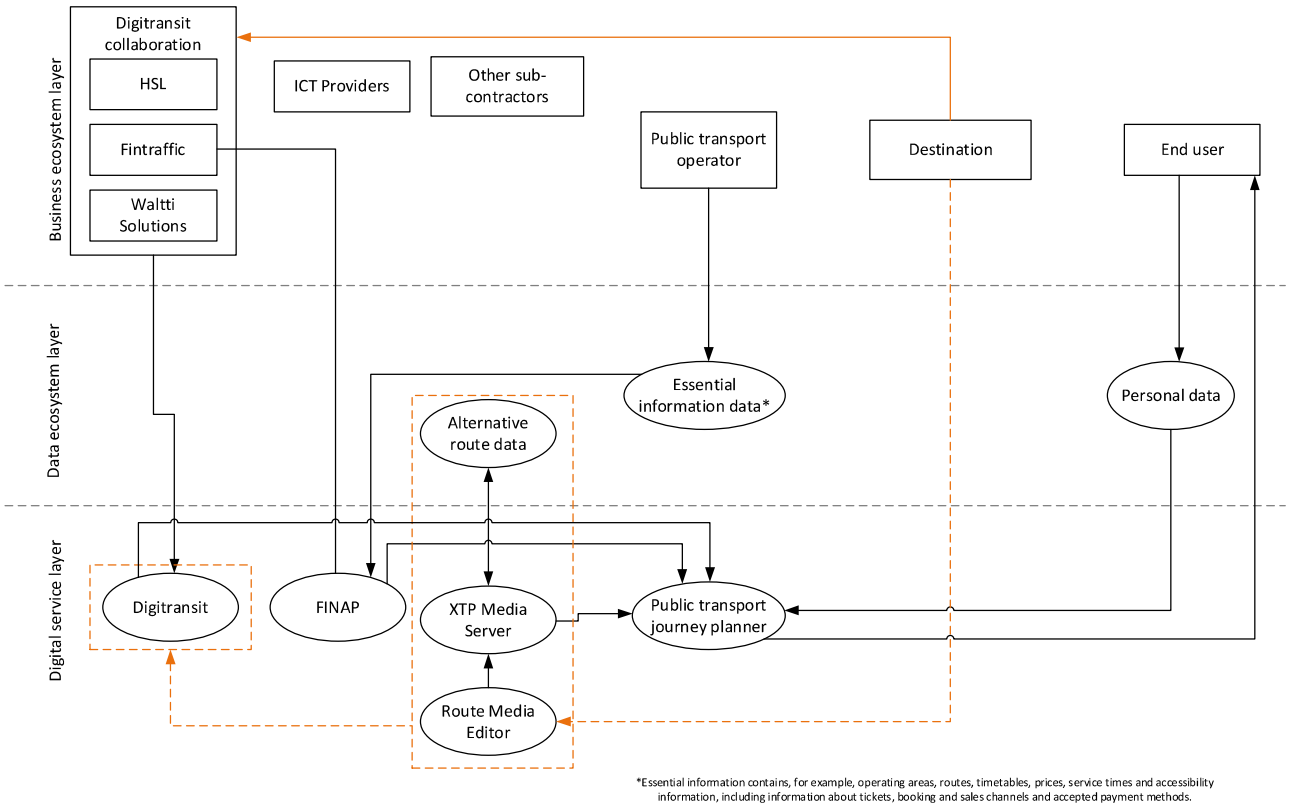


Figure 7. Option A: XTP integrated into Digitransit, with destinations maintaining route content.

4.2.4.2 Option B: XTP integrated into Digitransit, with a commercial route-content provider

In Option B (see Figure 8), the XTP would be integrated into Digitransit as in Option A, but destinations could purchase route creation, validation and maintenance from a specialist alternative-route provider. The provider's commercial offering could include initial route mapping, accessible-content production, seasonal updates, temporary detours, and agreed service levels for correcting outdated information. Options A and B could operate simultaneously: organisations with sufficient capability could maintain their own content, while others could procure the specialist service. The Digitransit partners would still need to determine how the shared platform capability is funded and governed.

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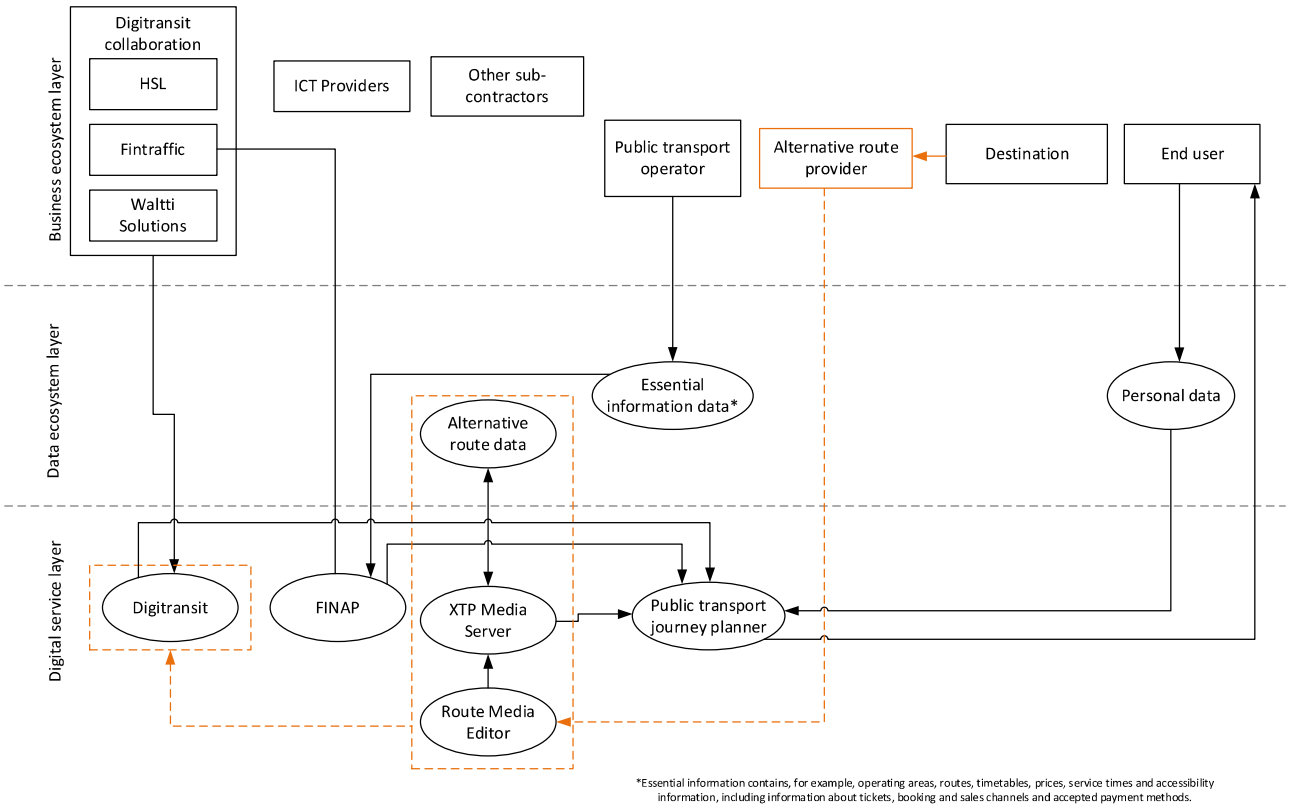


Figure 8. Option B: XTP integrated into Digitransit, with a commercial route-content provider.

4.2.4.3 Option C: a separate XTP application, with destinations maintaining route content

In Option C (see Figure 9), XTP would be offered through a separate application rather than through Digitransit. A commercial XTP provider would develop and operate the application, Route Media Server and publishing tools, while destinations would produce and maintain their own route content. This model gives the provider greater control over product development, branding and commercial features, but it also requires the provider to build a user base and integrate public transport data independently.

In Option C, destinations would produce and update alternative-route data, while the XTP provider would operate the application and the tools used to publish that data. The provider would consume public transport and destination-supplied route data to deliver enriched guidance. Charging destinations solely for contributing data may create weak incentives, but a business-to-business fee could still be justified if it covers platform access, hosting, validation, analytics or visibility benefits. End-user charges and advertising are additional possibilities, although both may limit adoption or weaken the user experience. A mixed model combining destination subscriptions, institutional sponsorship and optional premium services would therefore merit evaluation.

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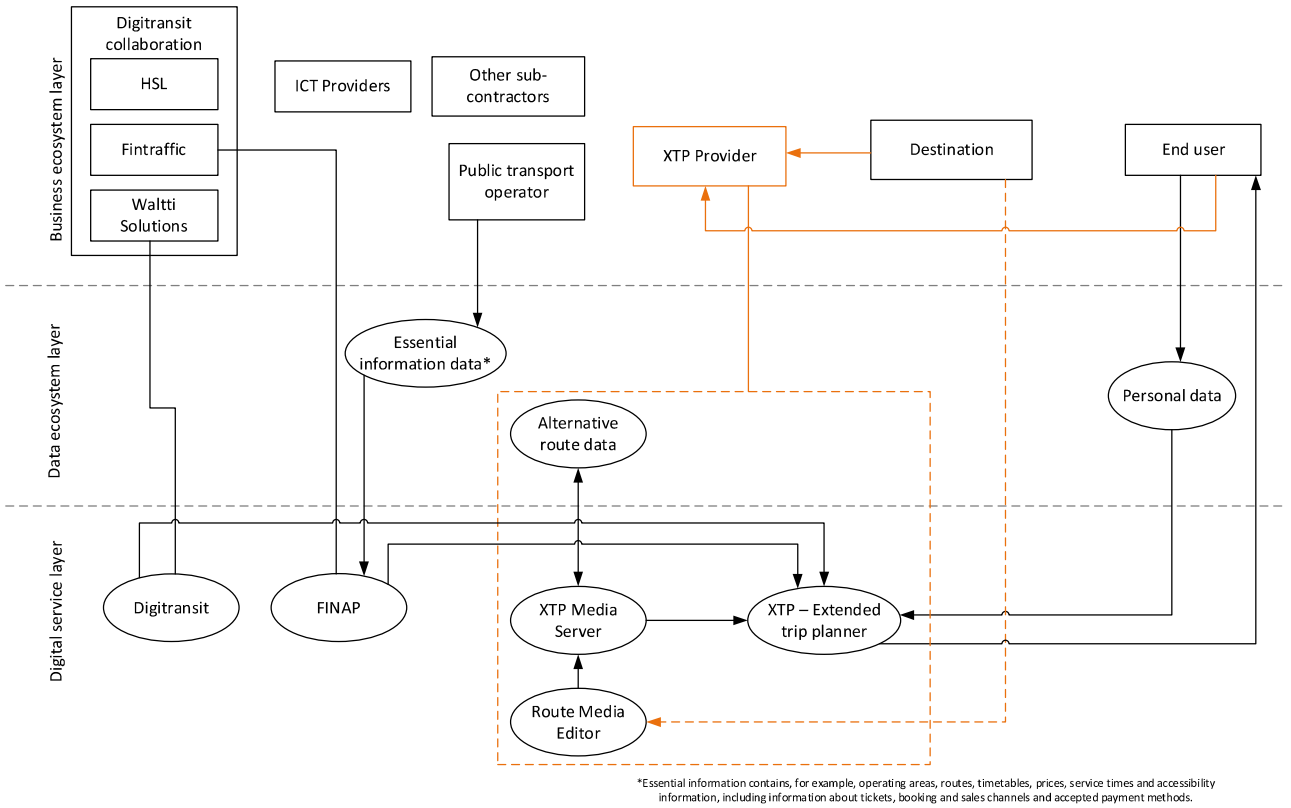


Figure 9. Option C: a separate XTP application, with destinations maintaining route content.

4.2.4.4 Option D: a separate XTP application, with an independent commercial route-content provider

Option D (see Figure 10) follows the separate-application model of Option C but adds an independent alternative-route provider that creates and maintains enriched route content as a commercial service for destinations. Destinations could either manage content internally or purchase specialist support, allowing both approaches to coexist. The model distributes responsibilities across two providers and may improve specialisation, but it requires clear interfaces, quality standards and contractual accountability between the application provider and the route-content provider.

As in Option C, the XTP provider would operate the separate application, while a specialist route provider would sell content-production and maintenance services to destinations. The two providers could use a partnership agreement, revenue-sharing arrangement or bundled offer to reduce transaction costs for customers. The application provider's revenue need not come only from end users: destinations, event organisers, property owners or public authorities may pay for platform access, integration, analytics or assured service levels when the guidance supports accessibility and visitor management.

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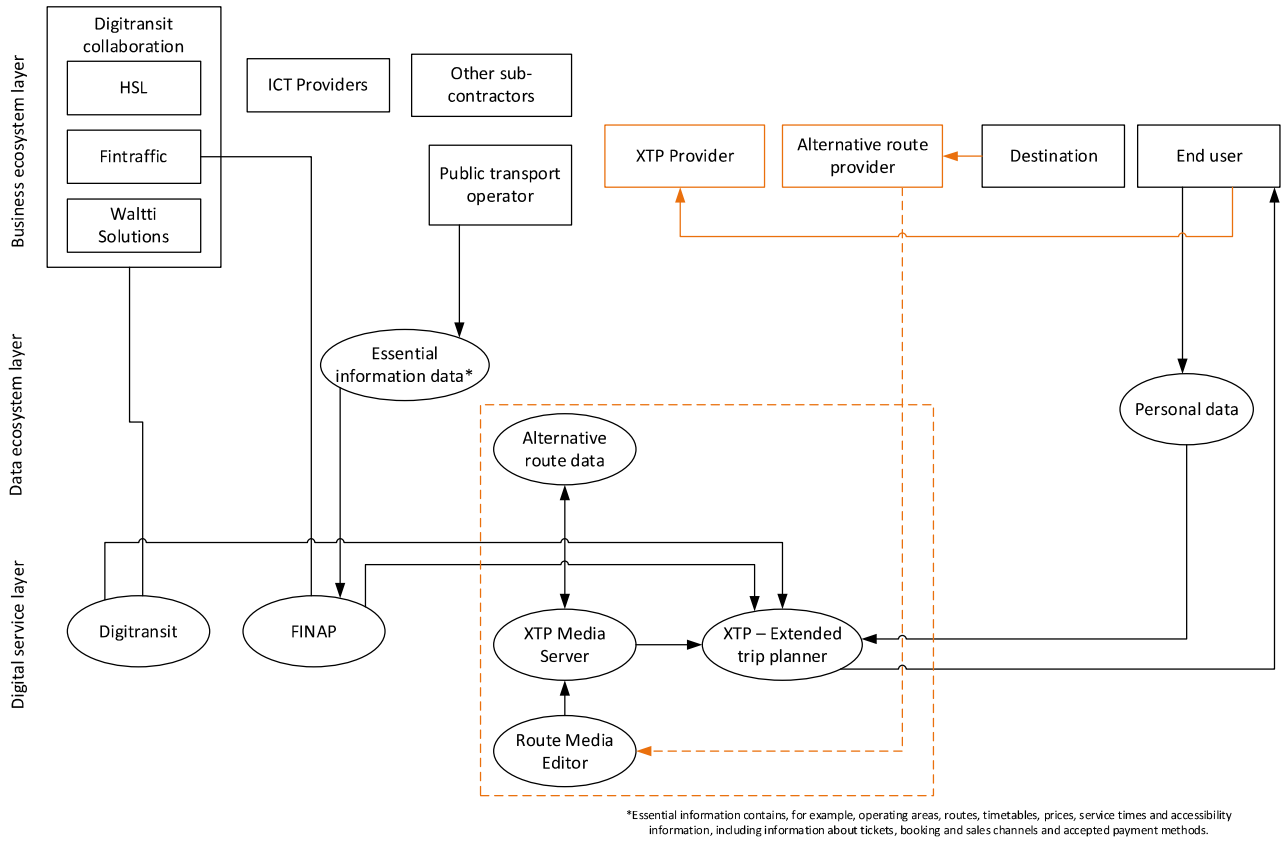


Figure 10. Option D: a separate XTP application, with an independent commercial route-content provider.

4.2.4.5 Option E: a separate XTP application whose provider also produces and maintains route content

In Option E (see Figure 11), one commercial actor would operate the separate XTP application and also provide route-content creation and maintenance services to destinations. Revenue could therefore come primarily from business-to-business contracts covering content production, platform access and maintenance, allowing the application to remain free for end users. Additional end-user revenue, such as advertising, could be considered, but it should not compromise usability, accessibility or trust. Vertical integration would simplify accountability, while also concentrating platform investment, content-quality obligations and market-development risks in one provider.

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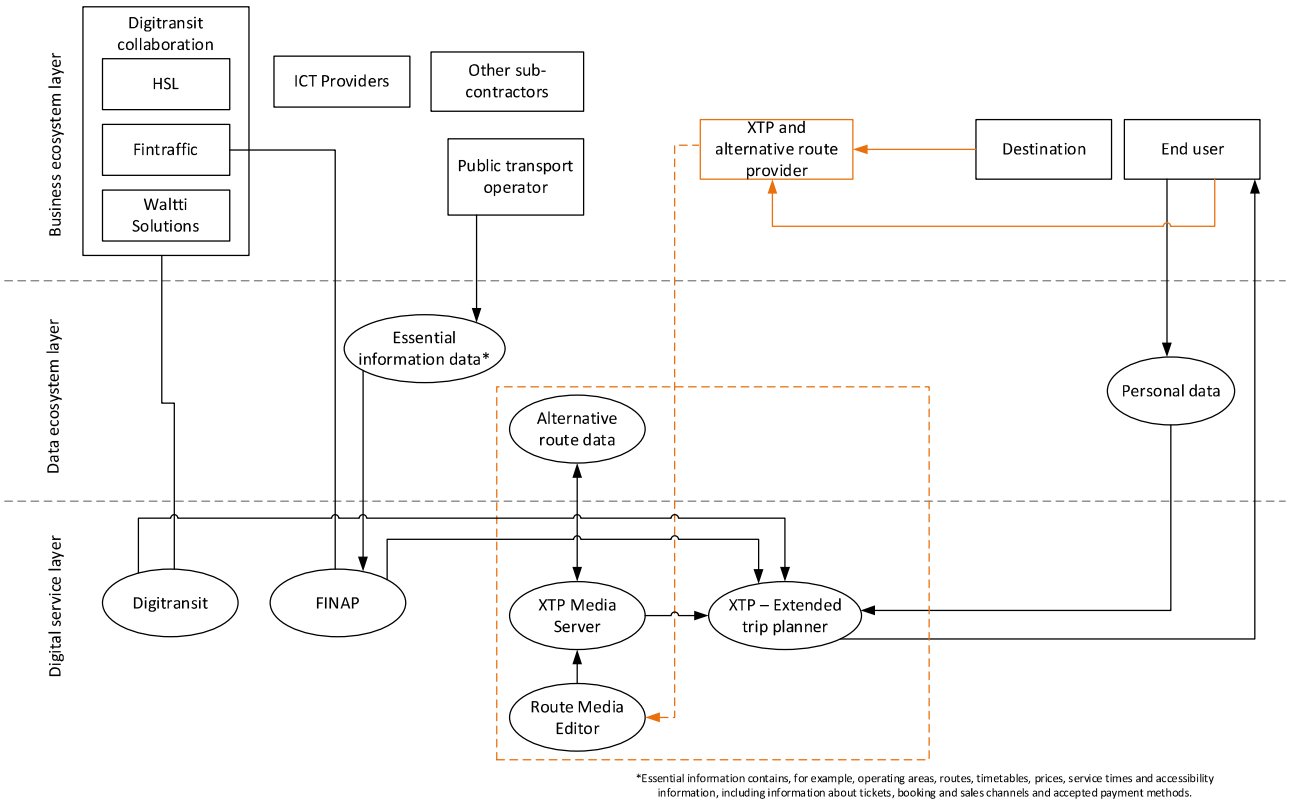


Figure 11. Option E: a separate XTP application whose provider also produces and maintains route content.

