D2.3 Enablers and barriers for public transport services involving passengers

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation / acronym	Definition
AI	Artificial Intelligence
BOStrab	Official German regulatory framework governing the construction and operation of tramways, light rail systems, and underground/metro networks (*Verordnung über den Bau und Betrieb der Straßenbahnen)*
CCTV	Closed-Circuit Television
CRA	Cyber Recilience Act
DGT	Directorate-General for Traffic
EDPB	European Data Protection Board
EU	European Union
GDPR	General Data Protection Regulation
GenAI	Generative Artificial Intelligence
HE	Horizon Europe
HMI	Human–Machine Interface
HVAC	Heating, Ventilation and Air Conditioning
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
KBA	German Federal Motor Transport Authority
LMM	Large Multimodal Model
PT	Public Transport
QR	Quick Response
SAE	SAE International
SC	Service Concept
SOTIF	Safety of the Intended Functionality
SPICE	Software Process Improvement and Capability Determination
STT	Speech-to-Text
TSI PRM	Technical Specification for Interoperability relating to Persons with Reduced Mobility
UC	Use Case
UN	United Nations
UNECE	United Nations Economic Commission for Europe
VLM	Vision-Language Model

Executive Summary

The OptiPEx project aims to improve comfort, safety, inclusiveness and trust in public transport by developing ethical, passenger-aware and privacy-preserving Artificial Intelligent (AI)-enabled services. These services use sensing, analytics and interaction technologies to better understand passenger needs and support more accessible, responsive and user-centred public transport systems. As AI-based technologies become increasingly common in public transport, their successful deployment depends not only on technical feasibility but also on regulatory, ethical, safety and organisational considerations.

This deliverable analyses the main enablers and barriers associated with the future deployment of passenger-aware public transport services developed within OptiPEx. The assessment covers eight service concepts addressing passenger assistance, passenger information, comfort, safety and operational efficiency. It aims to identify factors that may support or constrain future implementation and deployment and to guide the development of trustworthy, inclusive, and passenger-centred AI-enabled public transport services.

The analysis applies a five-dimensional assessment framework covering regulation and compliance, ethical and societal aspects, safety and security, technical validation and interoperability, and organisational and operational readiness. The assessment combines regulatory and standards reviews, service concept descriptions, mock-up stakeholder evaluation findings and expert workshops conducted within OptiPEx.

The results show that successful deployment depends on more than technical feasibility alone. Across the analysed service concepts, recurring enablers included clear passenger value, meaningful human oversight, accessible and inclusive design, privacy-preserving approaches and compatibility with existing transport systems. Common barriers were related to privacy and data protection requirements, passenger trust, validation of AI-based functions, availability of suitable training and testing data, system reliability and organisational readiness. The findings highlight the need to balance technological innovation with regulatory compliance, societal acceptance and operational feasibility. The results support OptiPEx's objective of developing passenger-aware services that improve comfort, safety, accessibility, and trust while remaining compatible with regulatory and operational requirements.

The analysis also revealed differences between service concepts. Services supporting passenger information, accessibility and comfort generally face fewer validation and operational challenges and can often build upon existing infrastructure and operational processes. In contrast, safety-related services require stronger evidence of reliability, validation under realistic operating conditions, cybersecurity measures, clearly defined responsibilities and appropriate human oversight. As the potential consequences of incorrect or delayed system outputs increase, so does the need for robust governance, operational procedures and lifecycle management.

The main contribution of this deliverable is the systematic identification of cross-cutting enablers and barriers affecting the deployment of passenger-aware public transport services. By analysing eight service concepts from regulatory, ethical, safety, technical and organisational perspectives, the study provides a structured understanding of the opportunities, risks and deployment challenges associated with AI-enabled passenger services. The identified themes, including passenger value, human oversight, privacy-preserving design, accessibility, technical validation and organisational readiness, provide practical guidance for future service development. The assessment framework developed in this work supported the analysis and offers a structured approach for examining similar services in future projects.