4.2.4.6 Comparison of options and recommendations

The options differ primarily in three respects: their integration with the established journey-planning ecosystem, responsibility for producing and maintaining enriched route content, and the source of revenue. Options A and B offer the broadest user reach and the lowest adoption barrier because XTP is integrated into Digitransit. Option B additionally creates a specialist market for route-content production and maintenance. Options C and D provide greater commercial autonomy but require the XTP provider to attract users to a separate application, making user acquisition and end-user monetisation more challenging. Option E offers the clearest integrated commercial proposition because one provider controls both the application and the route-content service, but it also concentrates platform, content-quality and market-development risks in a single actor. For large-scale public deployment, the Digitransit-based options appear most promising, provided that responsibilities, service-level requirements and funding for content maintenance are agreed. A separate application may be better suited to specialised contexts, such as event venues, campuses, tourist destinations or accessibility-focused services.

4.2.5 Results and further research

Overall, the evaluations and received feedback suggest that XTP has strong potential to improve user confidence, accessibility, and the attractiveness of public transport by addressing known weaknesses in last-mile navigation. However, its practical viability depends on resolving challenges related to scalable data production, maintenance processes, and integration into existing ecosystems.

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Future research should therefore focus on mechanisms for efficient and scalable content creation and updating, including semi-automated or user-assisted approaches. In addition, further investigation is needed into multi-modal and adaptive guidance strategies that can respond to changing environmental conditions and user needs, including accessibility and safety considerations. Another important direction is the exploration of integrated service concepts, where navigation is combined with contextual information, experiences, and behavioural nudging to support both user engagement and sustainable mobility choices. Finally, research is required to evaluate the real-world impacts of such solutions through larger pilot deployments, including their effects on user behaviour, mode choice, and overall travel experience.

4.3 E-scooter user behaviour data pilot

4.3.1 Introduction

The Helsinki E-scooter study was a 12-week pilot conducted in Helsinki during 2023 to examine how advanced safety technologies can improve e-scooter operation and interaction with urban infrastructure (Drover et al., 2023). The study was carried out as a collaborative effort between Drover, Voi Technology, VTT, Vianova, Mobility Lab Helsinki, Forum Virium Helsinki, and City of Helsinki. Its main objective was to explore how AI-based sensing, real-time behavioural interventions, and data analytics can enhance rider behaviour, reduce conflicts with pedestrians, and support data-driven urban planning. This section provides a summary of the case study report by Drover et al. (2023).

4.3.2 Methodology and implementation

The study deployed approximately 25 e-scooters equipped with AI-powered PathPilot devices across Helsinki, focusing on both central and suburban areas over a 12-week period from late July to October. These devices utilised computer vision and sensor fusion to classify infrastructure types (e.g., pavement, bike lane, street), detect surrounding conditions, and trigger real-time behavioural interventions.

The methodology consisted of two phases:

- Phase 1: Baseline period without interventions
- Phase 2: Deployment of behavioural nudges, including audible alerts and speed control mechanisms when riding in restricted areas

In parallel, extensive data collection was conducted, integrating:

- Real-time telemetry data on riding behaviour
- Infrastructure data (e.g., bike lanes, surfaces)
- AI-based detection of pedestrians, obstructions, and potholes

The analysis focused on both citywide patterns and specific neighbourhoods such as Central Railway Station, Esplanadi, Hietalahti, and Töölö, enabling a detailed understanding of local conditions and behavioural dynamics.

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4.3.3 Key results

The study produced several important findings related to rider behaviour, infrastructure, and the effectiveness of safety technologies.

Behavioural change through real-time nudging. The introduction of audible alerts and speed controls was associated with improved riding behaviour. Over the 12-week period, pavement riding decreased while use of appropriate infrastructure increased. For example, the study observed an overall reduction in pavement riding and a shift towards street and bike lane use, indicating that real-time nudges can help guide users toward safer riding practices.

Measurable shift in infrastructure usage. Comparative analysis showed clear changes between the beginning and later phases of the pilot. By the end of the study:

- Pavement riding decreased by approximately 15%
- Street riding increased significantly (about 55%)

These findings suggest a behavioural transition toward more appropriate infrastructure use when supported by technology.

Link between infrastructure quality and user behaviour. The study demonstrated a clear correlation between the quality and continuity of cycling infrastructure and rider behaviour. In areas with well-designed, separated bike lanes (e.g., Esplanadi and parts of Hietalahti), users were more likely to ride correctly and conflicts with pedestrians were reduced. Conversely, in areas with fragmented or low-quality infrastructure (e.g., Central Railway Station or major intersections in Hietalahti), riders frequently shifted to pavements due to perceived safety concerns.

Urban hotspots and conflict zones identified. The data enabled identification of high-risk locations and behavioural hotspots, particularly in dense city centre areas. These insights provide a practical basis for prioritising infrastructure improvements, enforcement efforts, and policy interventions.

Added value of AI-based sensing and data. Beyond behavioural monitoring, the deployed technology can enable:

- Detection of pedestrians and potential conflict situations
- Identification of bike lane obstructions
- Mapping of infrastructure issues such as potholes

This demonstrates the potential of micromobility fleets as mobile sensing platforms to support city maintenance and planning.

4.3.4 Conclusion

The pilot results suggest that AI-enabled sensing and real-time interventions can contribute to safer e-scooter use, particularly when combined with appropriate infrastructure. Importantly, the study reinforces that technology alone is not sufficient: optimal outcomes require a holistic approach integrating infrastructure design, regulation, and user behaviour management. The findings provide valuable input for future urban mobility policies and support the development of data-driven strategies to enhance safety and sustainability in shared micromobility systems.

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4.4 Finland's "Cycling Renaissance" – a data, infrastructure, and policy case study

Modal shift from transport based on fossil fuels to active mobility (walking and cycling) is a key goal in sustainable transport policy. The concept of "cycling renaissance" refers to how this type of modal shift happens after a city supports cycling through investments in cycling infrastructure. After cycling policy was neglected during the intense motorization of the second half of the twentieth century, some cities (mostly in Germany, the Netherlands, and Denmark) resumed their support for cycling, and this resulted in varied but significant increases in the cycling modal share. The "cycling renaissance" assumption has since become established in transport research. This is relevant for the DeMo project precisely because digital technology is absent from this idea. The relevant policy mechanism here is physical infrastructure, not smart devices.

However, the "Cycling Renaissance" does not seem to hold for the case of Finland. This section is an adaptation to the DeMo themes, and a summary, of the doctoral dissertation of Carlos Lamuela Orta (2026). Parts of this article-based dissertation were carried out in connection with the DeMo project. The dissertation has four published articles:

I. 'What are patterns of rise and decline?' Raulo, Aura, Alexis Rojas, Björn Kröger, Antti Laaksonen, Carlos Lamuela Orta, Silva Nurmio, Mirva Peltoniemi, Leo Lahti, and Indrė Žliobaitė. 2023. *Royal Society Open Science, 10*(11), 230052. https://doi.org/10.1098/rsos.230052

II. 'Women's experiences with light rail in a Finnish "smart city": the technological acceleration of public transport vs. daily realities.' Carlos Lamuela Orta & Olli Pihlajamaa. 2025. *Applied Mobilities, 10*(4), 379–396. https://doi.org/10.1080/23800127.2025.2491785

III. 'Helsinki's cycling traffic trend in 2018-2024: overall decline but growth in one cycling highway.' Carlos Lamuela Orta. 2025. *Journal of Cycling and Micromobility Research, 5,* 100075. https://doi.org/10.1016/j.jcmr.2025.100075

IV. 'Bicycles' double learning: combining organization and transport research to explain a cycling paradox in Helsinki.' Carlos Lamuela Orta. 2026. *Transportation Research Interdisciplinary Perspectives, 38*, 102122. https://doi.org/10.1016/j.trip.2026.102122

Cycling data from the city of Helsinki shows that, despite the prominent expansion of its cycling network, cycling traffic has decreased since 2018 (article III). However, one particular route, Pohjoisbaana, has seen a 50% increase in this period. The effects of infrastructure improvements can thus have different effects within the same city or not have any expected effect at all. In this article, the issue of data generation is explored by collecting observations of what type of vehicle (traditional bicycle, e-bike or e-scooter) and what user (child or adult, woman or man) is generating the cycling data. The existing automatic counters do not distinguish between these vehicle and user categories.

In Tampere (article II), the new tram has been a success, despite its lack of multimodal integration with cycling. Tampere presents a possible explanation for the failure of "the cycling renaissance" in Finland by showing how the logic behind public transport modernization does not currently include cycling. The light rail project has been an important factor in the revitalization of the real estate market in Tampere, and more in general of its branding as a modern and economically active city. From this perspective, cycling is not relevant to local boosterism (to policies of economic growth) and this gives a useful theoretical argument as to why the cycling comeback is unlikely to happen. At least not at any relevant scale in relation to the goals of transport emission reduction.

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This is not to say that Helsinki and Tampere are not successful in implementing new cycling routes, or that these routes would fail to attract cyclists. On the contrary. In fact, Helsinki is ranked sixth in a global index of bicycle-friendly cities (Copenhagenize Index, 2025), and Tampere was recently recognized for its cycling improvements and included in the ranking (Haapala, 2025). However, the point is not whether transport strategies result in cycling infrastructure, but whether these changes in the cycling network generate a modal shift. To understand this nuance, it is important to consider the difference between evolution (i.e., long-term change) and progress (planned change resulting in improved situations).

The main question about the evolution of cycling is whether it will regain its past prominence. The conclusion of this doctoral dissertation is that it is very unlikely to recover, given the structural character of the pressures in its “environment”, the transport system as a whole. Since automobility constitutes a mature system that is not synergistic with cycling, it is more plausible that cycling will continue to decline than to see a reverse of the trend.

The tension between cycling and automobility in Finnish municipal planning is explored in article IV, which presents a case study from Helsinki. Drawing from theories in both transport and organisation studies, the interpretation of the Helsinki case is that the cycling infrastructure innovation known as “cycling highway” (i.e., *baana* in Finnish) reveals how, in fact, cycling planning is used to support the status quo of car mobility. Furthermore, cycling planning has learned from car planning, as a way for the planning organisation to cope with sustainability paradoxes, given new and contradictory goals (e.g., *not* reducing car access and at the same time prioritising cycling). Here, a planning culture that avoids conflict has also precluded innovation (e.g., using tactical urbanism, which could be combined with smart devices into smart and tactical living labs).

In article I, the question of single-peak (unimodal) patterns is considered with a multidisciplinary approach. If the unimodal hypothesis holds true for cycling, instead of a cycling renaissance what we have is a "dead clade” (i.e., a species that does not fully recover from an extinction event and will eventually disappear because of its “extinction debt”). In the framework proposed in this article, patterns of change are studied with a combined analysis of abundance (i.e., how many entities) and composition (i.e., the features present in those entities). For example, having an electric motor is a feature of electric bikes, and hence these (normal bicycles vs. electric bikes) are different entities with different abundances.

Finally, and most interestingly for the DeMo project, the thesis includes the conclusion that bicycles have barely evolved. The composition of bicycles has not really changed since the “safety bicycle” was established at the end of the nineteenth century (i.e., a normal modern bicycle). An exception is the current electrification trend, although in fact the first patent for an electric bicycle is more than a century old. In any case, digitalization still has not brought a distinguishing character to cycling. In fact, one of the bicycle companies that made a more decisive bet on integrating digitalization with electrification recently went bankrupt (Vanmoof in 2023; see NL Times (2023)).

However, this is not to say that bicycles don’t evolve at all, nor that electric bicycles could not bring with them a different cycle of growth in electrified micromobility. Perhaps the right combination of digital and electric features on the technological side, together with new synergies with public transport and on the organisational side, will change the current trend in Finland. Further research following from DeMo could go in this direction, and include the consideration of how cycling is affected by changing trends in the macro natural-social environment, such as warmer winters, or a low rate of economic growth (or even post-growth scenarios).

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5. Sandbox environment to test data-driven mobility solutions

5.1 Background and motivation

The intersection of data and artificial intelligence (AI) is fundamentally reshaping the mobility domain. As cities become increasingly congested and transportation systems face growing operational, environmental, and societal demands, there is a rising need for data-driven solutions that improve efficiency, safety, and sustainability. Mobility-related data generated by vehicles, sensors, infrastructure systems, and digital services provides detailed insights into traffic patterns, system performance, and user behaviour. AI techniques enable this data to be analysed at scale, supporting prediction, optimisation, and intelligent decision-making.

Despite all this potential, the mobility data landscape remains highly fragmented. Relevant data is distributed across organisations and sectors such as transport, energy, and the built environment, described using heterogeneous formats and governed by different policies. This fragmentation leads to high integration costs, limited data reuse, and slow deployment of new services. The emergence of advanced AI methods further amplifies these challenges, as AI systems require access to high-quality, real-time, and semantically consistent data, while simultaneously increasing demands related to governance, privacy, explainability, and regulatory compliance.

These challenges motivate the need for secure and interoperable environments that enable controlled experimentation with data-intensive and AI-enabled mobility services. Addressing this need was the primary objective of Work package 3 (WP3) in the DeMo project.

5.2 The Mobility data sandbox concept

WP3 established a concept of the Mobility data sandbox as a controlled development and experimentation environment for data-intensive mobility services. The objective was to design, integrate, and evaluate novel service concepts in a secure and flexible setting before deployment in operational systems. The goal is to support sustainable modal shift by enabling data-driven mobility services that reduce emissions and improve the attractiveness of low-carbon transport modes.

The sandbox addresses the fragmentation and complexity of current mobility data ecosystems. Mobility-related data originates from diverse sources, including static public transport schedules (e.g. GTFS, NeTEx), real-time sensor and vehicle data, spatial information related to the built environment, and personal mobility data. These datasets are typically siloed across organisations and domains, governed by different policies, and described using incompatible data models. As a result, combining data across sectors and scaling new services remains challenging.

The Mobility data sandbox is organised as a layered technology stack. At the foundation is the *data layer*, which includes raw data assets and supporting infrastructure such as sensors, vehicle systems, databases, streaming pipelines, and compute resources. Above this, the *data space layer* provides governed publishing, discovery, and access to data products through standardised connectors, metadata catalogues, and policy enforcement mechanisms. On top of the data space layer, *digital twins* provide structured and machine-interpretable representations of mobility systems. Digital twins combine data models, ontologies, and real-time state information to create contextual views of vehicles, infrastructure, and their interactions. This contextualisation layer enables consistent interpretation of data across domains and supports simulation, prediction, and system-level reasoning. The top layer of the stack consists of *AI services*, including analytics, optimisation tools, and AI agents. These services consume governed, semantically enriched data and digital twin context to generate insights, support decision-making, or automate actions. By separating concerns across layers, the sandbox enables modular development, repeatability, and safe evaluation of complex mobility services.

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Figure 12 illustrates the conceptual architecture of the Mobility data sandbox. The architecture is organised as a layered stack consisting of data, data spaces, digital twins, and AI services, complemented by cross-cutting vertical concerns such as secure connectivity, governance, and semantic interoperability. Each layer builds on the capabilities of the underlying layers, enabling a controlled flow from raw data to intelligent action. The following subsections briefly explain each of the layers and verticals presented in Figure 12.

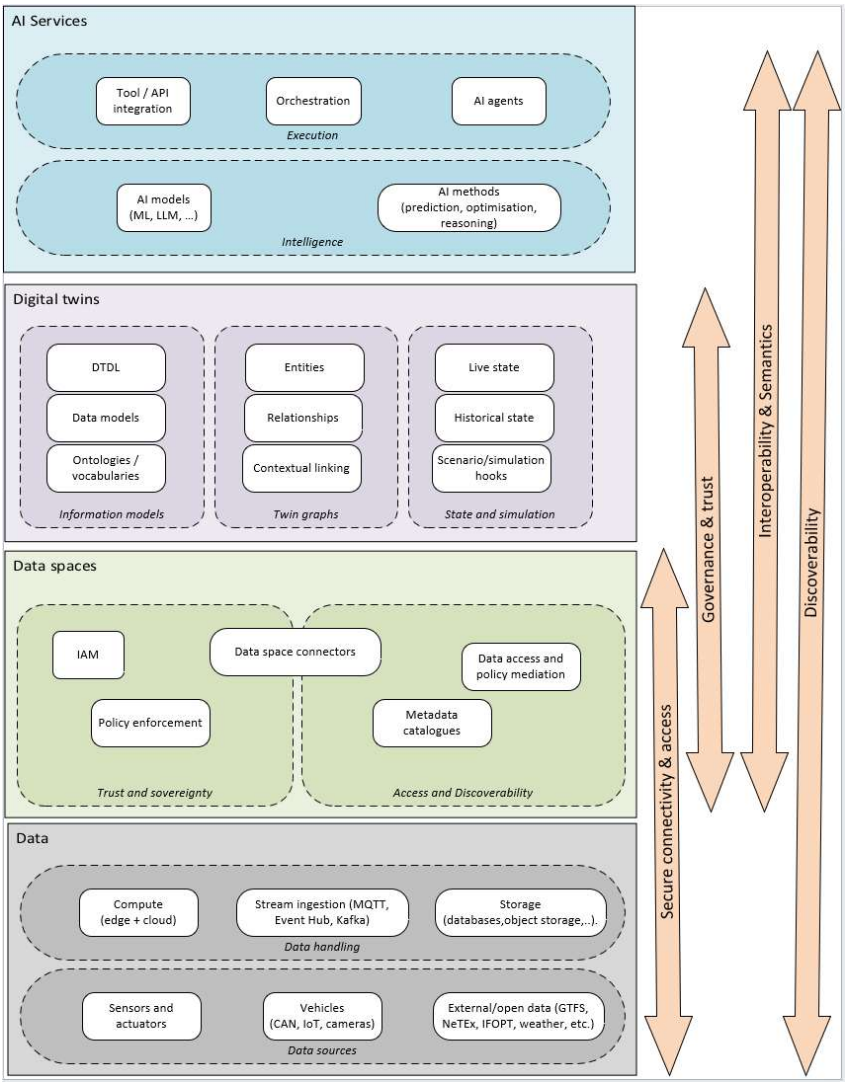


Figure 12. Layered stack architecture for the sandbox, illustrating how data is transformed into AI-enabled services through data spaces and digital twins, with cross-cutting concerns such as governance, interoperability, and secure access spanning all.

5.2.1 Data layer

The data layer forms the foundation of the Mobility data sandbox. It consists of raw and semi-processed data originating from diverse sources, including vehicles, sensors, infrastructure systems, and external digital services. Typical data types include static reference data (e.g. public transport schedules and infrastructure descriptions), real-time streams (e.g. vehicle telemetry, location data, sensor measurements), and historical datasets used for analysis and model training. The data layer also includes the technical infrastructure required for data ingestion, storage, streaming, and basic processing across edge and cloud environments.

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Benefits and potential:

- Provides the primary source of information required by higher layers and AI services
- Enables real-time and historical analysis of mobility systems
- Supports cross-sectoral use cases when data from mobility, energy, and built environment domains are combined
- Allows experimentation with edge-cloud data pipelines, which is essential for time-critical mobility applications

Challenges:

- High heterogeneity of data formats, interfaces, and quality levels
- Ensuring data quality, temporal consistency, and provenance across sources
- Managing scalability and performance, especially for high-volume real-time streams
- Handling privacy-sensitive data already at the lowest layer

5.2.2 Data space layer

The data space layer provides a governed and interoperable framework for publishing, discovering, and accessing data across organisational and sectoral boundaries. It introduces mechanisms for identity management, access control, policy enforcement, and metadata-based discovery, aligned with European data space principles such as the European mobility data space (EMDS), Gaia-X, and IDSA.

Rather than centralising data, the data space enables federated data sharing, where data providers retain sovereignty while authorised consumers gain controlled access. In addition, data spaces are designed to provide a trusted infrastructure for secure and standardized data sharing, which is essential for fuelling sophisticated AI applications. Their use presents both significant opportunities to enhance AI and complex challenges that need to be addressed for successful adoption.

Data spaces can fundamentally transform AI development by addressing the critical need for high-quality, relevant, and diverse data while maintaining data sovereignty and compliance.

A key component is the data space connector, which acts as a trusted intermediary enforcing governance rules. All data access requests, including those originating from AI services, are evaluated against agreed policies before data is released. This ensures that data providers retain control over how their data is used, while enabling authorised consumers to access data in a compliant manner.

Benefits/potential:

- Enables trusted and policy-controlled data sharing across organisations
- Reduces integration effort through standardised connectors, metadata, and APIs
- Facilitates discoverability and reuse of data assets
- Provides a compliance-by-design foundation for AI and analytics services
- Acts as a key enabler for scaling AI adoption in the mobility domain

Challenges:

- Achieving interoperability across different data spaces (inter-data-space interoperability)
- Aligning technical standards, identity models, and semantics across domains

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- Designing and maintaining shared governance models for access, trust, quality, and pricing
- Lowering the onboarding barrier, especially for SMEs and smaller data providers

5.2.3 Digital twin layer

The digital twin layer provides structured, machine-interpretable representations of physical assets, systems, and processes in the mobility domain. Digital twins combine data models, ontologies, relationships, and real-time state information to create contextual views of vehicles, infrastructure, and their interactions. In the sandbox, digital twins act as a semantic and contextual bridge between raw data and AI services, enabling consistent interpretation, simulation, and reasoning across domains.

Benefits and potential:

- Enables semantic interoperability and consistent understanding of data
- Supports system-level reasoning, simulation, and scenario analysis
- Improves decision-making by providing contextualised views rather than isolated data points
- Facilitates advanced use cases such as predictive maintenance, optimisation, and impact assessment
- Reduces risk by enabling safe experimentation in virtualised environments

Challenges:

- Complexity of modelling large and evolving systems
- Integration with legacy systems and heterogeneous data sources
- Managing model evolution and versioning over time
- Ensuring scalability when maintaining large, real-time twin graphs

5.2.4 AI services layer

The AI services layer represents the top of the stack, where data and context are transformed into insights, decisions, and actions. It includes AI models, large language models (LLMs), AI agents, analytics tools, and orchestration mechanisms. AI services consume governed data and digital twin context through controlled interfaces (e.g. MCP-servers) and operate within defined security, safety, and compliance constraints. This layer is where value creation for users, operators, and businesses primarily occurs.

Benefits/potential:

- Enables advanced analytics, optimisation, and intelligent automation
- Supports user-centric mobility services, such as personalised recommendations
- Improves responsiveness and explainability through contextual data access
- Allows rapid experimentation and prototyping of AI-driven services
- Bridges research outcomes with practical applications and business value

Challenges:

- Strong dependence on data quality and semantic consistency
- Ensuring trust, transparency, and explainability of AI outputs

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- Managing regulatory and ethical requirements across the AI lifecycle
- Integrating AI safely into operational and safety-critical environments

5.2.5 Secure connectivity and access vertical

Secure connectivity and access are cross-cutting concerns spanning all layers of the sandbox. It covers network-level security, encrypted communication, identity-aware access, and secure edge-cloud connectivity. Technologies such as VPN overlays and secure messaging protocols provide an additional protection layer beneath logical data space governance.

Benefits and potential:

- Ensures **confidentiality and integrity** of data in transit
- Enables **secure edge-to-cloud communication** for real-time services
- Supports **identity-aware access**, reducing reliance on perimeter-based security
- Simplifies secure collaboration across organisational boundaries

Challenges:

- Additional **operational complexity** in distributed environments
- Dependency on **network reliability and configuration**
- Need to align **network-level security** with higher-level governance mechanisms

5.2.6 Governance, trust and compliance vertical

Governance, trust, and compliance span all layers of the Mobility data sandbox. This vertical addresses data protection (e.g. GDPR), policy enforcement, usage control, auditability, and alignment with emerging regulation such as the EU Data Act and AI Act. Governance is embedded into the architecture rather than treated as an external constraint.

Benefits and potential:

- Enables trustworthy data sharing and AI usage
- Reduces legal and ethical risks through compliance-by-design
- Supports auditability and transparency of data and AI operations
- Increases acceptance of AI-driven mobility services by stakeholders

Challenges:

- Complexity of multi-jurisdictional regulatory environments
- Balancing innovation and compliance without over-restricting experimentation
- Ensuring governance models remain scalable and adaptable over time

5.2.7 Interoperability and semantics vertical

Interoperability and semantics connect all layers by ensuring that data, models, and services are consistently understood across systems and domains. This includes shared data models, vocabularies, ontologies, and mappings between them. Semantic alignment is a prerequisite for cross-sectoral integration and meaningful AI operation.

Benefits and potential:

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- Enables cross-domain data integration and reuse
- Reduces ambiguity and errors in AI training and inference
- Improves portability and replicability of solutions
- Supports alignment with European and international standards

Challenges:

- High effort required to develop and maintain shared semantics
- Managing evolution of models across domains and stakeholders
- Need for both technical solutions and organisational agreement

5.3 Mobility data sandbox proof-of-concept implementation

5.3.1 Purpose and scope of the proof-of-concept (POC) implementation

The POC implementation of the Mobility data sandbox was designed to validate the feasibility and usefulness of the layered sandbox architecture introduced in Section 5.2. Rather than aiming for a complete production-ready platform, the POC focused on demonstrating how data, data spaces, digital twins, and AI services can be integrated into a coherent and reusable development environment.

The implementation was realised through a set of demonstrators carried out in parallel projects and pilot environments. These demonstrators shared a common architectural backbone but addressed different aspects of data-driven mobility services, such as real-time data sharing, vehicle-level intelligence, and AI-enabled analytics. The emphasis was on architectural integration, governance, and interoperability, rather than on optimising individual components.

Sections 5.3.2–5.3.9 describe the high-level sandbox architecture and the implemented components grouped by layers and cross-cutting verticals. Section 5.4 presents selected use-case demonstrators that illustrate how the sandbox enabled concrete services and experiments. Together, these sections provide an implementation-level view of the Mobility data sandbox and its role in supporting data-intensive mobility research and development.

5.3.2 High-level sandbox architecture

The proof-of-concept (POC) implementation of the Mobility data sandbox was designed to validate the layered sandbox architecture introduced in Section 5.2. Rather than implementing a monolithic system, the POC focused on demonstrating how data-driven and AI-enabled mobility services can be developed by composing interoperable components across multiple layers, while maintaining governance, security, and semantic consistency.

At a high level, the implemented architecture follows a data → data space → digital twins → AI services stack, complemented by cross-cutting vertical concerns such as secure connectivity, governance, and interoperability. The implementation integrates edge and cloud environments, enabling real-time data ingestion from vehicles, governed data sharing through data space components, contextualisation via digital twins, and experimentation with AI-based analytics and agents.

The architecture intentionally separates concerns across layers. Raw data ingestion, storage, and streaming are handled independently from data governance and access control. Semantic alignment and contextual modelling are encapsulated in the digital twin layer, while AI services interact with the sandbox through controlled interfaces rather than direct access to underlying data

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sources. This separation allows individual components to evolve independently and supports reuse of the sandbox architecture across multiple demonstrations and pilots.

Figure 13 presents the high-level architecture of the Mobility data sandbox POC, illustrating the main layers, their interactions, and the role of the cross-cutting verticals in ensuring secure, interoperable, and trustworthy operation. The POC implementation did not include all the components specified in the concept model, but rather those that were needed for the selected demonstrators and could be implemented within project constraints. The main components and modules are described in more detail in the demonstrator section (Section 5.4).

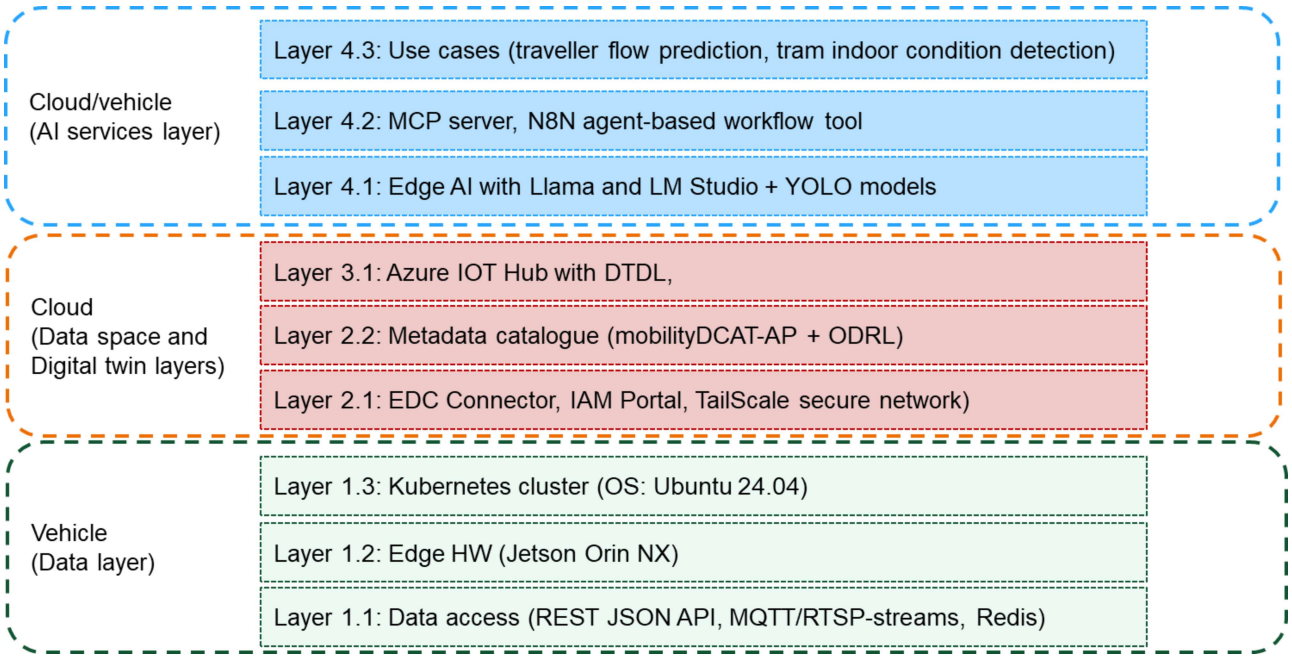


Figure 13. Layered tool stack for the POC implementation of the sandbox, illustrating how data is transformed into AI-enabled services through data spaces and digital twins.

5.3.3 Data layer implementations

In the POC implementation, the data layer provided the foundational data sources and technical infrastructure required for sandbox operation. The focus was on integrating heterogeneous, real-world mobility data rather than exhaustive coverage of all possible data types.

The implemented data layer included:

- Edge cluster for heavy computational AI-services/algorithms
- on-vehicle data sources such as IoT and CAN data from public transport vehicles and service vehicles,
- real-time telemetry streams and event-based data ingestion,
- cloud-based data ingestion, storage, and processing infrastructure,
- support for both real-time and historical data access.

The data layer enabled continuous data flows from vehicles and pilot environments into the sandbox, forming the basis for higher-layer functions. Edge-to-cloud data pipelines were implemented to support time-critical use cases while allowing scalable processing and storage in the cloud.

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5.3.4 Data space layer implementations

The data space layer implemented in the POC provided governed access to data across organisational and system boundaries. Its role was to ensure data sovereignty, policy-controlled access, and interoperability in line with European data space principles. In DeMo, this layer was implemented selectively: some demonstrators used concrete connector-based data sharing components, while others primarily relied on the layer as a target architectural pattern for scaling beyond isolated pilots.

Key implemented components included:

1) *Data space connectors*, acting as trusted intermediaries that enforce access policies and data usage conditions,
2) *Metadata catalogues and vocabulary repositories* supporting discoverability and semantic alignment,
3) *Identity and access control mechanisms* ensuring that only authorised entities can access data,
4) *Integration with an MCP server*, which exposed governed data and functions to AI services in an AI-friendly manner.

The MCP server acts as an abstraction layer between AI services and the governed data space infrastructure. It exposes selected data assets, digital twin context, and available operations in a form that is directly consumable by AI agents and large language models, without requiring them to interact with low-level data space APIs. This design allows AI services to operate within governance constraints while reducing integration complexity and supporting rapid experimentation.

In the proof-of-concept implementation, the MCP server was used primarily as a tool-oriented access gateway for AI agents and large language models. Rather than exposing the underlying data space APIs directly to AI components, the MCP server provided a curated set of read-only tools for discovery and retrieval of approved data products and digital-twin context. This approach reduced integration complexity for AI experimentation while keeping data access aligned with data space governance principles.

The MCP server exposed capabilities such as policy-filtered discovery of available data assets, retrieval of asset metadata (e.g. schema, provenance, temporal coverage and usage constraints), bounded queries over time windows, and access to digital-twin state and relationships for contextual reasoning. In the demonstrators, write operations and actuation were intentionally not enabled through MCP. This ensured that AI experimentation remained separated from operational systems and that the POC focused on validating governed data access and contextualisation.

In the POC, all access to data by AI services was mediated through the data space layer. This ensured that governance rules were enforced consistently and that AI experimentation could be conducted without bypassing data protection or usage constraints. The data space layer served multiple demonstrations simultaneously, illustrating how a shared governance infrastructure can support diverse use cases.

All MCP tool calls were designed to be executed within the same governance boundary as other data consumers in the data space. The data space connector remained the authoritative enforcement point for data provider policies and usage conditions: requests originating from AI services were evaluated against agreed access rules before data was released. The MCP server acted as an additional guardrail layer by restricting available tools, limiting request parameters (e.g. time ranges, fields, and result sizes), and shaping outputs into AI-friendly formats. This layered control ensured that AI services could not bypass the connector's policy enforcement, while still benefiting from a simplified tool interface.

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While the demonstrators focused on read-only access, the Mobility data sandbox concept also supports an “action” path where AI outputs can trigger controlled workflows or operational actions. In such a setup, actuation must be treated as a separate, higher-assurance capability compared to data access. It requires stricter authorisation, explicit policies defining permissible actions, stronger safety controls (e.g. approval workflows, simulation-first validation, and separation of duties), and comprehensive auditability. This distinction ensures that the sandbox can evolve from AI-assisted insights toward automation without compromising safety, accountability, or regulatory compliance.

To support transparency and traceability, the architecture is intended to provide auditable logs at both levels: (i) MCP-level logs capturing which tools were invoked and with which parameters, and (ii) connector-level logs capturing policy decisions and data releases. Correlating these logs enables reconstruction of AI access paths and supports compliance reporting in environments where real-world, potentially privacy-sensitive mobility data is used.

Although data spaces are an essential part of the overall sandbox concept, it should be noted that they were not implemented as a full, end-to-end layer in every DeMo demonstrator. Instead, the extent to which data space components (e.g. connectors, catalogues, and policy enforcement) were used depended on the specific use case, available data sources, and integration constraints. Nevertheless, the data space layer is included here to document the intended target architecture and to highlight the governance and interoperability capabilities required for scaling data-driven mobility services beyond isolated pilots.

5.3.5 Digital twin layer implementations

The digital twin layer was implemented as a contextualisation and semantic alignment layer between raw data and AI services. Digital twins were used to represent vehicles, infrastructure elements, and their relationships in a machine-interpretable form.

The POC implementation included:

- digital twin models defined using Digital Twin Definition Language (DTDL),
- representation of vehicles and mobility assets as part of a connected twin graph,
- integration of real-time state updates from the data layer into digital twin instances,
- exposure of contextualised data and relationships to higher layers.

Digital twins enabled AI services to reason about system state and relationships rather than consuming isolated data streams. They also supported safe experimentation with modelling, transformation, and prediction logic without direct interaction with production systems. While the POC focused on a limited set of digital twin models, it demonstrated how the approach can scale to more complex system-level representations.

5.3.6 AI services layer implementations

The AI services layer represented the top of the POC stack and was the primary consumer of the sandbox capabilities. The focus in DeMo was on enabling experimentation with AI-based analytics and agents in a controlled and compliant manner, rather than on deploying production-grade autonomous services.

To support AI integration, an MCP server is introduced as an AI-friendly interface on top of the data space. The MCP server translates governed data and available functions into formats suitable for AI agents and large language models, abstracting the complexity of underlying data space APIs.

Implemented components included:

1) *AI services and clients* consuming data through the MCP server,

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2) *orchestration mechanisms* for managing AI workflows and agent interactions,
3) *experimentation environments* for analytics, model development, and testing,
4) support for both *cloud-based and edge-based AI processing*.

AI services accessed data and contextual information exclusively through governed interfaces, ensuring that all interactions were auditable and policy-compliant. This design allowed AI models and agents to be tested using real-world data and digital twin context while maintaining separation from operational systems.

In this architecture, the MCP server functions as an AI-oriented tool catalogue and execution gateway on top of the governed data space and digital-twin services. It provides AI agents with a constrained set of machine-callable tools (e.g. data product discovery, metadata retrieval, bounded data queries, and digital-twin lookups) that can be used for planning and reasoning without requiring the AI component to understand or integrate directly with low-level data space APIs.

In the WP3 demonstrators, MCP-mediated access was limited to read-only tools. This design choice was made to maintain strict separation between AI experimentation and any operational actuation, and to minimise the risk of unintended actions when testing early-stage AI agents. The POC therefore validated the feasibility of governed, auditable, and semantically contextualised access for AI services, while leaving actuation capabilities outside the implementation scope.

The Lyyli AI agent demonstrator (Section 5.4) illustrates how these principles extend from read-only AI analytics toward controlled, policy-governed intervention.

5.3.7 Secure connectivity and access

Secure connectivity in the sandbox was realised using encrypted network overlays based on WireGuard technology. A software-defined VPN overlay (TailScale) was used to interconnect edge devices, cloud services, data space components, and AI services into a single private network, independent of their physical location.

This approach enabled identity-aware, peer-to-peer connectivity between sandbox components without exposing services to the public internet. The network overlay simplified secure edge-to-cloud communication and reduced the need for complex firewall and network configuration across organisational boundaries. By separating network-level security from application-level governance, the sandbox ensured that all data flows were encrypted in transit while higher-level access control and policy enforcement remained the responsibility of the data space layer.

The sandbox security model follows a *zero-trust* approach. In a zero-trust model, no component, user, or network segment is trusted by default, even if it is located inside a private network or within an organisational boundary. Instead, every access request is continuously evaluated based on explicit identity, context, and policy. In practice, zero trust replaces perimeter-based assumptions (“inside the network = trusted”) with a model where trust is established dynamically and minimally for each request.

Zero trust is particularly important when integrating **AI agents and large language model (LLM) based services.** Unlike traditional applications with fixed call patterns, AI agents can generate tool calls dynamically based on prompts, retrieved context, or intermediate reasoning steps. This creates new attack and misuse paths (e.g., prompt injection, over-broad tool use, and unintended data exposure) that cannot be sufficiently mitigated by network isolation alone. As a result, AI-agent access must be governed as if it were coming from an untrusted environment, and all actions must be restricted to the minimum necessary scope.

In the Mobility data sandbox, this means that AI agents do not access data sources directly, and “being connected” to the sandbox network does not grant implicit permission. Instead, access is mediated through governed interfaces such as data space connectors and the MCP-based tool

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gateway, where requests are authenticated, authorised, and constrained. Zero-trust is realised through strong, verifiable identities for services and organisations (e.g., certificate-based identities and verifiable credentials), policy-based access control at the connector level, and additional guardrails at the AI-facing gateway (e.g., restricting available tools, limiting query parameters, and shaping responses). This layered enforcement supports data sovereignty and prevents AI services from bypassing usage policies even when the underlying infrastructure is shared across projects and organisations.

Finally, zero trust supports accountability, which is essential for compliant AI operation. Because AI agents can act at scale and execute sequences of actions quickly, the architecture must provide end-to-end traceability of what the agent accessed and why. A zero-trust approach therefore emphasises auditable interactions (who invoked which tool, with what parameters, under which policy decision, and what was released), enabling monitoring, incident response, and compliance reporting when real-world and potentially privacy-sensitive mobility data is used.

5.3.8 Governance, trust, and compliance

Identity and access management (IAM) was a core element of governance in the sandbox. All participating services and organisations were authenticated using strong, certificate-based identities rather than shared credentials. In the data space context, identities were represented using verifiable digital credentials and decentralised identifiers (DIDs), enabling machine-to-machine trust establishment without relying on centralised user accounts.

In the deployEMDS demonstrator, certificate-based identities were used to authenticate data space connectors and establish trust relationships between data providers and consumers. These identities were used by the data space infrastructure to evaluate access requests against usage policies before data was released. This approach demonstrated how IAM, cryptographic identities, and policy enforcement can be combined to support GDPR-compliant and auditable data sharing for AI-enabled mobility services.