The findings support future implementation, integration and validation activities within OptiPEx and provide transferable lessons for the wider development of trustworthy, inclusive and human-centred AI-enabled mobility services. By identifying opportunities and constraints early, the analysis contributes to developing passenger-aware public transport solutions that are technically feasible, socially acceptable, and operationally viable.

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1 Introduction

The OptiPEx project aims to improve the comfort, safety, inclusiveness and trustworthiness of public transport by developing ethical, passenger-aware and privacy-preserving Artificial Intelligence (AI)-enabled services. Through co-creation with passengers and other stakeholders, the project explores how advanced sensing, analytics and interaction technologies can be used to better understand passenger needs and support more accessible, responsive and user-centred public transport systems.

As AI and digital technologies become increasingly common in public transport, their deployment depends not only on technical performance but also on regulatory, ethical, safety and organisational considerations. Services that collect, analyse or respond to passenger-related information must comply with applicable regulations while maintaining passenger trust, accessibility, safety and operational feasibility. Understanding the factors that support or constrain deployment is therefore important for the responsible development of passenger-aware public transport services.

This deliverable contributes to Task 2.3, Ethics, security and privacy in public transport services involving passengers. Its objective is to identify and assess the main enablers and barriers associated with the future deployment of the passenger-aware service concepts developed within OptiPEx. The assessment combines regulatory, ethical, safety, technical and organisational perspectives to analyse opportunities, risks and deployment considerations across the service concepts.

The deliverable examines eight service concepts addressing passenger assistance, passenger information, comfort, safety and operational efficiency. Particular attention is given to services that measure, analyse or interact with passengers during boarding, on-board travel and off-boarding. The analysis considers relevant regulatory frameworks, including data protection, AI governance, accessibility, and safety requirements, along with broader issues related to passenger acceptance, human oversight, technical validation, and operational readiness.

The main contribution of this deliverable is a systematic analysis of the factors that influence the deployment of passenger-aware public transport services. By assessing eight service concepts from regulatory, ethical, safety, technical and organisational perspectives, the study identifies recurring enablers and barriers associated with the implementation of AI-enabled passenger services. The findings provide practical guidance for developing trustworthy, inclusive, and passenger-centred public transport services and highlight common opportunities and challenges relevant beyond the specific OptiPEx use cases. The five-dimensional assessment framework developed in this work supported the analysis and provides a structured approach for examining similar services in future projects.

The remainder of the deliverable is structured as follows. Section 2 describes the methodology and assessment framework. Section 3 provides the regulatory, ethical and safety context for passenger-aware public transport services. Section 4 presents the identified enablers and barriers, including both common and service-specific findings. Section 5 discusses the implications of the results for future AI-enabled public transport services, and Section 6 concludes the deliverable.

2 Methodology

This section describes the methodology used to identify and assess enablers and barriers affecting the development and future deployment of passenger-aware public transport services in OptiPEx. A qualitative, multidimensional socio-technical approach was applied, recognising that deployment depends on technical feasibility as well as regulatory, ethical, safety and organisational conditions.

2.1 Data sources

The analysis draws on four types of material:

- **Regulatory and standards review:** Relevant EU regulations, ethical guidance, safety and cybersecurity frameworks, and interoperability standards.
- **OptiPEx service concept material:** Descriptions of the intended passenger benefits, interaction mechanisms, operating contexts and expected data use.
- **OptiPEx mock-up evaluation results:** Findings concerning user needs, acceptance, implementation challenges and deployment considerations.
- **Expert workshop and analysis material:** Workshop discussions and documented assessments of the service concepts against the five analysis dimensions.

The service concepts analysed in this study were developed through the OptiPEx co-creation process and are presented in Table 1. Evidence availability and details varied across service concepts. The regulatory and standards review provided the basis for the general assessment, while the service concept and evaluation materials provided concept-specific information. Expert workshops applied the framework and consolidated the findings.