5.3.9 Interoperability and semantics

Semantic interoperability in the sandbox was supported through the use of explicit digital twin models defined using the Digital Twin Definition Language (DTDL). DTDL models were used to describe vehicles, sensors, and infrastructure assets in a structured and machine-interpretable form, including their properties, telemetry, and relationships.

In the proof-of-concept implementation, real-time telemetry from vehicles and devices was ingested through an IoT integration layer and mapped to corresponding digital twin instances. This enabled consistent interpretation of data across services and allowed AI components to interact with semantically enriched representations rather than raw data streams. The use of standardised digital twin models reduced ambiguity, improved reuse across demonstrators, and provided a stable interface between the data layer and AI services.

5.4 Use-case demonstrators enabled by the Mobility data sandbox

To validate the Mobility data sandbox architecture in practical settings, WP3 supported several demonstrator use cases implemented in parallel projects and pilots. These demonstrators were not isolated implementations but shared the same architectural principles and sandbox components, illustrating how a common, layered infrastructure can support diverse mobility services. In DeMo, the main contribution was to define the sandbox concept, validate its layered architecture, and demonstrate how selected components could be reused across related mobility R&D activities.

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The following subsections describe the main demonstrators and highlight how the sandbox enabled their development and evaluation.

5.4.1 Lyyli Living Lab demonstrator

The Lyyli Living Lab served as the primary real-world experimentation environment for the Mobility data sandbox. Lyyli is an operational tram-based living lab deployed in Tampere, integrating data from public transport vehicles and supporting systems into a shared research and development environment.

Within the sandbox, the Lyyli demonstrator validated the end-to-end data flow from on-vehicle data sources to governed access and analytics. Data assets included real-time vehicle telemetry, environmental measurements, positioning data, and selected passenger-related information streams. These data were ingested into the sandbox infrastructure and made available through controlled interfaces for analytics and AI experimentation.

The Lyyli demonstrator showed how a living lab environment can be connected to a data space-based sandbox architecture, enabling multiple projects to reuse the same data foundation. The implementation also highlighted practical challenges related to data ownership and privacy, as some datasets originate from external stakeholders and are subject to GDPR constraints, particularly for camera-based data. Despite these constraints, Lyyli demonstrated the feasibility of continuous data collection and experimentation in an operational public transport environment.

5.4.2 OPTIPEX WP4 demonstrators

The OPTIPEX EU project WP4 demonstrators focused on adaptive and AI-driven public transport services, with particular emphasis on vehicle-level intelligence and edge computing. The work defined and validated a layered vehicle architecture that integrates physical infrastructure (sensors, interaction devices, vehicle ICT systems) with digital infrastructure supporting data access, interoperability, and control logic.

Within the Mobility data sandbox, OPTIPEX WP4 activities contributed use cases and requirements related to AI-enabled perception, interaction, and adaptation in tram and shuttle bus environments. The sandbox provided a controlled environment for testing how vehicle-level data and contextual information can be exposed through governed interfaces and consumed by higher-level services.

The OPTIPEX service concept demonstrators further explored adaptive vehicle technologies and infrastructure integration. These demonstrators relied on real-time data acquisition, semantic modelling, and AI-based analytics to support passenger-centric services and vehicle adaptation scenarios. The sandbox architecture enabled these experiments by separating data ingestion, governance, contextualisation, and AI logic, allowing vehicle-level innovation without tight coupling to backend systems.

5.4.3 deployEMDS Tampere real-time data sharing demonstrator

The deployEMDS Tampere demonstrator focused on implementing a data space-based approach for sharing real-time mobility information in an urban context. Tampere acted as a deployment site within the deployEMDS project, contributing to the development of a decentralised technical infrastructure and common governance mechanisms for urban mobility data spaces.

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In this demonstrator, the Mobility data sandbox was used to implement and test data space connectors for sharing real-time information related to public transport and traffic conditions in Tampere. The shared data included tram-related information and other mobility-relevant datasets, exposed through standardised interfaces aligned with European data space specifications. The implementation demonstrated how local data sources can be connected to a wider European data space infrastructure while maintaining local control and compliance.

The Tampere deployEMDS demonstrator validated the feasibility of using connector-based architectures to support interoperability between city-level data platforms, national access points, and European-level data spaces. It also highlighted the importance of clear governance models and onboarding processes when extending data sharing beyond local pilots.

5.4.4 Lyyli AI agents for intelligent tram monitoring and data interaction

As a fourth AI application demonstrator within the sandbox environment, AI agents were implemented on the Lyyli Mobility data platform operating on the Lyyli Living Lab tram in Tampere. The platform collects real-time and historical sensor data covering passenger counts, vehicle location, cabin environmental conditions (temperature, humidity, CO_2), and vehicle telemetry. The objective of this demonstrator was to evaluate how AI agents can be deployed on top of an existing mobility data platform to improve data accessibility and enable proactive monitoring, without interfering with core data ingestion or operational systems. In DeMo, this demonstrator provided a concrete testbed for validating how governed data access and AI services can be combined in a live mobility research environment.

While the core sandbox POC focused on read-only AI access, the Lyyli demonstrators extended this model by exposing carefully scoped actuator tools through MCP, illustrating a controlled path toward AI-assisted intervention.

5.4.4.1 Agent 1: Lyyli Data assistant

The first agent, Lyyli Data assistant, provides a conversational interface allowing users to query tram sensor data using natural language. Users can ask questions such as average passenger counts over a selected period, cabin temperature trends, or identification of peak CO_2 levels.

The agent translates natural-language queries into structured database queries using a controlled AI-data interface based on the Model Context Protocol (MCP). Queries are executed against historical sensor data, and results are returned in a human-readable form. This demonstrator shows how AI can significantly lower the barrier to exploiting complex mobility datasets, enabling researchers and operators to access insights without direct database access or query expertise. Figure 14 shows the Lyyli Data assistant agent user interface.

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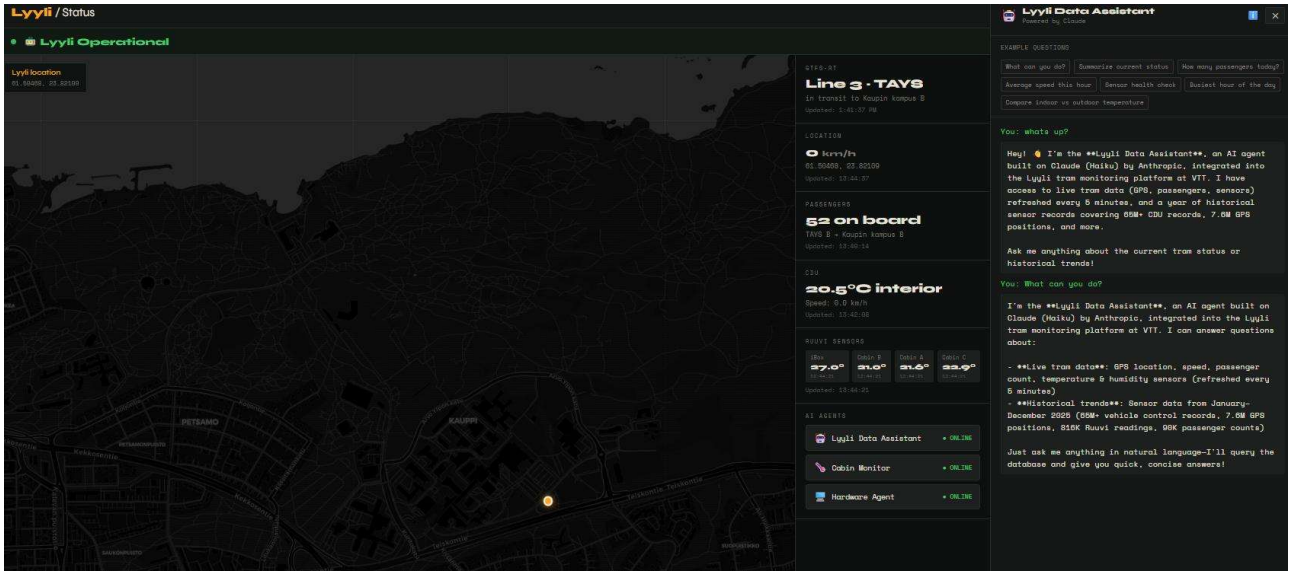


Figure 14. Lyyli Data assistant agent user interface.

5.4.4.2 Agent 2: Lyyli Cabin comfort monitor

A second AI agent was implemented to take a proactive and autonomous monitoring role following a closed-loop sense-reason-act pattern. The Cabin comfort monitor continuously observes cabin temperature, humidity, CO_2 levels, and passenger occupancy through a structured data interface exposed via the MCP. MCP serves as the agent's governed access layer, providing read-only sensor data and controlled action interfaces without granting the AI direct access to underlying databases or systems.

The agent operates in a control loop where incoming observations are periodically evaluated against predefined thresholds and contextual factors, such as passenger load and vehicle operational state. When abnormal or degrading conditions are detected, a large language model is invoked to reason over the situation, assess likely causes and severity, and select an appropriate response based on the available context.

Agent actions are executed exclusively through MCP-exposed actuator tools, which define a restricted and auditable set of interactions with the environment. These include generating structured alerts, notifying the driver or control centre, escalating issues to maintenance, or adjusting monitoring parameters. By exposing actuators as MCP tools, all AI-initiated actions remain policy-controlled, traceable, and decoupled from the AI model itself.

Alerts and agent-initiated actions are distributed through the platform's messaging infrastructure and visualised on the operational status interface. This demonstrator illustrates how AI agents can combine contextual reasoning with controlled actuation, enabling continuous situation awareness and responsive intervention in public transport environments while maintaining governance and operational safety. Figure 15 shows the Lyyli Cabin comfort monitor agent user interface.

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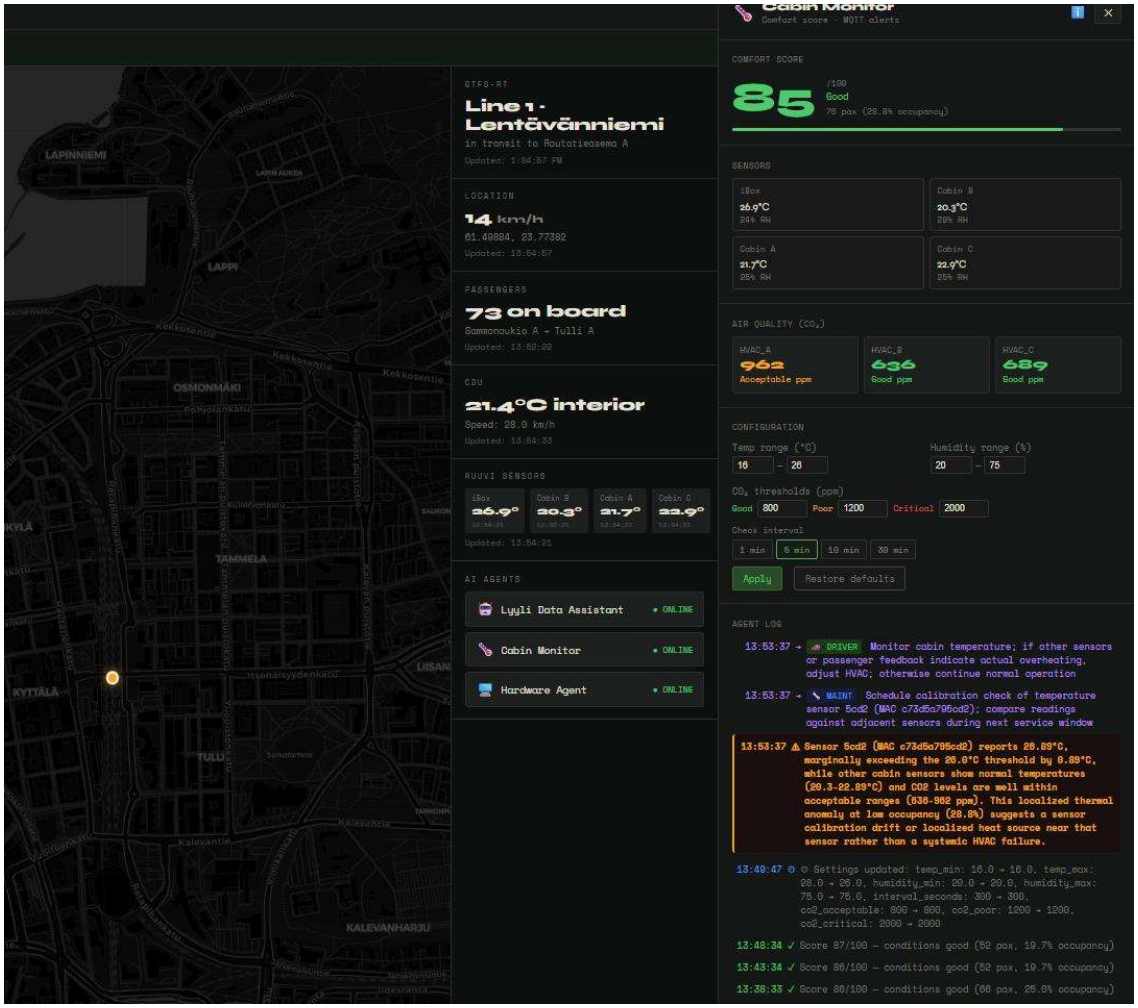


Figure 15. Lyyli Cabin comfort monitor agent user interface.

5.4.4.3 Agent 3: Lyyli Hardware monitor

The Lyyli Hardware monitor agent was implemented as an autonomous hardware-level monitoring agent operating according to a closed-loop sense-reason-act model. The agent continuously monitors onboard computing and sensor hardware telemetry, such as device availability, resource utilisation, data freshness, and communication health, through MCP-exposed data tools that provide a governed and structured view of the underlying systems.

The agent evaluates these observations in a control loop, detecting anomalies such as missing data streams, delayed sensor updates, or degraded system performance. When abnormal behaviour is identified, a large language model is invoked to reason over the operational context, infer likely failure modes, and assess the severity and urgency of the situation.

Agent responses are executed exclusively through MCP-exposed actuator tools, which define a restricted and auditable set of hardware-level actions. These actions include issuing structured status messages, notifying the driver or control centre, triggering service restart procedures, or escalating issues to maintenance. By exposing hardware interactions as MCP tools, all AI-initiated actions remain policy-controlled, traceable, and decoupled from the AI model itself.

This demonstrator shows how AI agents can support resilient operation of edge computing and sensor infrastructure by combining contextual reasoning with controlled actuation, enabling early

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detection and response to hardware-level issues in real-world mobility environments. Figure 16 shows the Lyyli Hardware monitor agent user interface.

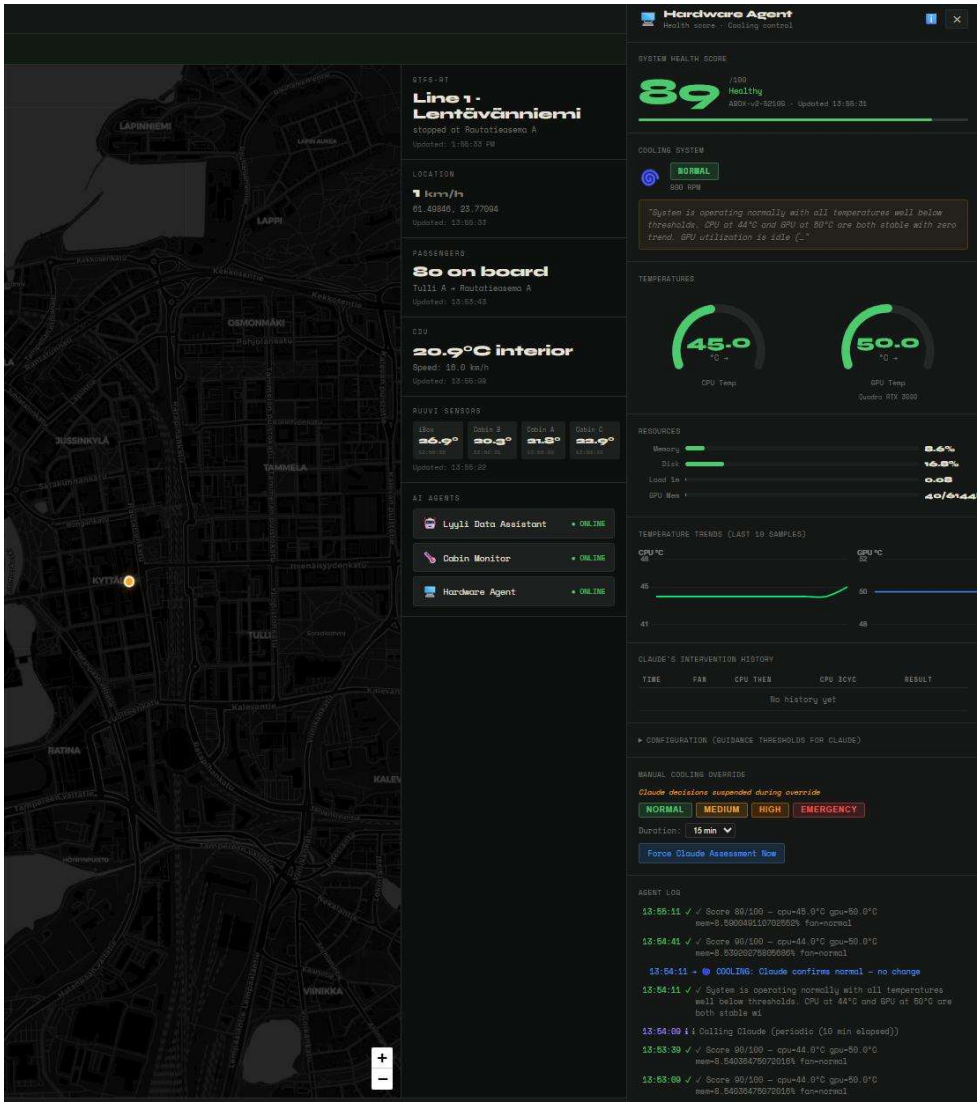


Figure 16. Lyyli Hardware monitor agent user interface.

5.4.4.4 Cross-demonstrator observations

Across all demonstrators, the Mobility data sandbox proved effective as a shared enabling infrastructure rather than a project-specific platform. Lyyli, OPTIPEX, and deployEMDS activities reused the same architectural principles while addressing different aspects of data-driven mobility services, from vehicle-level intelligence to cross-city data sharing.

These demonstrators collectively showed that:

- a layered sandbox architecture supports parallel experimentation across projects,
- data space-based governance enables controlled reuse of real-world data,
- digital twins and semantic alignment improve AI usability and reliability,

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- integration with operational environments is feasible when governance and security are embedded by design.

The lessons learned from these demonstrators are synthesised in Section 5.5. In addition to demonstrating technical feasibility, the Lyyli AI agent deployment provided concrete operational, architectural, and security-related insights. These lessons informed both the refinement of the sandbox architecture and the practical requirements for deploying AI agents alongside live mobility systems and are summarized in the following section.

5.5 Lessons learned and further research

5.5.1 Lessons learned from the Mobility data sandbox implementation

The Mobility data sandbox demonstrated that a layered, data-space-based architecture provides a robust foundation for developing and testing data-intensive and AI-enabled mobility services. Several key lessons emerged from the proof-of-concept implementation and associated demonstrators.

1) Ensuring seamless interoperability both within a data space (intra-data space) and across different domain-specific data spaces (inter-data space) is not achievable yet. This involves aligning technical standards, communication protocols, identity management, and, most critically, semantic interoperability, ensuring that data models and APIs from different sources are consistently understood.
2) Developing and maintaining common governance models (for access policies, pricing, trust, and quality) across different domains and jurisdictions is highly complex. The governance of data spaces must also intersect effectively with the newer discipline of AI governance to ensure the entire AI lifecycle is compliant and ethical.
3) Simplifying and automating access/onboarding for participants, especially smaller entities (SMEs), is essential for widespread adoption. Scaling data spaces requires robust, decentralized infrastructure and a clear roadmap for migration and evolution of existing systems. In addition, for SMEs and public organisations, the connector-as-a-service model is usually a more practical approach (compared to on-premises approaches). The sandbox should be able to host connector deployments for ecosystem participants.
4) Data spaces enable controlled reuse of real-world data. The implementation showed that data space concepts – such as federated access, policy enforcement, and metadata-based discovery – are essential for enabling reuse of operational data in research and innovation contexts. By mediating access through connectors and governed interfaces, the sandbox allowed AI experimentation without compromising data sovereignty or regulatory compliance. This was particularly important when working with real-time and privacy-sensitive mobility data.
5) Semantic models and digital twins are critical enablers for AI. The demonstrators confirmed that AI systems benefit significantly from semantically enriched and contextualised data. Digital twins, implemented as structured models with explicit relationships and real-time state, reduced ambiguity and improved the usability of data for analytics and AI services. Without this contextual layer, AI integration would have required extensive case-specific data preparation, reducing scalability and reuse.
6) Governance must be embedded by design. Governance, trust, and compliance cannot be retrofitted after technical solutions are built. The sandbox architecture demonstrated that embedding access control, usage policies, and auditability directly into the data space layer enables safe experimentation while maintaining stakeholder trust. This approach also reduced friction when integrating data from multiple projects and organisations.

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7) AI experimentation benefits from separation of concerns. Separating data ingestion, governance, contextualisation, and AI services into distinct layers proved valuable for managing complexity. AI developers were able to focus on model behaviour and service logic, while data providers retained control over how data was accessed and used. This separation supports parallel development and reduces coupling between components.

5.5.2 Lessons learned from AI agent deployment (Lyyli platform)

The separation of AI workloads into a dedicated execution environment proved to be a sound architectural decision. Running the AI agents on a separate server with an independent database replica ensured that experimental AI services did not interfere with the stability or performance of the primary data ingestion platform. This isolation significantly simplified iterative development and fault recovery.

Container-based deployment enabled rapid iteration and controlled restarts, supporting experimentation with different agent logics and configurations. The use of large language models in combination with MCP-based data access proved effective for natural-language interaction with mobility data, producing reliable structured queries from both Finnish and English questions.

5.5.3 Limitations identified during the project

While the Mobility data sandbox achieved its primary objectives, several limitations were identified.

1) First, the scope of implemented digital twins was intentionally limited. Although the POC demonstrated the feasibility of digital twin-based contextualisation, scaling to comprehensive, city-wide system models would require additional effort in modelling, data harmonisation, and lifecycle management.
2) Second, data availability and ownership constraints limited the range of experiments. Some potentially valuable datasets, particularly camera-based and passenger-related data, were restricted due to privacy and ownership considerations. This underlines the importance of continued work on privacy-preserving analytics and AI techniques.
3) Third, the operational maturity of data space components varied across demonstrators. While connector-based sharing worked well in controlled settings, onboarding new participants and aligning governance models remains resource-intensive. Further simplification and automation are needed to support wider adoption.
4) Fourth, the separation of system components across different virtual networks complicated integration between the operational portal and the AI services, and required additional design effort to enable secure cross-component interaction. This highlights the importance of validating network reachability and trust boundaries early in AI-enabled system design.

5.5.4 Implications for future mobility platforms

The results suggest that future mobility platforms should be designed as modular, layered systems rather than tightly coupled applications. Data spaces should be treated as a core infrastructural component, enabling trusted data exchange across sectors and projects. Digital twins and semantic models should be considered foundational for AI-enabled services, not optional extensions.

The sandbox also highlighted the importance of aligning technical architectures with emerging European regulation, including the Data Act, AI Act, and the European mobility data space. Architectures that embed governance and compliance by design are better positioned to evolve alongside regulatory frameworks.

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5.5.5 Security considerations

Layered access control was essential for safely deploying AI agents alongside live mobility systems. Network-level restrictions, authenticated service endpoints, and fine-grained messaging permissions together formed a defence-in-depth approach. A security review identified and corrected configuration gaps early, demonstrating the value of continuous security validation even in restricted environments.

The deployment also highlighted that exposing AI services through controlled network boundaries is feasible but requires careful consideration if access is to be expanded beyond internal research use. Future deployments would need stronger transport-level security and identity management if external access is required.

5.5.6 Directions for further research and development

Based on the lessons learned, several directions for further research are identified.

1) *Scaling digital twins and semantic models*. Future work should investigate methods for scaling digital twin representations from individual assets to system-level and city-level models, including lifecycle management, versioning, and automated model alignment.
2) *Privacy-preserving AI and data analytics.* Research is needed on techniques that enable advanced AI analysis while respecting privacy constraints, such as edge AI, federated learning, and synthetic data generation. These approaches are particularly relevant for mobility contexts involving personal and behavioural data.
3) *Operationalisation of data spaces*. Further development is required to simplify onboarding, automate governance processes, and integrate data spaces with existing city and national data platforms. This includes tooling, best practices, and reference implementations.
4) *AI governance and explainability.* As AI systems increasingly influence operational decisions in mobility, research should focus on explainability, accountability, and lifecycle-level governance of AI services operating on shared data infrastructures.

5.5.7 Concluding remarks

The Mobility data sandbox provided a practical blueprint for how cities, researchers, and industry can collaborate on data-driven mobility innovation. By addressing data fragmentation through data spaces, enabling safe experimentation with digital twins, and supporting AI-enabled services in a governed environment, the sandbox contributes to the broader goal of accelerating sustainable, low-carbon mobility solutions.

A key practical lesson was the effectiveness of using large language models both for reasoning about mobility system state and as development support tools during implementation. However, the most important architectural takeaway is the need to address infrastructure connectivity and trust boundaries at an early stage. Decisions about network segmentation and access paths significantly shape the feasible design space for AI agent integration and should be treated as first-class design concerns.

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6. Collaboration and business models to enable modal shift

One aspect of the DeMo project was to investigate collaboration and business models that would enable sustainable modal shift. As part of this work a literature review of stakeholder engagement (Section 6.1) was conducted. Furthermore, current challenges, barriers and opportunities related to collaboration and business models (Section 6.2) were identified from stakeholder interviews. As the interviews and stakeholder engagement literature suggested that collaboration and ecosystemic business models are needed to enable the data-driven modal shift, literature review on collaborative business models was conducted (Section 6.3). Section 6.4 synthesises these materials into recommendations.

6.1 Stakeholder engagement framework to advance urban mobility

6.1.1 Stakeholders in urban mobility

Stakeholder is a term that comprises individuals, groups and organisations that are affected by a project or plan, or who can influence its implementation (Lindenau & Böhler-Baedeker, 2014). In their manuscript, (Gonzalez-Feliu et al., 2018) categorize the different mobility stakeholders into *space users* and *space organisers* that need to be considered when implementing changes in mobility systems. **Space users** consist of generators of mobility demand, including *residents*, *economic activities* that attract work, shopping or leisure trips, *non-economic activities* such as historical monuments, parks, or sports areas, *transport operators*, and *interface roles* that connect operators to the generators of demand. **Space organisers**, on the other hand, comprise *public authorities with a legislative role*, public or private *stakeholders with a technical or expert role* (e.g., planning or consulting agencies), *professional bodies giving general advice* (e.g., trade associations, federations, industry clusters), and *decision support roles* (e.g., research organisations, sustainable development agencies).

Within the context of urban mobility, the different stakeholders can have differing, and sometimes conflicting goals. Governmental stakeholders, such as city representatives, strive towards strategic goals related to social and environmental sustainability, such as reduced congestion, emissions, and inequality. These interests, however, can juxtapose with the interests of other, non-governmental stakeholders, such as service providers and citizens who might not approach mobility issues from a strategic viewpoint but instead have more immediate and personal interests, such as convenience, profitability, or affordability (van der Linde et al., 2021). Additionally, different stakeholders may lack the capacity or willingness to understand and accommodate the interests of other stakeholders, leading to tensions in urban mobility development. To overcome these problems and find shared visions, stakeholder participation is essential when introducing new urban mobility service offerings.

6.1.2 Means for stakeholder participation

Stakeholder involvement processes serve a dual purpose: they can be considered a goal or a means (van der Linde et al., 2021). From the perspective of **stakeholder involvement as a goal**, it is used to empower different stakeholders, to build relationships and trust, increase possibilities to reach consensus and the legitimacy of different mobility policies and measures (van der Linde et al., 2021). On the other hand, from the perspective of **stakeholder involvement as a means**, it is

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used to enrich mobility planning by gathering knowledge and perspectives on the area from different domains. Therefore, from this perspective, stakeholder innovation fosters innovation, elucidates on the different societal needs and promotes synergies between different sectors (van der Linde et al., 2021).

The means for engaging stakeholders vary according to the underlying purpose of stakeholder participation. From the perspective of stakeholder participation as a goal, participation can, at one extreme, mean mere information provision. On the other extreme, power can be delegated to stakeholders so that they can make decisions on behalf of the entity that is engaging stakeholders (Petts & Leach, 2000). Accordingly, four different levels of stakeholder participation can be identified (Baker et al., 2010; Petts & Leach, 2000) that vary according to the degree to which participation is a goal in itself or a means for fostering innovation and identifying the different societal needs. On level 1, stakeholder engagement is concerned with *information provision and education* with the aim of satisfying the statutory requirements to consult, increase transparency of actions, to change stakeholder views, and to empower citizens (Baker et al., 2010; Petts & Leach, 2000). Level 1 participation methods include the likes of leaflets, newsletters, unstaffed exhibits, introductory videos, and site visits (Baker et al., 2010). On level 2, information provision is accompanied by the possibility to gather stakeholder feedback, with the additional aim of improving services, and to determine stakeholder needs and desires (Petts & Leach, 2000). On level 2, the participation methods include the likes of staffed exhibits, public meetings, and surveys (Baker et al., 2010; Petts & Leach, 2000). On level 3, the stakeholders are involved and consulted. At this level, the aims of stakeholder participation are similar to those on level 2, while the methods, including e.g., workshops, focus groups and open forums are more interactive and collaborative, potentially influencing the decision-making process to a greater extent. Finally, level 4 entails extended involvement to foster innovation and social learning using e.g., liaison groups, collaborative visioning, and community committees. The four levels of stakeholder participation are illustrated in Table 5.

Table 5. Stakeholder participation typology (adapted from (Baker et al., 2010; Le Pira et al., 2016)).

Level 1. Information provision and education • Purpose: Satisfy requirements, increase transparency, change stakeholder views, empower stakeholders • Example means: leaflets, brochures, media coverage, site visits, unstaffed exhibitions, advertising	**Level 2. Information provision feedback** • Purpose: service improvement, determining stakeholder needs and desires (in addition to level 1 purposes) • Example means: staffed exhibitions, public meetings, surveys, polls
Level 3. Involvement and consultation • Purpose: service improvement, determining stakeholder needs and desires (in addition to level 1 purposes) • Example means: workshops, focus groups, open forums	**Level 4. Extended involvement** • Purpose: fostering innovation, empowerment, social learning (in addition to level 1 purposes) • Example means: community committees, liaison groups, visioning

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6.1.3 Sustainable mobility service collaboration framework

Stakeholder engagement and participation is one of the key elements in planning and developing urban mobility (Lindenau & Böhler-Baedeker, 2014). In addition to service providers and operators, mobility touches a variety of groups and organisations, including economic activities and public sector services. Most notably, however, developments in urban mobility touch the citizens. This has led to a notion that transportation planning does not happen in a vacuum, and consequently, efforts to boost stakeholder engagement in urban mobility development have been implemented in many areas (Bulckaen et al., 2016; van der Linde et al., 2021). For example, in the European Union, the Sustainable Urban Mobility Planning concept is based on the principle of involving citizens early in the planning process as opposed to informing of the plans after they are completed (Lindenau & Böhler-Baedeker, 2014).

These stakeholders, however, often have differing and sometimes conflicting interests and perceptions of what constitutes a success or failure in a mobility project. While sustainable mobility has been established as the explicit aim of mobility planning and policy, its exact meaning remains ambiguous and how it is understood varies among the different stakeholders (Bulckaen et al., 2016). Moreover, in many cases stakeholders from different domains and sectors tend to engage and collaborate with actors within their own social, professional, institutional, or spatial niches (Puerari et al., 2018). These disconnections in cross-sectoral collaboration and in the perceptions of what constitutes sustainable development are some of the key barriers in realizing collaborative development efforts in urban mobility.

The need for cross-sectoral dialogue and shared visions of sustainable urban mobility is particularly prevalent for new forms of mobility that influence the cityscape, impacting how public space is used and perceived. As exemplified by the recent developments in micromobility services, the introduction of new mobilities in urban settings is far from unproblematic. The rapid introduction of e-scooter sharing systems that in many cases happened in the absence of appropriate regulatory frameworks, policies, and stakeholder dialogue, resulted in problems due to lack of dedicated infrastructure, accidents, conflicts regarding public space usage, and their environmental impacts. Moreover, it remains unclear whether new urban mobilities, such as rideshare e-scooters, contribute to sustainable urban mobility as current evidence suggests that they mainly replace sustainable options such as walking or public transport (Mladenović et al., 2022). These issues have resulted in negative media coverage for service providers, post-hoc restrictions for e-scooter use, and even banning them in certain cities. Currently, there exists little research on how to successfully engage stakeholders so that new mobility services, such as e-scooters, could be integrated within the existing settings towards more sustainable and inclusive urban mobility (König et al., 2022).

To address the shortcomings of engaging various stakeholders in the deployment of new urban mobility services, we identified clear pitfalls and good practices from literature:

Clear pitfalls:

- **Laissez-faire implementation:** Launching services without municipal dialogue can damage reputation, generate negative media coverage, and lead to post-hoc bans or strict restrictions (König et al., 2022).
- **Citizen exclusion:** Excluding citizens from the introduction process can reduce legitimacy, damage reputation, and generate negative media coverage (König et al., 2022).
- **Lack of strategic alignment:** Non-governmental actors may focus on short-term operational or commercial goals instead of broader sustainable mobility objectives (van der Linde et al., 2021).

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- **Selective participation:** Engagement processes may overrepresent already interested citizens and underrepresent less active or more vulnerable groups (van der Linde et al., 2021).
- **Dominance of vocal actors:** The loudest or most organised participants may disproportionately influence outcomes, reducing the representativeness of decisions (van der Linde et al., 2021).

Good practices:

- **Co-developed quality standards:** Establish quality standards together with municipalities and commit service providers to meeting them (König et al., 2022).
- **Cross-city harmonisation:** Harmonise quality standards across cities to reduce fragmentation and support scalable service deployment (König et al., 2022).
- **System integration:** Integrate new services with existing transport modes rather than treating them as separate systems (König et al., 2022).
- **Collaborative regulation:** Work with cities in policy creation and regulation to ensure that service deployment supports public goals (Latinopoulos et al., 2021).
- **Early citizen involvement:** Involve citizens, social associations, and citizen representatives early in the introduction process (König et al., 2022; Sopjani et al., 2019).
- **Public transport operator involvement:** Include public transport operators in planning and implementation to ensure operational fit and multimodal integration.
- **Sociodemographic analysis:** Collect sociodemographic data to identify underrepresented groups and design policies that attract them (Latinopoulos et al., 2021).
- **Spatiotemporal analysis:** Collect spatiotemporal data to identify modal-shift potential, safety implications, and location-specific service needs (Latinopoulos et al., 2021).
- **Diverse user involvement:** Engage both hesitant users and ambassador-type users early to identify barriers, improve services, and support wider adoption (Sopjani et al., 2019).
- **Clear participation purpose:** Define whether participation is used as a means to foster innovation and gather knowledge or as a goal to build legitimacy, trust, and empowerment (van der Linde et al., 2021).
- **Purpose-based participant selection:** Select participating citizen groups according to the purpose of engagement, such as including people with mobility difficulties when accessibility is central (Lindenau & Böhler-Baedeker, 2014).
- **Continuous stakeholder dialogue:** Involve stakeholders from the beginning and maintain dialogue throughout planning, deployment, and evaluation (Lindenau & Böhler-Baedeker, 2014).
- **Systematic stakeholder mapping:** Map stakeholders and analyse their interests to identify potential conflicts and support balanced decision-making (Lindenau & Böhler-Baedeker, 2014).

Building on this prior research and interviews with public and private actors, we propose a model that enables urban smart mobility co-creation and evaluation and provides a method to

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systematically account for the diverse needs and interests of mobility stakeholders. Overall, the proposed model supports future efforts to develop inclusive and sustainable urban mobility services. The model is presented in Figure 17.

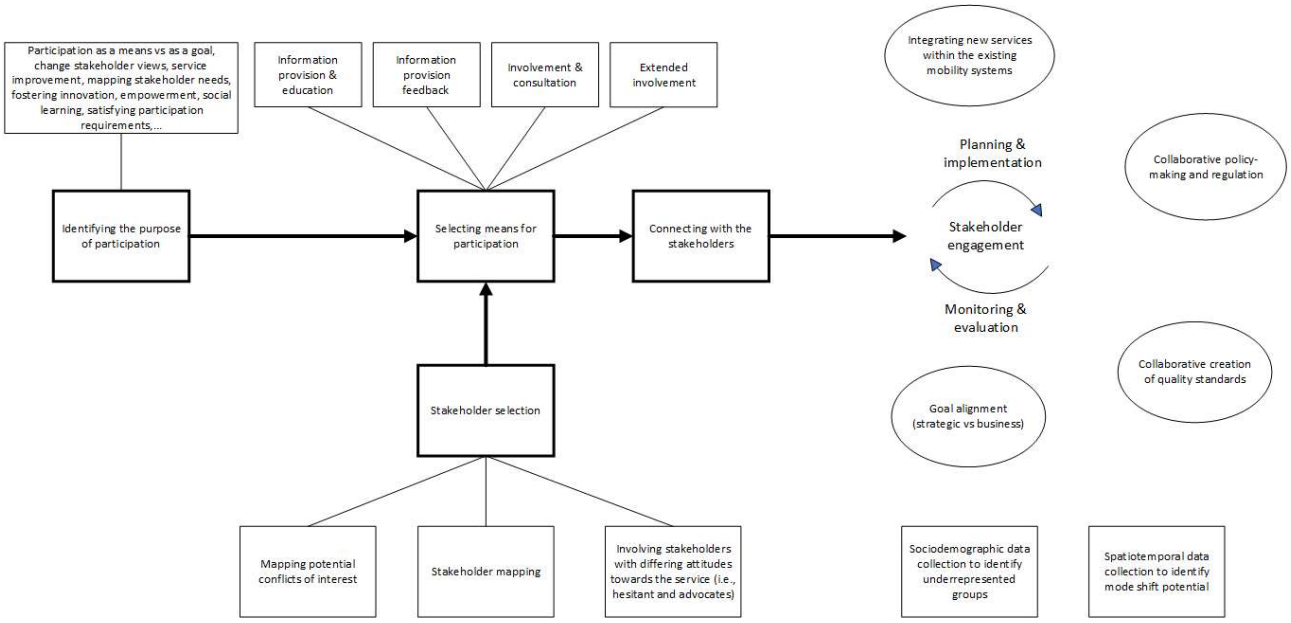


Figure 17. Sustainable mobility service collaboration framework.

6.2 Challenges, barriers and opportunities in achieving sustainable modal shift

To investigate challenges and opportunities in the operating environment, business needs and challenges, and future urban mobility, ten theme interviews were conducted during July 2023 and January 2024. Interviewees represented cities (2 interviews), government (2 interviews) and companies (6 interviews). Interviewed companies all work in the field of mobility and represent mobility operators, MaaS operators, and IT/tech companies. This section presents a synthesis of the interviews.

Stakeholder engagement is necessary but often insufficient. The interviews indicate that public–private interaction and ecosystem collaboration are widely regarded as necessary, but existing arrangements do not consistently support implementation. Respondents referred to different working groups, idea competitions, public procurement and development initiatives in which promising ideas may stall because procurement rules, established funding practices, institutional arrangements or conflicting interests restrict the route to implementation. Engagement therefore often remains consultative: stakeholders can articulate needs and propose solutions, but they have limited ability to reshape the structures through which services are funded, procured and governed.