Table 1. Use cases and service concepts (SC)

Use case	Service concept	SC name	Description	Key mechanism
Automatic assistance for passengers with special needs	SC1 	Notification to a driver about specific passenger types	Detects specific passenger types (e.g. wheelchair users, passengers with strollers or large items) and informs the driver when additional time or assistance may be needed to support safe boarding and exiting.	Video-based passenger group recognition + driver alerting
	SC2 	Audio information channel for tourists	Provides audio guidance (e.g. ticketing, boarding and exiting information) via passenger devices in different languages.	Passenger information system + targeted audio delivery
	SC3 	Save the seat	Provides real-time information on the availability of priority seating and designated spaces and guides passengers to appropriate boarding locations.	Video-based object and space detection + passenger guidance
Improving on-board safety with anomaly detection	SC4 	Communication with central control	Enables communication between passengers, the vehicle and central control to support	Event detection + control centre communication

Use case	Service concept	SC name	Description	Key mechanism
			incident management and coordinated responses.	
	SC5 	Optimised in-vehicle conditions to avoid travel discomfort	Monitors environmental conditions and adjusts vehicle systems to improve passenger comfort and reduce travel discomfort.	Environment sensing and forecasting + adaptive control
	SC6 	Passenger in-vehicle safety and security system	Detects abnormal or unsafe passenger behaviour and situations and supports timely intervention.	Video and audio analytics + anomaly detection and incident escalation
Pedestrian–vehicle communication	SC7 	Tram collision warning system	Detects potential collision risks between trams and pedestrians and provides warnings to drivers and/or pedestrians.	Sensor fusion + risk prediction + warning system
Passenger distribution optimisation	SC8 	Know before you go	Provides passengers with information about travel conditions (e.g. occupancy and accessibility) before boarding.	Data aggregation + passenger information services

2.2 Analysis framework for enablers and barriers

The analysis framework provides a common structure for assessing the eight service concepts from complementary socio-technical perspectives. It consists of five interconnected dimensions selected to reflect the main conditions that may influence the responsible and successful introduction of passenger-aware public transport services, as presented in Table 2:

Regulation and compliance cover applicable legal and regulatory requirements, including data protection, AI governance, accessibility, passenger rights, data sharing, cybersecurity and responsibilities among service actors.

Ethical and societal aspects cover passenger dignity, trust, transparency, fairness, non-discrimination, inclusiveness, human agency and societal acceptability. Particular attention was given to the potential effects on passengers with disabilities or other specific assistance needs.

Safety and security cover physical and operational safety, system failures, fail-safe and degraded-mode behaviour, misuse prevention, cybersecurity, emergency procedures and human escalation paths.

Technical validation and interoperability cover the reliability of sensing and analytics, data quality, robustness, validation under realistic conditions, integration with vehicles and infrastructure, scalability and interoperability across public transport modes and operating environments.

Organisational and operational readiness covers roles and responsibilities, staff competences, training, maintenance, control-centre readiness, procurement, service continuity and stakeholder preparedness. The assessment considered how the service could be integrated into existing public transport workflows and maintained throughout its lifecycle.

Table 2. Analysis framework for identifying enablers and barriers.

Dimension	Assessment focus	Indicative questions
Regulation and compliance	Legal basis, data protection, AI obligations, accessibility, data sharing and cybersecurity requirements.	What passenger data are processed, why, and under what safeguards? Does the function fall under AI Act obligations? Is the service accessible by design?
Ethical and societal aspects	Trust, dignity, transparency, fairness, non-discrimination, human agency and passenger acceptance.	Would passengers understand and accept the service? Could it stigmatise, misclassify or treat some groups unfairly? Can a human intervene when needed?
Safety and security	Passenger safety, system failures, emergency responses, misuse, cybersecurity and escalation paths.	What happens if sensors fail or AI misclassifies a situation? Are fallback procedures defined? Are data and interfaces protected against misuse?
Technical validation and interoperability	Testing, data quality, robustness, interoperability, scalability and operation under real-world conditions.	Can the service be tested across critical and edge scenarios? Does it work across vehicle types, lighting, acoustics, network conditions and passenger densities?
Organisational and operational readiness	Roles, procedures, training, maintenance, control-centre readiness, procurement and continuity.	Who is responsible for monitoring and response? What training, documentation and maintenance are needed? What is the fallback if the service is unavailable?

An **enabler** is defined as a factor that supports implementation, deployment, accessibility, safety, trust, scalability or operational feasibility. A **barrier** is defined as a factor that may slow, restrict or prevent implementation or deployment, or reduce the effectiveness, acceptance, safety or sustainability of a service.

A factor could be classified as an enabler and a barrier when its effect depends on the service design or operating context. For example, passenger sensing can enable improved assistance and situational awareness while also creating privacy, acceptance and validation challenges.

2.3 Analysis procedure

The analysis followed a structured four-step procedure to ensure that the service concepts were assessed consistently and that recurring findings could be identified across them:

1. **Service concept characterisation**: Each service concept was described by OptiPEx partners using a common set of characteristics, including its intended purpose, passenger interaction, operating context, expected data use and technical mechanism.
2. **Dimension-based assessment**: OptiPEx partners assessed each service concept against the five analysis dimensions and identified factors that could support or constrain its future implementation and deployment during dedicated workshops held on 27 May and 27 August 2026.
3. **Documentation and classification**: The workshop facilitators documented the findings in concept-level canvases containing one row for each assessment dimension and separate columns for enablers and barriers. Each identified factor was classified as an enabler, barrier or context-dependent factor. The concept-level results are presented in Appendix 1.
4. **Thematic grouping and expert consolidation**: Following the workshops, VTT experts reviewed the completed canvases and harmonised overlapping terminology. Factors expressing similar issues were grouped into broader themes while maintaining links to the original service concept and assessment dimension. Experts from VTT, UZ, and IAV then reviewed the concept-level findings and cross-cutting themes.

A theme was considered **cross-cutting** when similar factors were identified in at least two service concepts. A cross-cutting theme could be associated with more than one assessment dimension when its effects extended across regulatory, ethical, safety, technical or organisational considerations.

The results represent a qualitative synthesis. The analysis also considered OptiPEx design choices intended to balance functionality, privacy and passenger acceptance. These included aggregated, event-based, or limited-scope observations rather than continuous monitoring of identifiable individuals.

A three-level significance assessment was conducted for the classified enablers and barriers through expert consolidation. The assessment reflects the expected influence of each factor on the successful deployment, adoption, operation or sustainability of the service. As the assessment focuses mainly on service concepts rather than implemented systems, the significance ratings represent qualitative expert judgements rather than measured system performance or formal risk estimates. The significance criteria and resulting cross-use-case landscapes are presented in Section 4.2.

2.4 Limitations

The findings should be interpreted in relation to the scope and maturity of the analysed service concepts. The concepts differ in technical scope, development stage and available evidence, and the assessment, including the significance ratings, is based on qualitative expert judgement rather than measured system performance. It does not constitute a formal legal, safety or technical compliance evaluation. The relevance of individual findings may also vary by transport mode, operator, vehicle, deployment country and operating environment. Further assessment is therefore needed as the service concepts mature and move towards implementation and deployment.

3 AI and passenger-aware public transport

Passenger-aware public transport services rely on sensing, analytics and interaction technologies to support passenger needs and improve travel experiences. Their deployment is influenced not only by technical capabilities but also by regulatory requirements, ethical principles, safety considerations and societal expectations. This section provides the contextual background necessary for understanding the deployment environment of passenger-aware AI services and establishes the foundation for the enabler and barrier analysis presented in Section 4.

3.1 AI and digitalisation in public transport

Public transport is undergoing rapid digitalisation driven by advances in sensing technologies, connectivity, data analytics and AI. These technologies are increasingly used to support operational efficiency, passenger information, accessibility, safety monitoring and service personalisation. In this context, passenger-aware public transport services aim to use perception, analytics, and interaction technologies to better understand passenger needs and situations and provide more responsive and inclusive services.

Adopting AI-enabled services creates opportunities to improve accessibility, comfort, safety, and operational performance. At the same time, it raises new challenges related to privacy, transparency, reliability, cybersecurity and human oversight. Understanding these technological developments and their implications provides important context for assessing the enablers and barriers associated with passenger-aware public transport services.