This distinction is important because the interview material repeatedly calls for more comprehensive system change and identifies weak links between ideas, procurement, funding and implementation. Respondents also described competing interests and difficulties in jointly addressing customer needs across organisational and ecosystem boundaries. In particular, organisations may agree on broad objectives such as seamless travel chains or sustainable mobility while retaining different incentives at the operational level.

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Public–private partnership models are necessary but underdeveloped in practice. The findings point to a strong perceived need for public-private partnership arrangements. Urban mobility is strongly shaped by public funding, public transport, land-use decisions and regulation, while interviewees also emphasised the role of companies in mobility services, digital services, data use and innovation. Neither sector can independently produce integrated mobility services. However, the interviews also show that workable partnership models remain difficult to establish. Recurring uncertainties concern the division of roles, public procurements and funding of services, data-sharing responsibilities, and the sharing of costs, revenues and risks across actors. Furthermore, difficulties in establishing and governing new modes of transport were mentioned.

These tensions cannot be resolved through technical interoperability alone. Interviewees noted that mobility regulation has often concentrated on technical matters, while business and governance questions have received less attention. At the same time, market-based provision cannot be assumed to deliver all socially necessary services, particularly where demand is sparse or accessibility obligations apply. Conversely, public provision may crowd out market activity or leave companies without a credible route from experimentation to business. Effective partnerships therefore require explicit governance: a shared definition of public value, fair and transparent rules for market participation, and incentives and mechanisms for distributing costs and benefits. Long-term institutional support is also required because transport-system investments and behavioural effects develop over periods that exceed typical pilot projects.

Future mobility services require ecosystem thinking. The interview material suggests that mobility challenges should not be framed solely as service-integration problems. Seamless routing, ticketing and payment remain relevant, and respondents identified concrete needs related to demand-responsive transport, taxis, disruption management, personalised travel services, and interoperable data and digital systems. At the same time, interviews place these needs within a broader urban system that includes residential environment and services, land use, accessibility, walking and cycling, public procurement, taxation and environmental policy. This wider framing is necessary because respondents described the mobility system as highly car-dependent and called for more comprehensive system-level change.

Ecosystem thinking widens both the problem boundary and the range of relevant actors. The interviews emphasised that solutions must be adapted to different environments, including areas outside urban cores, and that not all solutions are suitable to all environments. They also highlighted fragmentation across administrative sectors and tensions between national and local interests. Accordingly, the transition towards sustainable mobility should be understood as a coordinated portfolio of service, infrastructure, regulatory and behavioural interventions.

Business models and sustainability objectives are often misaligned. The interviews reveal a mismatch between the conditions that make mobility services attractive to users and the conditions required to advance sustainability objectives. Adoption is primarily driven by immediate user value: services must be affordable, convenient, reliable and easy to use, and they must offer viable alternatives within everyday travel chains. Sustainability objectives, however, concern broader system-level outcomes, including reduced car dependence, lower transport emissions, improved accessibility and a more efficient use of publicly funded transport. These objectives do not automatically coincide. A commercially attractive service may generate new demand without replacing private-car trips, whereas a service that supports accessibility or emissions reduction may not attract enough paying customers to operate on a purely market-based basis. The interviews also indicate that providing information, such as the actual costs of driving, is unlikely to be sufficient on its own to change mode choice.

Bridging this gap requires business models and public–private partnership arrangements that combine customer value with public-policy objectives. The interviewees highlighted several relevant mechanisms: more equal tax treatment across transport modes, mobility plans (e.g. in

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corporations), incentives that encourage sustainable choices, pricing and compensation models and arrangements, ways to share costs and revenues, and the coordinated procurement of publicly funded transport. Such arrangements can help make sustainable services sufficiently attractive to users and viable for providers while ensuring that public funding and regulation steer development towards system-level benefits. Accessibility, barrier-free use, different levels of digital capability and the needs of special user groups must be integrated into these models from the outset.

Co-creation and ecosystem governance are key enabling capabilities. Across the themes, weaknesses in cross-organisational governance emerge as a common barrier. Interviewees highlighted the need to clarify actors' roles, responsibilities, processes and practices across organisational boundaries. They also identified trust, motivation and incentives as important conditions, and noted that competition can make it difficult for companies to address customer needs over organisational boundaries. Public organisations, meanwhile, strongly influence the operating environment through funding, regulation and procurement, yet existing procurement practices may prevent novel solutions from progressing.

These observations indicate that co-creation needs to extend beyond isolated development activities and be connected to sustained governance and implementation. The interview material particularly supports clear roles and responsibilities, cross-organisational data-management processes, incentives for data sharing, fair public–private rules, and mechanisms for allocating costs and revenues. It also shows the need for a pathway through which ideas and experiments can proceed to competitive procurement and implementation. Without such arrangements, promising solutions may fail to advance and actors may remain constrained by existing institutional practices and competing interests.

6.3 Collaborative business models – case mobility data spaces

6.3.1 Introduction to collaborative business models

A collaborative business model can be understood as a business model in which value is created, delivered and captured through a deliberately organised set of interdependent activities performed by multiple organisations rather than by a single firm alone. Zott and Amit's (2010) activity-system view is useful here because it defines a business model as a system of activities that can transcend the focal firm and span partners, suppliers and customers; the key design choices concern content, structure and governance, while the main sources of value are novelty, lock-in, complementarities and efficiency. This extends naturally into collaborative settings: the business model is not only "how one firm makes money" but how a network aligns activities, resources, risks and incentives around a shared value proposition. In data-space-specific literature, this is expressed even more directly: a data-space business model applies to a set of organisations, depends on the viability of participants' individual business models, and must consider their pains, gains, incentives and objectives (Gilsing et al., 2023).

The theoretical foundation for collaborative business models is strongest when combining six streams of literature. First, the relational view argues that competitive advantage can arise from inter-organisational relationships through relation-specific assets, knowledge-sharing routines, complementary resources and effective governance (Dyer & Singh, 1998). Second, ecosystem strategy defines an ecosystem as the alignment structure of the multilateral set of partners required for a focal value proposition to materialise, emphasising activities, actors, positions and links rather than only firm boundaries (Adner, 2017). Third, ecosystem theory explains why such arrangements emerge: modularity allows autonomous yet interdependent organisations to coordinate without full hierarchy, while non-generic complementarities create a need for alignment, shared roles and common rules (Jacobides et al., 2018). Fourth, platform ecosystem literature explains how a

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shared technological or service foundation can enable external innovators to create complementary offerings (Tiwana et al., 2010). Fifth, service-dominant logic frames value as co-created in use through the integration of resources by multiple actors, rather than embedded in a single product at the point of sale (Vargo & Lusch, 2008). Sixth, sustainable and collaborative business model literature emphasises mutual value creation and capture, meaning that participating actors should each be able to benefit from the shared model rather than one actor extracting disproportionate value (Berkers et al., 2022).

The key characteristics of collaborative business models are therefore: joint value proposition, distributed roles, shared enabling assets, coordinated governance, reciprocal incentives and mechanisms for value capture. Their value creation mechanisms include combining complementary assets, reducing transaction costs, enabling knowledge recombination, improving service integration and scaling innovation through network effects (Berkers et al., 2022; Verbrugge et al., 2024). Their value capture mechanisms can include participation fees, transaction fees, subscription models, licensing, revenue sharing, cost sharing, data/service monetisation, indirect public value, or improved operational efficiency (Berkers et al., 2022; Verbrugge et al., 2024). However, data-sharing research notes that scaling is often constrained by unclear ownership, decision rights, pricing and incentive alignment (Berkers et al., 2022). In sustainable contexts, the collaborative model must also account for social and environmental value, not only financial returns. Berkers et al. (2022) explicitly link collaborative business models with triple-bottom-line (financial, social and environmental value) ambitions and stress the need for governance structures that generate trust.

The evidence base is mixed in maturity. The theoretical foundations in strategy, ecosystem and service research are well established and peer-reviewed, while practical data-space business model evidence is still emerging and often comes from authoritative position papers, European deployment initiatives and case studies. The main benefits are clear: collaborative models can mobilise complementary resources, enable innovation that no single actor could deliver alone, and create scalable service ecosystems. The main risks are equally clear: misaligned incentives, free-riding, power asymmetries, lack of trust, unclear data valuation, insufficient governance, and difficulty balancing private revenue with public value. Successful collaborative business models therefore require explicit rules for participation, transparent value-sharing logic, trusted governance, interoperability standards, and mechanisms for resolving conflicts and adapting the model as the ecosystem evolves (Adner, 2017; Berkers et al., 2022; Dyer & Singh, 1998; Bakri et al., 2023; Verbrugge et al., 2024).

6.3.2 Collaborative business models in a mobility data space

A mobility data space is best understood as a federated socio-technical ecosystem that enables trusted data sharing among mobility actors while allowing data providers to retain control over their data. The common European Mobility Data Space materials define a data space as a decentralised infrastructure for data transactions between ecosystem parties based on a governance framework; data remains with the provider, while metadata or algorithms may be shared, and usage policies can be enforced for protected or sensitive data (Bakri et al., 2023). Authoritative EMDS recommendations position the value proposition around data sovereignty and trust, technical infrastructure, governance mechanisms, use-case acceleration, data and application availability, data quality, public funding for early adoption, and easier onboarding (Bakri et al., 2023). IDSA's data-space business model position paper similarly stresses that a singular data-space business model does not exist, because business models differ by perspective: governance authority, legal entity, intermediaries, data providers, data consumers and value-added service providers may each have distinct business models (Verbrugge et al., 2024).

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Conceptually, the mobility data space can be represented as shown below: a federated trust-and-governance layer connects independent data providers, value-adding service actors and end users through metadata discovery, connectors, policy enforcement, identity/trust services, semantic interoperability and agreed rulebooks (Bakri et al., 2023).

The core actors in such a space include data providers such as public transport operators, shared mobility providers, infrastructure managers, road authorities, parking and charging operators, city service providers and potentially users themselves; data consumers such as MaaS operators, journey planners, AI services, researchers, authorities and digital-twin developers; intermediaries such as metadata brokers, connector providers, identity/trust services, clearing or contract-management services; and governance actors such as a data space authority or neutral legal entity. The EMDS analysis identifies governance authority as a key role responsible for creating and maintaining the governance framework, and highlights interoperability between active data spaces in mobility and logistics as a central task. It also identifies discoverability, metadata brokering, data interoperability, data sovereignty and trust as core governance capabilities, with metadata catalogues and participant discovery helping actors find relevant data services and policies. (Bakri et al., 2023)

A collaborative business model in a mobility data space should therefore be designed around use cases, not around data monetisation alone. IDSA frames data-space value creation through the questions: what data products and related services create value, who brings them to market, how the data space is set up, to whom the value proposition is offered, and how costs and revenues are balanced (Verbrugge et al., 2024). This is consistent with the data-space business model design approach used in the Mobility data sandbox, where the value of a data space is made tangible by use cases and a process is proposed from ecosystem scoping to end-user value creation, participant business models, data-space business model design, governance design and agreements. For multimodal mobility, this means starting from end-user needs (e.g., seamless travel chains, accessibility, lower-emission choices, disruption management or integrated ticketing) and then specifying what data, APIs, services, rules and incentives are required across actors.

In practical implementation, collaborative business models can work through several complementary patterns. A federated participation model funds the shared infrastructure through member or stakeholder contributions while keeping data exchange free or low-cost to stimulate participation. A marketplace or transaction model enables data providers or service providers to price data products, analytics or APIs, while the data-space operator may charge usage or transaction fees. A hybrid model combines fixed contributions for shared infrastructure with usage-based fees, data-product pricing, or revenue sharing for specific use cases. A public-value model may rely on public funding, city/regional authority participation, or mission-oriented funding when the primary value is reduced emissions, accessibility, safety, resilience or transport-system efficiency rather than direct data sales. The important design principle is that the shared data-space business model must remain compatible with the individual business models of participants (Gilsing et al., 2023; Verbrugge et al., 2024); otherwise data providers, transport operators, technology firms and authorities will not contribute the assets required for the ecosystem to function.

For multimodal transport and mobility services, one of the most relevant applications is multimodal digital mobility services, where multiple transport modes, ticketing/payment systems and information services are integrated into user-facing offerings. However, such business ecosystems require public and private actors to cooperate and compete, and key actors commonly include mobility service providers, public transport authorities and regional authorities. The literature also shows persistent barriers in building such applications: regulatory and contractual constraints, lack of standardisation and technical interoperability, data availability and management, trust and collaboration between actors (Lusikka & Hakkarainen, 2025). A mobility data space framework can address these barriers by providing standardised connectors, common metadata, semantic

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interoperability, identity and trust mechanisms, and a governance structure for cross-organisational data sharing (Bakri et al., 2023).

The sustainability contribution is promising but not automatic. A systematic review of 85 MaaS studies (An & Shen, 2025) found that MaaS adoption is often driven by convenience, affordability, technological appeal and service reliability, while explicit sustainability motivations are secondary. The same review found that public transport integration, pricing structures favouring low-emission modes and targeted subsidies for disadvantaged groups are linked with positive sustainability outcomes. However, shared mobility services may substitute for walking, cycling or public transport rather than replacing private cars, so bundles including car-based services can unintentionally stimulate car use (An & Shen, 2025). This means collaborative business models in digital mobility services should not simply maximise transactions or app uptake. They should embed sustainability objectives holistically into service and business design (e.g. pricing, recommendations, governance and collaboration agreements).

A user-centric sustainable mobility model would therefore use the data space to support services such as personalised multimodal journey planning; real-time disruption management; accessibility-aware routing; demand-responsive feeders to public transport; shared-mobility integration for first/last mile; multimodal ticketing and payment; emissions-aware recommendations; digital twins for planning; and AI-based operational optimisation. Digitalisation, servitisation and data utilisation are opportunities to develop attractive, user-centric mobility services supporting sustainable modal shift from private car use to low-emission modes. Data is not the end product – the end product is a better mobility experience that makes sustainable options more convenient, reliable, affordable and inclusive.

In short, collaborative business models and mobility data spaces can boost user-centric sustainable mobility when they are designed as governance-led ecosystems for shared value creation: the data space reduces the friction and risk of collaboration, while the collaborative business model ensures that public authorities, operators, technology providers, data providers and users all have a reason to participate. Therefore, data sharing alone does not create sustainability, but trusted data sharing with aligned incentives and multimodal service innovation can make sustainable mobility choices easier, more attractive and more scalable.

Thus, key implications of collaborative business models in data ecosystems for user-centric sustainable mobility are:

- **The central claim should be framed as ecosystem alignment, not technology adoption.** Collaborative business models are needed because sustainable multimodal mobility depends on multiple actors aligning their activities, data, incentives and governance around user value (Adner, 2017; Vargo & Lusch, 2008).
- **A mobility data space should be positioned as shared enabling infrastructure.** Its core value is trusted, sovereign, interoperable and discoverable data sharing, not a single centralised database or one-size-fits-all data marketplace (Bakri et al., 2023).
- **Business model design should begin from concrete use cases.** The strongest approach is to identify end-user value first, then map required data products, actors, governance rules, revenue/cost sharing and participant incentives (Gilsing et al., 2023; Verbrugge et al., 2024).
- **Sustainability must be designed into incentives.** MaaS and mobility ecosystems can reduce car dependency only if public transport, active mobility and low-emission modes are made more attractive through pricing, service design, recommendations and governance rules; otherwise, convenience-led platforms may reinforce unsustainable travel patterns (An & Shen, 2025).

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- **Trust, interoperability and fair value capture are implementation conditions, not side issues.** Data providers will not share valuable or sensitive data without credible governance, clear usage policies, legal clarity, data sovereignty, security, and a fair logic for value capture (Berkers et al., 2022; Bakri et al., 2023).

6.4 Collaboration and governance models enable sustainable modal shift

Future public-private partnership models should be organised as long-term, mission-oriented ecosystems rather than temporary project consortia. The participating actors should agree on a shared objective, such as reducing car dependence, improving accessibility or increasing the use of public transport and active mobility, and translate this objective into measurable outcomes. Although individual pilots remain useful for experimentation, they should be connected to a credible pathway for continued financing, procurement, implementation and scaling.

Each partnership should have a clearly mandated orchestrator responsible for maintaining the shared vision, coordinating actors and overseeing ecosystem-level governance. Depending on the context, this role could be assigned to a city, regional authority, transport authority, neutral ecosystem organisation or jointly governed legal entity. The orchestrator should not necessarily operate all services, but it should ensure that responsibilities, decision rights and accountability are explicitly allocated.

PPP arrangements should establish transparent mechanisms for sharing costs, risks and benefits. Ticket and transaction revenues alone are unlikely to finance services that also generate public value through lower emissions, improved accessibility, safety or regional connectivity. Suitable models may therefore combine public funding, participant contributions, service fees, usage-based payments, revenue sharing and outcome-based compensation. The selected model should provide credible incentives for data providers, transport operators, technology companies and public authorities to participate over the long term.

Open data, interoperable interfaces and data spaces should be treated as shared enabling infrastructure rather than objectives in themselves. Partnerships should define responsibility for data quality, metadata, semantic interoperability, access conditions and long-term maintenance. Trusted governance, clear usage policies and fair value-sharing arrangements are particularly important for data that cannot be provided openly. The technical architecture should support federated data sharing while allowing providers to retain control over their data.

Procurement and innovation funding should provide a clearer route from experimentation to operational deployment. Public actors should use procurement models that allow solutions to be tested, evaluated and subsequently acquired or scaled through transparent and competitive processes. Evaluation criteria should cover not only technical performance and initial cost, but also user value, accessibility, interoperability, maintainability, environmental impact and ecosystem-level benefits.

Finally, PPP models should begin with concrete user needs and complete journey chains rather than individual technologies or transport modes. Services should make sustainable alternatives sufficiently convenient, reliable, affordable, understandable and accessible to compete with private-car use. This requires coordination across local, regional and national governance levels and integration between transport services, infrastructure, land use, digital services and behavioural measures. Continuous stakeholder involvement, including the participation of users and underrepresented groups, should accompany service design, implementation and evaluation.

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7. Conclusion and recommendations

7.1 Summary of project impact and lessons learned

The DeMo project examined how data-driven solutions can accelerate sustainable modal shift by making public transport, walking, cycling and shared mobility more attractive, accessible and reliable. The results show that modal shift is not achieved through a single technology, service or policy measure. It requires coordinated change across user experience, physical infrastructure, digital services, data governance, transport modelling, business models, and public-private collaboration.

A central conclusion is that mobility choices are shaped by both practical and experiential factors. Travel time, cost, reliability, accessibility, and ease of carrying goods remain important, but users also value confidence, comfort, freedom, safety, enjoyable surroundings, and a sense of control. These considerations become especially important in complex trip chains and under temporary conditions such as adverse weather, illness, tiredness or travelling outside daytime. Sustainable alternatives must therefore compete with private cars not only in efficiency but also in flexibility, reassurance and overall travel experience.

The project demonstrated that digital services could address these barriers when they are designed around concrete user needs. The Opastaja concept showed how multi-stop planning, destination discovery and route-aware recommendations can make walking, cycling and public transport appear more flexible and attractive. The Extended Trip Planner showed how visual, contextual and accessibility-sensitive guidance can reduce uncertainty, support pre-trip familiarisation, and improve last-mile navigation. Both concepts received positive feedback, but their transition from prototype to operational service requires richer and more reliable information, integration with established journey-planning platforms, clearer responsibilities for maintaining content and larger real-world evaluations.

The pilots also showed that data-driven interventions can influence behaviour and improve system management. In the Helsinki e-scooter study, real-time nudges and speed-control mechanisms were associated with safer infrastructure use, while AI-based sensing generated useful information on conflict locations and infrastructure condition. At the same time, the cycling case study demonstrated that technology and isolated infrastructure investments do not automatically produce system-wide modal shift. Physical networks must be coherent, public transport and active mobility must be integrated, and planning priorities must address the structural advantages of private car use.

The Mobility data sandbox provided a shared architecture for developing and testing data-intensive mobility services. Its layered approach – combining data infrastructure, governed data sharing, digital twins and AI services – proved useful across several demonstrators. The work confirmed that data spaces can enable controlled reuse of operational data, digital twins can provide the context needed by AI services, and governed interfaces can reduce the risks of deploying AI agents. However, interoperability between data spaces, semantic alignment, participant onboarding, data ownership and privacy remain major barriers to wider adoption. Governance, security, compliance and auditability must be embedded from the beginning rather than added after technical development.