3.2 EU regulatory context

Passenger-aware public transport services operate within a complex regulatory environment spanning data protection, AI governance, accessibility, safety, and cybersecurity. These requirements influence how services can be designed, deployed and operated and may act as both enablers and barriers to implementation. Passenger-aware public transport services are shaped by legal, regulatory, and standardisation requirements related to data processing, AI deployment, accessibility, safety, and cybersecurity.

In OptiPEx, the regulatory context was analysed to identify factors that may support or constrain the deployment of passenger-aware AI services. The review considered how different legal and regulatory frameworks apply to services that measure, analyse or respond to passenger-related information in public transport environments. Particular attention was given to privacy, human rights, safety, accessibility, cybersecurity and the responsible use of AI.

The following sections summarise the regulatory areas that are most relevant to the OptiPEx service concepts and provide the foundation for the enabler and barrier analysis presented in Section 4.

3.2.1 Data protection and surveillance law

Many passenger-aware services rely on sensors, cameras or audio technologies that process passenger-related information. Data protection and privacy legislation therefore form a fundamental consideration for their deployment. This section summarises the key requirements related to personal data processing and surveillance that are relevant to the OptiPEx service concepts.

The baseline legal framework for video- and audio-based in-cabin monitoring is Regulation (EU) 2016/679, the General Data Protection Regulation (GDPR). In public transport vehicles, camera images, audio recordings, behavioural observations, and derived analytics usually qualify as personal data when passengers are identifiable or can reasonably be singled out. This triggers the GDPR principles of lawfulness, fairness and transparency, purpose limitation, data minimisation, accuracy, storage limitation, integrity and confidentiality, and accountability (European Parliament and Council of the European Union, 2016). For OptiPEx, this means

that monitoring functions must be linked to a specific and legitimate purpose, such as passenger safety, emergency response, accessibility support or operational incident handling.

A data protection impact assessment should be expected for systematic monitoring in shared public spaces, particularly where new technologies are used, audio is processed, vulnerable passenger groups are involved, or the processing may affect access to assistance or safety measures. The European Data Protection Board (EDPB) Guidelines 3/2019 on processing personal data through video devices are directly relevant because they clarify the requirements for lawfulness, necessity, proportionality, transparency, retention periods, data subject rights, disclosure of footage, biometric data and technical and organisational safeguards (European Data Protection Board, 2020). In practice, this favours edge processing, event-based recording, short retention periods, access logging, encryption, visible signage, and layered passenger information via QR codes or web links.

- **Laws and standards considered:** GDPR and EDPB Guidelines 3/2019 on processing personal data through video devices, particularly for lawful basis, purpose limitation, data minimisation, transparency, storage limitation, data protection impact assessment, biometric data and technical and organisational safeguards.

Depending on the purpose of processing, different legal bases may apply under GDPR. While some passenger-aware services may rely on legitimate interests, public task or safety-related purposes, other services involving voluntary participation, personalised functions or user-generated information may require explicit user consent. The appropriate legal basis should therefore be assessed separately for each service concept and deployment context

3.2.2 AI Act risk classification

The EU AI Act introduces a risk-based regulatory framework for AI systems and establishes different obligations depending on their intended purpose and potential impact. For passenger-aware public transport services, understanding how different functions may be classified matters because regulatory requirements can vary substantially across service concepts.

Regulation (EU) 2024/1689, the Artificial Intelligence Act, adds a risk-based governance layer for AI systems placed on the market, put into service or used in the European Union (European Parliament and Council of the European Union, 2024a). For in-cabin monitoring, the decisive question is whether the AI system is limited to aggregated information or decision support, or whether it performs biometric categorisation, emotion recognition, safety-relevant decision support or functions connected to transport safety. AI functions that merely estimate passenger density or provide aggregated comfort information may raise lower AI Act concerns if they avoid identification and safety-critical effects. By contrast, AI systems used for incident detection, emergency escalation, door-control support, collision-risk mitigation or other safety-related transport functions require stronger attention to risk management, technical documentation, transparency, human oversight, accuracy, robustness, cybersecurity and post-market monitoring.