The project further confirmed that sustainable mobility services depend on ecosystem alignment. No single actor controls all the required data, infrastructure, customer relationships or service components. Cities and public authorities provide policy direction, public value objectives and key infrastructure; transport operators and other service providers deliver operational capabilities; technology companies provide platforms and specialist services; and research organisations

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support experimentation and evaluation. Collaborative business models are therefore needed to align roles, incentives, costs, risks and value capture around clearly defined user value.

Overall, DeMo produced an integrated evidence base, service concepts, technical architectures, demonstrators and business-model options for sustainable modal shift. The results support continued development, but the project also identified a persistent implementation gap between promising prototypes and scalable services. Closing this gap requires long-term ownership, operational funding, agreed governance, interoperable data, measurable impact targets, and sustained public-private collaboration.

7.2 Recommendations for future development

The recommendations below are derived from the project's user studies, technical demonstrations, ecosystem analyses, business model investigations, and pilot activities. While the project demonstrated the feasibility and potential value of several concepts, many findings were generated in pilot-scale environments and should therefore be interpreted as evidence-informed directions for future development rather than definitive prescriptions.

7.2.1 User-centred mobility services

The project findings suggest that mobility services may benefit from supporting complete travel situations rather than isolated trip legs. Future service development should place greater emphasis on multi-stop trip chains, different travel purposes, and contextual factors such as reliability, weather conditions, accessibility needs (both physical and digital), carrying requirements, and users' need for flexibility during travel.

The user studies also indicate that experiential qualities may play an important role in the attractiveness of sustainable mobility options. Factors such as comfort, perceived safety, ease of orientation, reliability, and confidence during the journey could therefore receive greater attention alongside traditional performance metrics such as travel time and cost.

The project further suggests that integration with established journey-planning ecosystems may offer a more scalable deployment pathway than creating entirely new standalone applications. Future work could explore how concepts developed within DeMo can be incorporated into existing platforms while retaining opportunities for specialised solutions in contexts such as campuses, events, tourism destinations, and accessibility services.

7.2.2 Data, digital infrastructure and AI

The Mobility data sandbox demonstrated potential as a shared experimentation environment for data-driven mobility services. Future initiatives could build on this foundation by investigating opportunities for greater interoperability, reusable components, scalable data connections, and support for emerging AI-enabled applications.

The project findings also highlight the importance of establishing clear responsibilities for the maintenance and quality assurance of data and user-facing content. Future operational deployments should consider governance arrangements that define ownership, update procedures, quality requirements, and long-term maintenance responsibilities.

As AI and data-sharing solutions advance, future developments would benefit from addressing governance, security, privacy and compliance considerations from the outset. In particular, further

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work could explore practical approaches to identity management, access control, auditing, and secure integration of AI capabilities within mobility ecosystems.

7.2.3 Ecosystem development and business models

The ecosystem analyses suggest that successful service development is likely to depend on clearly articulated user needs and value propositions. Future business-model development could begin with user and societal objectives before identifying the required actors, data resources, governance structures, and funding mechanisms.

The project also highlighted the value of collaboration between cities, public authorities, transport operators, technology providers, and research organisations. Continued experimentation may benefit from mechanisms that support long-term coordination, shared asset development, and alignment of strategic priorities across stakeholders.

Several concepts and technical components developed within the project may also warrant further assessment from commercialisation and replication perspectives. Additional operational pilots could help evaluate their transferability to other regions and their alignment with emerging European data-sharing and mobility initiatives.

7.2.4 Piloting and impact assessment

Although several concepts demonstrated technical feasibility and received encouraging feedback from users and stakeholders, their longer-term impacts remain uncertain. Larger-scale and longer-duration pilots would therefore be valuable for assessing behavioural change, user adoption, accessibility outcomes, operational performance, emissions reductions, and business models under real-world conditions.

The project also identified opportunities to strengthen impact assessment methodologies. Future research could explore how transport models might better represent integrated mobility services, shared mobility solutions, complex trip chains, and behavioural responses to digital interventions. Closer integration between pilot monitoring data and modelling activities may support more robust assessment of policy and investment alternatives.

7.2.5 Accessibility, inclusion and sustainable mobility transitions

The findings suggest that accessibility and inclusion should remain important considerations throughout service design and evaluation. Future development efforts could involve a broader range of users, including infrequent public transport users, older adults, and people facing mobility, sensory, or cognitive barriers, in order to better understand diverse travel needs and potential adoption challenges.

The project results further indicate that digital services alone are unlikely to overcome barriers to sustainable mobility. Lasting change is likely to require complementary improvements in transport infrastructure, service availability and quality, land-use planning, pricing policies, accessibility measures, and other supporting interventions. Future work should therefore investigate how digital solutions can most effectively complement broader mobility-system development.

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Finally, the project raised several questions concerning the long-term interaction between digitalisation, behavioural change, transport systems, and sustainability objectives. Further research could examine how digital mobility services contribute to wider system transformation, the extent to which they generate additional sustainable travel rather than redistributing existing travel patterns, and the policy conditions required to support sustained modal shift away from private car use.

8. List of publications

The DeMo project has produced several internationally recognized scientific publications and conference presentations on data-driven mobility services, user motivation, route planner solutions, and promoting sustainable mobility. Results have been widely disseminated in both scientific and practical forums, and project outputs are openly available on VTT's research portal.

Scientific Articles and Conference Presentations:

- Wallius, E., Lamuela Orta, C., Lusikka, T., Pihlajamaa, O., & Hautala, R. (2025). Decarbonizing urban mobility through data-driven services: How to achieve modal shift? In *McNally, C., Carroll, P., Martinez-Pastor, B., Ghosh, B., Efthymiou, M., Valantasis-Kanellos, N. (Eds.). Transport Transitions: Advancing Sustainable and Inclusive Mobility. TRA conference 2024. Lecture Notes in Mobility.* Springer, Cham. pp. 576–581. https://doi.org/10.1007/978-3-031-85578-8_77

- Lamuela Orta, C. (2024). Bicycles, technology, gender: the paradox of cycling infrastructure growth in Helsinki. Presented at *ICTA-UAB Conference 2024 GrowthvsClimate*, Barcelona, 13–15 March 2024.

- Wallius, E., Pihlajamaa, O., Heino, I., Lahti, J., & Lusikka, T. (2025). AI in future mobility: A multimodal journey chain perspective. Presented at *16th ITS European Congress*, Seville, Spain.

- Lamuela Orta, C. (2025*).* Cycling and ecological economics – for degrowth or against delusions? Presented at *ISEE-Degrowth 2025*, Oslo, 24–27 June 2025.

- Lusikka, T. (2025). Opastaja app presentation. Presented at *ITS European Congress 2025, Nordic+ stand*, Seville, Spain.

- Lusikka, T., & Hakkarainen, M. (2025). Data ecosystem of tourism mobility: challenges and opportunities. *Matkailututkimus, 21*(3), 48-69. https://doi.org/10.33351/mt.163794

- Wallius, E., Kaipainen, K., & Pihlajamaa, O. (2026). Trip chain characteristics and situational factors influencing private car mode choices – A survey study in two Finnish urban areas. *Transportation Research Interdisciplinary Perspectives, 36, 101821. https://doi.org/10.1016/j.trip.2025.101821*

- Wallius, E., Kaipainen, K. & Pihlajamaa, O. (2026, in press). Temporary external and internal conditions affecting mode choices: Results from a survey study in Finland. Presented at *Transport Research Arena 2026*, 18-21 May 2026, Budapest, Hungary.

Other Publications and Communication:

- Project website: https://cris.vtt.fi/en/projects/decarbonizing-transport-and-mobility-through-data-driven-modal-sh

Docusign Envelope ID: 43CB1ACC-328F-8A0E-83E5-998D6592ED02

- Drover, Voi Technology, VTT, Vianova, Mobility Lab Helsinki, Forum Virium Helsinki & City of Helsinki. (2023). Helsinki e-scooter safety tech case study, December 2023: https://lnkd.in/p/dECD3rte
- Master's thesis: Timoskainen, L. (2025). Designing a trip planning application for sustainable mobility: a user-centred approach. Master's Thesis. Faculty of Information Technology and Communication Sciences. Tampere University. (Opastaja app): https://trepo.tuni.fi/handle/10024/226227
- Doctoral thesis: Lamuela Orta, C. (2026). Waiting for the Cycling Renaissance: the Limits of the Sustainability Transition Assumption in the Finnish Urban Mobility Case. Dissertationes Universitatis Helsingiensis, 259/2026. http://hdl.handle.net/10138/630921
- DeMo project final seminar held on 27 May 2026.
- Results presented at ITS Factory development forum, Tourism-as-a-Service project workshop, and several other stakeholder and results webinars.

References

Adner, R. (2017). Ecosystem as structure: An actionable construct for strategy. *Journal of Management, 43*(1), 39–58. https://doi.org/10.1177/0149206316678451

Allen, J., Muñoz, J. C., & Ortúzar, J. de D. (2019). Understanding public transport satisfaction: Using Maslow's hierarchy of (transit) needs. *Transport Policy, 81*, 75–94. https://doi.org/10.1016/j.tranpol.2019.06.005

Altieri, M., Silva, C., & Terabe, S. (2020). Give public transit a chance: A comparative analysis of competitive travel time in public transit modal share. *Journal of Transport Geography, 87*. https://doi.org/10.1016/j.jtrangeo.2020.102817

An, C., & Shen, J. (2025). Assessing the impact of Mobility-as-a-Service (MaaS) on sustainable urban travel behaviors: A systematic literature review. *Frontiers in Sustainable Cities, 7*, 1645488. https://doi.org/10.3389/frsc.2025.1645488

Andersson, A., Winslott Hiselius, L., & Adell, E. (2018). Promoting sustainable travel behaviour through the use of smartphone applications: A review and development of a conceptual model. *Travel Behaviour and Society*, *11*, 52–61. https://doi.org/10.1016/j.tbs.2017.12.008

Aydin, A., & Telceken, S. (2015). Artificial Intelligence Aided Recommendation Based Mobile Trip Planner For Eskisehir City. *2015 IEEE 10th Conference on Industrial Electronics and Applications (ICIEA)*, Auckland, New Zealand, 2015, 1650–1654. https://doi.org/10.1109/ICIEA.2015.7334374.

Bajorunaite, L., Brewster, S., & Williamson, J. R. (2021). Virtual Reality in transit: How acceptable is VR use on public transport? *Proceedings - 2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops, VRW 2021*, 432–433. https://doi.org/10.1109/VRW52623.2021.00098

Bajorunaite, L., Brewster, S., & Williamson, J. R. (2023). Reality Anchors: Bringing Cues from Reality to Increase Acceptance of Immersive Technologies in Transit. *Proceedings of the ACM on Human-Computer Interaction*, *7*(MHCI), 1–28. https://doi.org/10.1145/3604266

Docusign Envelope ID: 43CB1ACC-328F-8A0E-83E5-998D6592ED02

Baker, M., Hincks, S., & Sherriff, G. (2010). Getting involved in plan making: Participation and stakeholder involvement in local and regional spatial strategies in England. *Environment and Planning C: Government and Policy, 28(4)*, 574–594. https://doi.org/10.1068/c0972

Bakri, T., Bastiaansen, H., Benmayor, A., Blaya, M., Böge, G., Cases, J.-F., Eisenrauch, A., Engh, E., Epardeau, D., Federl, S., Fernandes, E., van der Hoeven, G., King, L., Kirstein, L., Kraft, V., Lenz, G., Lilja, J., Morgan, J., Nagel, I., Öörni, R., Pretzsch, S., Scholliers, J., Schulz, H., Spijkers, N. (2023). Towards a common European mobility data space: Perspectives, recommendations and building blocks (*Deliverable D3.1, Version 2*). PrepDSpace4Mobility.

Berkers, F., Gilsing, R., & Lamerichs, G. (2022). D2.3: Archetypes and methodology for designing governance & collaborative business models for 0FLW data space and applications (*Deliverable D2.3, Version 1.1*). ZeroW Project.

Bhandal, J., & Noonan, R. J. (2022). Motivations, perceptions and experiences of cycling for transport: A photovoice study. *Journal of Transport and Health*, *25*. https://doi.org/10.1016/j.jth.2022.101341

BikeMaps. (n.d.). *BikeMaps*. Retrieved from https://bikemaps.org/

Bösehans, G., & Walker, I. (2020). Do supra-modal traveller types exist? A travel behaviour market segmentation using Goal framing theory. *Transportation*, *47*(1), 243–273. https://doi.org/10.1007/s11116-018-9874-7

Bouscasse, H., Joly, I., & Bonnel, P. (2018). How does environmental concern influence mode choice habits? A mediation analysis. *Transportation Research Part D: Transport and Environment*, *59*, 205–222. https://doi.org/10.1016/j.trd.2018.01.007

Buehler, R. (2011). Determinants of transport mode choice: a comparison of Germany and the USA. *Journal of Transport Geography*, *19*(4), 644–657. https://doi.org/10.1016/j.jtrangeo.2010.07.005

Bulckaen, J., Keseru, I., & Macharis, C. (2016). Sustainability versus stakeholder preferences: Searching for synergies in urban and regional mobility measures. *Research in Transportation Economics, 55*, 40–49. https://doi.org/10.1016/j.retrec.2016.04.009

Burian, J., Zajíčková, L., Ivan, I., & Macků, K. (2018). Attitudes and motivation to use public or individual transport: A case study of two middle-sized cities. *Social Sciences*, *7*(6). https://doi.org/10.3390/socsci7060083

Camacho, T., Foth, M., Rittenbruch, M., & Rakotonirainy, A. (2015). TrainYarn: Probing perceptions of social space in urban commuter trains. *OzCHI 2015: Being Human - Conference Proceedings*, 455–464. https://doi.org/10.1145/2838739.2838760

Canales, D., Bouton, S., Trimble, E., Thayne, J., Da Silva, L., Shastry, S., Knupfer, S., & Powell, M. (n.d.). *Connected Urban Growth: Public-Private Collaborations for Transforming Urban Mobility*. Retrieved from http://newclimateeconomy.net/content/cities-working-papers.

Charity Miles. (n.d.). *Charity Miles*. Retrieved from https://charitymiles.org/.

Charreire, H., Roda, C., Feuillet, T., Piombini, A., Bardos, H., Rutter, H., Compernolle, S., Mackenbach, J. D., Lakerveld, J., & Oppert, J. M. (2021). Walking, cycling, and public transport for commuting and non-commuting travels across 5 European urban regions: Modal choice correlates and motivations. *Journal of Transport Geography*, *96*. https://doi.org/10.1016/j.jtrangeo.2021.103196

Docusign Envelope ID: 43CB1ACC-328F-8A0E-83E5-998D6592ED02

Cohen-Blankshtain, G., & Rotem-Mindali, O. (2016). Key research themes on ICT and sustainable urban mobility. *International Journal of Sustainable Transportation*, *10*(1), 9–17. https://doi.org/10.1080/15568318.2013.820994

Copenhagenize Index. (2025). The Global Ranking of Bicycle-Friendly Cities EIT Urban Mobility Edition. Copenhagenize. Retrieved from https://copenhagenizeindex.eu/

Din Offentlige Transport. (n.d.). *Event Ticket*. Retrieved from https://dinoffentligetransport.dk/en/find-tickets/day-tickets/event-ticket

Drabicki, A., Cats, O., Kucharski, R., Fonzone, A., & Szarata, A. (2023). Should I stay or should I board? Willingness to wait with real-time crowding information in urban public transport. *Research in Transportation Business and Management*, *47*. https://doi.org/10.1016/j.rtbm.2023.100963

Drover, Voi Technology, VTT, Vianova, Mobility Lab Helsinki, Forum Virium Helsinki & City of Helsinki. (2023). Helsinki e-scooter safety tech case study, December 2023. *Report PDF*. Retrieved from https://lnkd.in/p/dECD3rte

Dyer, J. H., & Singh, H. (1998). The relational view: Cooperative strategy and sources of interorganizational competitive advantage. *Academy of Management Review, 23*(4), 660–679. https://doi.org/10.5465/amr.1998.1255632

Egset, K. S., & Nordfjærn, T. (2019). The role of transport priorities, transport attitudes and situational factors for sustainable transport mode use in wintertime. *Transportation Research Part F: Traffic Psychology and Behaviour*, *62*, 473–482. https://doi.org/10.1016/j.trf.2019.02.003

Foth, M. & Schroeter, R. (2010). Enhancing the experience of public transport users with urban screens and mobile applications. In *Safran, C, Lugmayr, A, Sotamaa, O, Aaltonen, T, & Franssila, H (Eds.). Proceedings of the 14th International Academic MindTrek Conference: Envisioning Future Media Environments. Association for Computing Machinery*, United States, 33–40.

Fu, X., & Juan, Z. (2017). Understanding public transit use behavior: integration of the theory of planned behavior and the customer satisfaction theory. *Transportation*, *44*(5), 1021–1042. https://doi.org/10.1007/s11116-016-9692-8

Fujii, S., Kitamura, R. (2003). What does a one-month free bus ticket do to habitual drivers? An experimental analysis of habit and attitude change. *Transportation 30*, 81–95. https://doi.org/10.1023/A:1021234607980

Gilsing, R., Berkers, F., Lamerichs, G., Dalmolen, S., Cornelisse, E., van den Berg, W., van Houwelingen, G., Trifkovic, K. & Bunderla, M. (2023). D2.6 Methodology and learnings from applying the prototype kit to the SILLs. (*Deliverable 2.6*). ZeroW project.