For OptiPEx, the AI Act is therefore used as a classification lens. Each in-cabin use case was assessed according to its intended purpose, risk to passengers, degree of autonomy, dependency on biometric or behavioural inference, possible effect on safety-relevant decisions, and the availability of human oversight. This is especially important where the same technical sensor stream can support different risk profiles. For example, a camera used only for anonymous passenger-density estimation is legally different from a camera used to classify passenger types, infer distress or trigger a direct operational response.

- **Laws and standards considered:** EU AI Act, particularly the risk-based classification approach, high-risk AI obligations, transparency requirements, biometric categorisation, emotion recognition, human oversight, robustness, accuracy, cybersecurity, technical documentation and post-market monitoring.

3.2.3 Video, audio, biometric and emotion-related processing

Video, audio and behavioural sensing technologies can support safety, accessibility and operational awareness in public transport environments. However, these technologies also raise important privacy, ethical and regulatory considerations, particularly when processing may involve biometric characteristics or behavioural interpretations.

The most sensitive regulatory issues arise when in-cabin monitoring moves beyond detecting observable safety events and toward biometric or emotion-related interpretation. Video-based skeleton analysis, head/body orientation and posture estimation can be framed as privacy-preserving alternatives if they transform raw images into abstracted outputs such as “fallen passenger detected”, “unsafe standing position”, “blocked door area” or “passenger density above threshold”. However, these techniques still originate from sensor streams that generate personal data and therefore require appropriate data protection safeguards, validation of their intended functionality, and clear data-retention rules (European Data Protection Board, 2020; European Parliament and Council of the European Union, 2016, 2024a).

Audio processing requires particular caution because continuous recording of conversations can be highly intrusive and difficult to justify in public transport. A more proportionate design is event-based acoustic detection, for example recognising sounds associated with emergency calls, crashes, falls or alarm-button activation, while avoiding continuous storage of intelligible speech. Emotion-related detection should be considered only in narrowly defined, safety-related cases and must not be used for profiling, passenger classification, or service personalisation. Under the AI Act and GDPR, such use requires a clear lawful basis, necessity and proportionality, passenger transparency, data minimisation, human oversight and appropriate technical and organisational safeguards (European Parliament and Council of the European Union, 2016, 2024a). For OptiPEx, the preferred framing is therefore not general emotion recognition, but the detection of predefined, observable safety-relevant indicators that may trigger human review or escalation.

- **Laws and standards considered:** GDPR, EDPB Guidelines 3/2019 on video devices, and the EU AI Act, particularly regarding video/audio processing, biometric categorisation, emotion recognition, transparency, lawful basis, data minimisation and safeguards.

3.2.4 Vehicle safety, type approval and operational safety

Some passenger-aware services may influence safety-related decisions, operational procedures or interactions with vehicle systems. In such cases, deployment considerations extend beyond data protection and AI governance to include vehicle safety, operational safety and system validation requirements.

Regulation (EU) 2019/2144 on general vehicle safety and type approval was addressed because it is relevant where passenger-aware AI functions contribute to occupant protection, vulnerable road-user protection, collision warning, emergency intervention or automated vehicle safety functions (European Parliament and Council of the European Union, 2019a). A monitoring function that only informs a driver, control centre or passenger is legally different from a function that directly influences vehicle behaviour, such as inhibiting door closure, triggering an emergency stop, supporting collision avoidance or changing operational states. This distinction between informational and executive functions is central to OptiPEx service concepts. For example, informing the driver that a wheelchair user is boarding represents an informational function, whereas automatically adjusting vehicle indoor conditions to reduce travel discomfort involves a more direct system response. The closer the AI output is to a safety-relevant vehicle action, the stronger the need for a safety concept, validation evidence, fallback behaviour, control-centre procedures, and allocation of responsibilities between the technology provider, vehicle manufacturer, and public transport operator.