Gonzalez-Feliu, J., Pronello, C., & Salanova Grau, J. M. (2018). Multi-stakeholder collaboration in urban transport: State-of-the-art and research opportunities. *Transport, 33(4)*, 1079–1094. https://doi.org/10.3846/transport.2018.6810

Gössling, S. (2018). ICT and transport behavior: A conceptual review. *International Journal of Sustainable Transportation*, *12*(3), 153–164. https://doi.org/10.1080/15568318.2017.1338318

Docusign Envelope ID: 43CB1ACC-328F-8A0E-83E5-998D6592ED02

Grigoletto, A., Loi, A., Maietta Latessa, P., Marini, S., Rinaldo, N., Gualdi-Russo, E., Zaccagni, L., & Toselli, S. (2022). Physical Activity Behavior, Motivation and Active Commuting: Relationships with the Use of Green Spaces in Italy. *International Journal of Environmental Research and Public Health*, *19*(15). https://doi.org/10.3390/ijerph19159248

Guo, Y., Peeta, S., Agrawal, S., & Benedyk, I. (2022). Impacts of Pokémon GO on route and mode choice decisions: exploring the potential for integrating augmented reality, gamification, and social components in mobile apps to influence travel decisions. *Transportation*, *49*(2), 395–444. https://doi.org/10.1007/s11116-021-10181-9

Haapala, R. (2025). Tampere pääsi maailman parhaiden pyöräilykaupunkien listalle – "Tulos osoittaa, että kaupunki on oikealla tiellä". *Tamperelainen, 26.11.2025*. Retrieved from https://www.tamperelainen.fi/paikalliset/9027222

Hadas, Y., Tillman, A., Tsadikovich, D., & Ozalvo, A. (2022). Assessing public transport passenger attitudes towards a dynamic fare model based on in-vehicle crowdedness levels and additional waiting time. *International Journal of Transportation Science and Technology, 12*(3), 836–847. https://doi.org/10.1016/j.ijtst.2022.08.003

Hamari, J., Sjöklint, M., & Ukkonen, A. (2016). The sharing economy: Why people participate in collaborative consumption. *Journal of the Association for Information Science and Technology*, *67*(9), 2047–2059. https://doi.org/10.1002/asi.23552

Hersh, M. (2022). Wearable Travel Aids for Blind and Partially Sighted People: A Review with a Focus on Design Issues. *Sensors*, *22*(14), 5454. MDPI. https://doi.org/10.3390/s22145454

Hiscock, R., Macintyre, S., Kearns, A., & Ellaway, A. (2002). Means of transport and ontological security: Do cars provide psycho-social benefits to their users? *Transportation Research Part D: Transport and Environment 7*(2). https://doi.org/10.1016/S1361-9209(01)00015-3

Hounsell, N. B., Shrestha, B. P., McDonald, M., & Wong, A. (2016). Open Data and the Needs of Older People for Public Transport Information. *Transportation Research Procedia*, *14*, 4334–4343. https://doi.org/10.1016/j.trpro.2016.05.355

Höysniemi, S., & Salonen, A. O. (2019). Towards carbon-neutral mobility in Finland: Mobility and life satisfaction in day-to-day life. *Sustainability*, *11*(19), 5374. https://doi.org/10.3390/su11195374

Hunecke, M., Blöbaum, A., Matthies, E., & Höger, R. (2001). Responsibility and environment: Ecological norm orientation and external factors in the domain of travel mode choice behavior. *Environment and Behavior*, *33*(6), 830–852. https://doi.org/10.1177/00139160121973269

Jacob, R., Shalaik, B., Winstanley, A.C., Mooney, P. (2011). Haptic Feedback for Passengers Using Public Transport. In *Cherifi, H., Zain, J.M., El-Qawasmeh, E. (Eds.). Digital Information and Communication Technology and Its Applications. DICTAP 2011. Communications in Computer and Information Science, 166.* Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-21984-9_3

Jacobides, M. G., Cennamo, C., & Gawer, A. (2018). Towards a theory of ecosystems. *Strategic Management Journal, 39*(8), 2255–2276. https://doi.org/10.1002/smj.2904

Jariyasunant, J., Carrel, A., Ekambaram, V., Gaker, D., Sengupta, R., & Walker, J. L. (2012). The Quantified Traveler: Changing transport behavior with personalized travel data feedback. UC Berkeley: University of California Transportation Center. Retrieved from https://escholarship.org/uc/item/3047k0dw

Docusign Envelope ID: 43CB1ACC-328F-8A0E-83E5-998D6592ED02

Jones, C. H. D., & Ogilvie, D. (2012). Motivations for active commuting: a qualitative investigation of the period of home or work relocation. *International Journal of Behavioral Nutrition and Physical Activity*, *9*, 109. https://doi.org/10.1186/1479-5868-9-109

Kamargianni, M., Li, W., Matyas, M., & Schäfer, A. (2016). A Critical Review of New Mobility Services for Urban Transport. *Transportation Research Procedia*, *14*, 3294–3303. https://doi.org/10.1016/j.trpro.2016.05.277

Kang, A. S., Jayaraman, K., Soh, K. L., & Wong, W. P. (2019). Convenience, flexible service, and commute impedance as the predictors of drivers' intention to switch and behavioral readiness to use public transport. *Transportation Research Part F: Traffic Psychology and Behaviour*, *62*, 505–519. https://doi.org/10.1016/j.trf.2019.02.005

Karpashevich, P., Hornecker, E., Dankwa, N. K., Hanafy, M., & Fietkau, J. (2016). Blurring boundaries between everyday life and pervasive gaming - An interview study of ingress. In *Proceedings of the 15th International Conference on Mobile and Ubiquitous Multimedia (MUM '16)*, 217–228. https://doi.org/10.1145/3012709.3012716

Kent, J. L. (2014). Driving to save time or saving time to drive? The enduring appeal of the private car. *Transportation Research Part A: Policy and Practice*, *65*, 103–115. https://doi.org/10.1016/j.tra.2014.04.009

Kirk, M. (2017). Singapore May Have Designed the World's Best Bus Stop. Bloomberg. Retrieved from https://www.bloomberg.com/news/articles/2017-03-01/singapore-may-have-designed-the-world-s-best-bus-stop

Kırdar, G., & Ardıç, S. İ. (2020). A design proposal of integrated smart mobility application for travel behavior change towards sustainable mobility. *Civil Engineering and Architecture*, *8(5)*, 1095–1106. https://doi.org/10.13189/cea.2020.080536

Kuramoto, I., Ishibashi, T., Yamamoto, K., & Tsujino, Y. (2013). Stand Up, Heroes! : Gamification for Standing People on Crowded Public Transportation. In *Marcus, A. (Eds.). Design, User Experience, and Usability. Health, Learning, Playing, Cultural, and Cross-Cultural User Experience. DUXU 2013. Lecture Notes in Computer Science, 8013*. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-39241-2_59

König, A., Gebhardt, L., Stark, K., & Schuppan, J. (2022). A Multi-Perspective Assessment of the Introduction of E-Scooter Sharing in Germany. *Sustainability, 14*(5), 2639. https://doi.org/10.3390/su14052639

Laakko, T., Kostiainen, J., & Pihlajamaa, O. (2020). Estimating passenger experience from vehicle data: Preconditions for using machine learning. In *Lusikka, T. (Ed.). Proceedings of TRA2020, the 8th Transport Research Arena: Rethinking transport – towards clean and inclusive mobility*, Liikenne- ja viestintävirasto Traficom. Retrieved from https://www.researchgate.net/publication/339848623_Estimating_passenger_experience_from_vehicle_data_Preconditions_for_using_machine_learning

Lamuela Orta, C. (2026). Bicycles' double learning: combining organization and transport research to explain a cycling paradox in Helsinki. *Transportation Research Interdisciplinary Perspectives, 38*, 102122. https://doi.org/10.1016/j.trip.2026.102122

Lamuela Orta, C. (2026). Waiting for the Cycling Renaissance: the Limits of the Sustainability Transition Assumption in the Finnish Urban Mobility Case. *Dissertationes Universitatis Helsingiensis, 259/2026*. http://hdl.handle.net/10138/630921

Docusign Envelope ID: 43CB1ACC-328F-8A0E-83E5-998D6592ED02

Lamuela Orta, C., & Pihlajamaa, O. (2025). Women's experiences with light rail in a Finnish smart city: The technological acceleration of public transport versus daily realities. *Applied Mobilities, 10*(4), 379–396. https://doi.org/10.1080/23800127.2025.2491785

Lamuela Orta, C. (2025). Helsinki's cycling traffic trend in 2018–2024: Overall decline but growth in one cycling highway. *Journal of Cycling and Micromobility Research, 5*, 100075. https://doi.org/10.1016/j.jcmr.2025.100075

Latinopoulos, C., Patrier, A., & Sivakumar, A. (2021). Planning for e-scooter use in metropolitan cities: A case study for Paris. *Transportation Research Part D: Transport and Environment, 100*, 103037. https://doi.org/10.1016/j.trd.2021.103037

Le Pira, M., Ignaccolo, M., Inturri, G., Pluchino, A., & Rapisarda, A. (2016). Modelling stakeholder participation in transport planning. *Case Studies on Transport Policy, 4*(3), 230–238. https://doi.org/10.1016/j.cstp.2016.06.002

Lindenau, M., & Böhler-Baedeker, S. (2014). Citizen and Stakeholder Involvement: A Precondition for Sustainable Urban Mobility. *Transportation Research Procedia, 4*, 347–360. https://doi.org/10.1016/j.trpro.2014.11.026

Lindenberg, S. (2022). Goal-framing theory. English original version, a translation of which appeared a French Dictionary of Environmental Psychology in 2022: *Psychologie environnementale, 100 notions clés*, sous la direction de D. Marchand, E. Pol et K. Weiss, 115–120. Malakoff: Dunod. Retrieved from https://www.researchgate.net/publication/362579209

Lindenberg, S., & Steg, L. (2007). Normative, gain and hedonic goal frames guiding environmental behavior. *Journal of Social Issues*, *63*(1), 117–137. https://doi.org/10.1111/j.1540-4560.2007.00499.x

Lusikka, T., & Hakkarainen, M. (2025). Data ecosystem of tourism mobility: challenges and opportunities. *Matkailututkimus, 21*(3), 48–69. https://doi.org/10.33351/mt.163794

Lyons, G., Hammond, P., & Mackay, K. (2019). The importance of user perspective in the evolution of MaaS. *Transportation Research Part A: Policy and Practice*, *121*, 22–36. https://doi.org/10.1016/j.tra.2018.12.010

Mapway. (n.d.). Augmented Reality: The future of navigation. Retrieved from https://www.mapway.com/Augmented-Reality-New-Bus-Times-London/.

Marquart, H., & Schuppan, J. (2022). Promoting sustainable mobility: To what extent is "health" considered by mobility app studies? a review and a conceptual framework. *Sustainability 14(1)*, 47. https://doi.org/10.3390/su14010047

Medeiros, D., McGill, M., Ng, A., McDermid, R., Pantidi, N., Williamson, J., & Brewster, S. (2022). From Shielding to Avoidance: Passenger Augmented Reality and the Layout of Virtual Displays for Productivity in Shared Transit. *IEEE Transactions on Visualization and Computer Graphics*, *28*(11), 3640–3650. https://doi.org/10.1109/TVCG.2022.3203002

Meng, M., Memon, A. A., Wong, Y. D., & Lam, S. H. (2018). Impact of traveller information on mode choice behaviour. *Proceedings of the Institution of Civil Engineers: Transport*, *171*(1), 11–19. https://doi.org/10.1680/jtran.16.00058

Docusign Envelope ID: 43CB1ACC-328F-8A0E-83E5-998D6592ED02

Mirri, S., Prandi, C., Salomoni, P., Callegati, F., & Campi, A. (2014). On combining crowdsourcing, sensing and open data for an accessible smart city. *Proceedings - 2014 8th International Conference on Next Generation Mobile Applications, Services and Technologies, NGMAST 2014*, 294–299. https://doi.org/10.1109/NGMAST.2014.59

Mladenović, M. N., Dibaj, S., & Lopatnikov, D. (2022). Evaluation of electric scooter deployment in the City of Helsinki: A perspective on sociotechnical transitions dynamics and adaptive governance. Aalto University. https://urn.fi/URN:NBN:fi:aalto-202211236570

Musselwhite, C., & Roberts, K. (2021). Accessibility and informational barriers to an age friendly railway. *Quality in Ageing and Older Adults*, *22*(2), 114–129. https://doi.org/10.1108/QAOA-02-2021-0015

NL Times. (2023). Dutch bicycle firm VanMoof declared bankrupt, founders reveal. 18 July 2023. Retrieved from https://nltimes.nl/2023/07/18/dutch-bicycle-firm-vanmoof-declared-bankrupt-founders-reveal

Novaco, R. W., & Gonzalez, O. I. (2009). Commuting and well-being. In: *Amichai-Hamburger Y, ed. Technology and Psychological Well-Being. Cambridge University Press, 2009,* 174–205. https://doi.org/10.1017/CBO9780511635373.008

Paundra, J., Rook, L., van Dalen, J., & Ketter, W. (2017). Preferences for car sharing services: Effects of instrumental attributes and psychological ownership. *Journal of Environmental Psychology*, *53*, 121–130. https://doi.org/10.1016/j.jenvp.2017.07.003

Pelikh, K. (n.d.). Super Apps and the future of MaaS (Mobility as a Service). Retrieved from https://www.o-city.com/blog/maas-the-future-of-mobility-as-a-service-o-city

Petts, J., & Leach, B. (2000). Evaluating Methods for Public Participation: Literature Review. *R&D Technical Report E135*. Environment Agency, UK.

Pihlajamaa, O., Kostiainen, J., Federley, M., Kuusisto, O., & Luhtala, M. (2020). Framework for developing solutions for accessible mobility: Potential of IoT solutions in public transportation. In *Lusikka, T. (Ed.). Proceedings of TRA2020, the 8th Transport Research Arena: Rethinking transport – towards clean and inclusive mobility*, Liikenne- ja viestintävirasto Traficom. Retrieved from https://www.researchgate.net/publication/340487558

Pihlajamaa, O., Lusikka, T., & Eckhardt, J. (2022). Enriched travel chains with Beyond MaaS. *3rd International Conference on Mobility as a Service, ICoMaaS 2022*, Tampere, Finland.

Puerari, E., de Koning, J. I. J. C., von Wirth, T., Karré, P. M., Mulder, I. J., & Loorbach, D. A. (2018). Co-creation dynamics in Urban Living Labs. *Sustainability, 10*(6), 1893. https://doi.org/10.3390/su10061893

Raulo, A., Rojas, A., Kröger, B., Laaksonen, A., Lamuela Orta, C., Nurmio, S., Peltoniemi, M., Lahti, L., & Žliobaitė, I. (2023). What are patterns of rise and decline? *Royal Society Open Science, 10*(11), 230052. https://doi.org/10.1098/rsos.230052

Redman, L., Friman, M., Gärling, T., & Hartig, T. (2013). Quality attributes of public transport that attract car users: A research review. *Transport Policy*, *25*, 119–127. https://doi.org/10.1016/j.tranpol.2012.11.005

Riggs, W. (2017). Painting the fence: Social norms as economic incentives to non-automotive travel behavior. *Travel Behaviour and Society*, *7*, 26–33. https://doi.org/10.1016/j.tbs.2016.11.004

Docusign Envelope ID: 43CB1ACC-328F-8A0E-83E5-998D6592ED02

Saif, M. A., Zefreh, M. M., & Torok, A. (2019). Public transport accessibility: A literature review. *Periodica Polytechnica Transportation Engineering, 47*(1), 36–43. https://doi.org/10.3311/PPtr.12072

Sandberg, B., Hurmerinta, L., Leino, H. M., Lehtonen, E., & Lyytimäki, J. (2023). Time-related aspects of commute well-being. *Transportation Research Part F: Traffic Psychology and Behaviour*, *95*, 177–187. https://doi.org/10.1016/j.trf.2023.04.010

Schneider, R. J. (2013). Theory of routine mode choice decisions: An operational framework to increase sustainable transportation. *Transport Policy*, *25*, 128–137. https://doi.org/10.1016/j.tranpol.2012.10.007

Schwanen, T., Banister, D., & Anable, J. (2012). Rethinking habits and their role in behaviour change: the case of low-carbon mobility. *Journal of Transport Geography*, *24*, 522–532. https://doi.org/10.1016/j.jtrangeo.2012.06.003

Shaheen, S., & Cohen, A. (2019). Mobility on demand (MOD) and mobility as a service (MaaS): Early understanding of shared mobility impacts and public transit partnerships. In *Demand for Emerging Transportation Systems: Modeling Adoption, Satisfaction, and Mobility Patterns*, 37–59. Elsevier. https://doi.org/10.1016/B978-0-12-815018-4.00003-6

Simons, D., Clarys, P., De Bourdeaudhuij, I., de Geus, B., Vandelanotte, C., & Deforche, B. (2014). Why do young adults choose different transport modes? A focus group study. *Transport Policy*, *36*, 151–159. https://doi.org/10.1016/j.tranpol.2014.08.009

Sopjani, L., Stier, J. J., Ritzén, S., Hesselgren, M., & Georén, P. (2019). Involving users and user roles in the transition to sustainable mobility systems: The case of light electric vehicle sharing in Sweden. *Transportation Research Part D: Transport and Environment, 71*, 207–221. https://doi.org/10.1016/j.trd.2018.12.011

Sourbati, M., & Behrendt, F. (2021). Smart mobility, age and data justice. *New Media and Society*, *23*(6), 1398–1414. https://doi.org/10.1177/1461444820902682

Steg, L. (2005). Car use: Lust and must. Instrumental, symbolic and affective motives for car use. *Transportation Research Part A: Policy and Practice*, *39*(2–3 SPEC. ISS.), 147–162. https://doi.org/10.1016/j.tra.2004.07.001

Strava Support. (n.d.). Group Events for Clubs. Retrieved from https://support.strava.com/Hc/En-Us/Articles/216918607-Group-Events-for-Clubs

Su, J. G., Winters, M., Nunes, M., & Brauer, M. (2010). Designing a route planner to facilitate and promote cycling in Metro Vancouver, Canada. *Transportation Research Part A: Policy and Practice*, *44*(7), 495–505. https://doi.org/10.1016/j.tra.2010.03.015

Tampere. (n.d.). Liikkumisen hiilijalanjälkilaskuri. Retrieved from https://www.tampere.fi/luonto-ja-ymparisto/ilmastotyo-tampereella/liikkumisen-hiilijalanjalkilaskuri

Timmer, S., Bösehans, G., & Henkel, S. (2023). Behavioural norms or personal gains? – An empirical analysis of commuters' intention to switch to multimodal mobility behaviour. *Transportation Research Part A: Policy and Practice*, *170*. https://doi.org/10.1016/j.tra.2023.103620

Timoskainen, L. (2025). Designing a trip planning application for sustainable mobility: a user-centred approach. *Master's Thesis.* Faculty of Information Technology and Communication Sciences. Tampere University. Retrieved from https://trepo.tuni.fi/handle/10024/226227

Docusign Envelope ID: 43CB1ACC-328F-8A0E-83E5-998D6592ED02

Tiwana, A., Konsynski, B., & Bush, A. A. (2010). Platform evolution: Coevolution of platform architecture, governance, and environmental dynamics. *Information Systems Research, 21*(4), 675–687. https://doi.org/10.1287/isre.1100.0323

Tolppanen, S., & Kang, J. (2021). The effect of values on carbon footprint and attitudes towards pro-environmental behavior. *Journal of Cleaner Production*, *282*. https://doi.org/10.1016/j.jclepro.2020.124524

Tuominen, A., & Ahlqvist, T. (2010). Is the transport system becoming ubiquitous? Socio-technical roadmapping as a tool for integrating the development of transport policies and intelligent transport systems and services in Finland. *Technological Forecasting and Social Change*, *77*(1), 120–134. https://doi.org/10.1016/j.techfore.2009.06.001

University of Helsinki. (n.d.). Green Paths. Retrieved from https://www.helsinki.fi/en/researchgroups/digital-geography-lab/green-paths

van der Linde, L. B. A., Witte, P. A., & Spit, T. J. M. (2021). Quiet acceptance vs. the 'polder model': stakeholder involvement in strategic urban mobility plans. *European Planning Studies, 29*(3), 425–445. https://doi.org/10.1080/09654313.2020.1735310

van Exel, N. J. A., de Graaf, G., & Rietveld, P. (2011). "I can do perfectly well without a car!": An exploration of stated preferences for middle-distance travel. *Transportation*, *38*(3), 383–407. https://doi.org/10.1007/s11116-010-9315-8

Vargo, S. L., & Lusch, R. F. (2008). Service-dominant logic: Continuing the evolution. *Journal of the Academy of Marketing Science, 36*(1), 1–10. https://doi.org/10.1007/s11747-007-0069-6

Verbrugge, S., Herregodts, A.-L., Kraemer, P., Heindl, A., Schlüter-Langdon, C., Gelhaar, J., Schäfer, M., de Roode, M., & Verstraete, M. (2024). Data spaces business models. International Data Spaces Association. https://doi.org/10.5281/zenodo.14101303

Wallius, E., Kaipainen, K., & Pihlajamaa, O. (2026). Trip chain characteristics and situational factors influencing private car mode choices – A survey study in two Finnish urban areas. *Transportation Research Interdisciplinary Perspectives, 36*, 101821. https://doi.org/10.1016/j.trip.2025.101821

Wallius, E., Kaipainen, K., & Pihlajamaa, O. (2026, in press). Temporary external and internal conditions affecting mode choices: Results from a survey study in Finland. *Transport Research Arena 2026*, 18–21 May 2026, Budapest, Hungary.

Wallius, E., Lamuela Orta, C., Lusikka, T., Pihlajamaa, O., & Hautala, R. (2025). Decarbonizing urban mobility through data-driven services: How to achieve modal shift? In *McNally, C., Carroll, P., Martinez-Pastor, B., Ghosh, B., Efthymiou, M., Valantasis-Kanellos, N. (Eds.). Transport Transitions: Advancing Sustainable and Inclusive Mobility. TRA conference 2024. Lecture Notes in Mobility*, 576–581. Springer, Cham. https://doi.org/10.1007/978-3-031-85578-8_77

Zhang, N., Lee, Y., Radhakrishnan, M., & Balan, R. K. (2015). GameOn: P2p gaming on public transport. *MobiSys 2015 - Proceedings of the 13th Annual International Conference on Mobile Systems, Applications, and Services*, 105–119. https://doi.org/10.1145/2742647.2742660

Zott, C., & Amit, R. (2010). Business model design: An activity system perspective. *Long Range Planning, 43*(2–3), 216–226. https://doi.org/10.1016/j.lrp.2009.07.004