Safety-related AI should not be described only as a user experience feature. It must be assessed as part of the wider operational safety chain, including sensor performance, false-alarm handling, missed detections, degraded-mode operation, human escalation paths, and the response time of drivers or control centres. In development, relevant state-of-the-art standards should be considered, in particular International Organization for Standardization (ISO) 26262 for functional safety of automotive electrical/electronic systems

and ISO 21448 for Safety of the Intended Functionality (SOTIF), which is especially relevant for AI-based perception and prediction systems whose limitations may create hazards even without a technical fault (International Organization for Standardization, 2018, 2022). These standards support hazard analysis and risk assessment, definition of safety requirements, validation of edge cases and fault-tolerant design for functions such as door control, emergency intervention and collision warning or avoidance. Automotive Software Process Improvement and Capability Determination (SPICE) may additionally support structured software and system development processes, while Human–Machine Interface (HMI) guidance such as ISO 15005 can be relevant where warnings or interventions interact with drivers or control-centre staff (International Organization for Standardization, 2017). This links the regulatory context directly to the safety and security dimension of the enabler–barrier matrix.

- **Laws and standards considered:** Regulation (EU) 2019/2144, ISO 26262, ISO 21448/SOTIF, Automotive SPICE and ISO 15005, particularly for type approval, safety concepts, hazard analysis, safety requirements, validation, fault-tolerant design and HMI-related warnings or interventions.

3.2.5 Cybersecurity and software-update requirements

Passenger-aware services depend on connected digital systems, communication networks and software components that must remain secure throughout their lifecycle. Cybersecurity therefore represents both a regulatory requirement and a key prerequisite for maintaining passenger trust and operational reliability.

Vehicle-integrated AI services depend on cameras, microphones, vehicle-status signals, passenger interfaces, control-centre communication, cloud or edge components and software updates. For this reason, cybersecurity and software-update governance were addressed as core elements of the regulatory assessment. Relevant requirements and good practices are reflected in the Cyber Resilience Act (CRA, Regulation (EU) 2024/2847), UNECE Regulations No. 155 and No. 156, Regulation (EU) 2019/2144, and ISO/SAE 21434, covering areas such as cybersecurity management, secure software updates and lifecycle security engineering. The applicability of these instruments depends on the product and system concerned. In particular, products with digital elements to which Regulation (EU) 2019/2144 applies are excluded from the scope of the CRA (European Parliament and Council of the European Union, 2024b).

Within the vehicle type-approval context, UNECE Regulation No. 155 addresses cybersecurity management, while UNECE Regulation No. 156 addresses software-update management (United Nations Economic Commission for Europe, 2021a, 2021b). These requirements are linked to Regulation (EU) 2019/2144, making cyberattack prevention and secure update processes integral elements of vehicle development (European Parliament and Council of the European Union, 2019a).

From a development perspective, ISO/SAE 21434 provides a relevant standard for cybersecurity engineering across the road-vehicle lifecycle (International Organization for Standardization & SAE International, 2021). It defines engineering requirements for cybersecurity risk management covering vehicle E/E systems from concept and development through production, operation, maintenance and decommissioning. For in-cabin monitoring, cybersecurity is closely connected to passenger trust and safety: unauthorised access to video/audio streams, manipulation of detection results, compromised software updates or denial-of-service attacks against control-centre communication could undermine both privacy and operational response. Therefore, cybersecurity-by-design, secure data interfaces, update traceability, and monitoring of system health should be treated as core enablers of compliance and safety.

- **Laws and standards considered:** Regulation (EU) 2024/2847 (Cyber Resilience Act), UNECE Regulation No. 155, UNECE Regulation No. 156, Regulation (EU) 2019/2144 and ISO/SAE 21434:2021.

3.2.6 Accessibility, passenger rights and inclusive service design

Improving accessibility is a central objective of several OptiPEx service concepts. At the same time, these services must comply with legal requirements on accessibility, non-discrimination, and passenger rights.

The analysis addressed Regulation (EU) No. 181/2011 on bus and coach passenger rights, which establishes non-discrimination and assistance obligations for disabled persons and persons with reduced mobility, as well as minimum passenger information requirements (European Parliament and Council of the European Union, 2011). For passenger-aware AI services, this supports functions that improve boarding, alighting, orientation, assistance requests and access to passenger information, but it also requires that such services do not create new barriers or unequal treatment.

From a vehicle perspective, UNECE Regulation No. 107 is relevant for buses in vehicle categories M2 and M3 because it addresses the general construction of buses and coaches, including accessibility, wheelchair access, internal layout, boarding devices, passenger information and safety features (United Nations Economic Commission for Europe, 2015). Its accessibility-related requirements, including accessible stop-request, door-opening or assistance-request interfaces, are directly relevant where OptiPEx concepts interact with passengers inside the vehicle or support passengers with reduced mobility.

Digital passenger interfaces are also affected by Directive (EU) 2019/882, the European Accessibility Act, which applies to certain transport-related digital services, including websites, mobile services, electronic tickets, ticketing machines and passenger information services (European Parliament and Council of the European Union, 2019b). For OptiPEx, this is particularly relevant for passenger apps, passenger information displays, e-ticketing links and multimodal interaction channels. Accessibility requirements for ICT products and services (2021-03), EN 301 549, ETSI harmonised European standard and universal design principles should therefore be considered early in development to ensure that information and alerts are perceivable, operable, understandable and robust for passengers with different sensory, cognitive or mobility needs (European Telecommunications Standards Institute, 2021).

- **Laws and standards considered:** Regulation (EU) No. 181/2011, UNECE Regulation No. 107, Directive (EU) 2019/882, EN 301 549 and universal design principles, particularly for passenger rights, assistance obligations, accessible bus design and accessible digital passenger information.

3.2.7 National requirements and operator responsibilities

Although many requirements are defined at the European level, deployment also depends on national legislation, supervisory practices and operator responsibilities. These factors may shape implementation requirements, approval processes, and operational obligations across countries. EU-level requirements, including the Cyber Resilience Act (CRA, Regulation (EU) 2024/2847), should also be considered where applicable to products with digital elements used in the service (European Parliament and Council of the European Union, 2024b). The CRA does not apply to products with digital elements to which Regulation (EU) 2019/2144 applies.

For OptiPEx, the countries of particular relevance are Germany, Finland, Spain and Austria. The following country sections summarise national aspects that should be checked for each pilot site or operating environment, especially regarding data protection supervision, CCTV or video surveillance in public transport, audio processing, vehicle and operator responsibilities, accessibility or passenger-information obligations, and national automated-vehicle rules.

- **Laws and standards considered:** GDPR, Regulation (EU) 2019/2144, Regulation (EU) 2024/2847 (CRA); Germany's Road Traffic Act, AFGBV, Passenger Transport Act and the official German regulatory framework governing the construction and operation of tramways, light rail systems, and underground/metro networks (*Verordnung über den Bau und Betrieb der Straßenbahnen*, BOStrab); Finland's Road Traffic Act and Vehicle Act; Spain's Directorate-General for Traffic (DGT) automated-vehicle testing framework, including Instruction VEH 2022/07; Austria's Automated Driving Ordinance, Motor Vehicle Act and Road Traffic Act.

3.2.7.1 Germany

In Germany, the GDPR is complemented by the Federal Data Protection Act (BDSG). Its provisions on video surveillance of publicly accessible spaces are relevant to passenger monitoring in public transport, including requirements concerning purpose, necessity, transparency and data retention (Federal Ministry of Justice, n.d.). The BDSG expressly addresses video surveillance in vehicles and publicly accessible facilities of public rail, ship and bus transport. If monitoring also covers staff areas, employment-related data protection rules and works council involvement may be relevant.

Regarding automated vehicles, Germany has a comparatively advanced national framework. The amended Road Traffic Act and the Autonomous Vehicles Approval and Operation Ordinance (*Verordnung zur Genehmigung und zum Betrieb von Kraftfahrzeugen mit autonomer Fahrfunktion in festgelegten Betriebsbereichen*, AFGBV), which is Germany's pioneering federal legal framework for autonomous driving allow regular operation of Level 4 vehicles in defined operational areas, including potential public transport applications. Approval requires a vehicle-related type approval by the German Federal Motor Transport Authority (KBA) and an operational permit for the defined operating area, with responsibilities split between the national type-approval authority and the competent regional authority. A Technical Supervisor must be designated for operation. For public transport, the Passenger Transport Act and accessibility obligations remain relevant, while tramway applications are subject to BOStrab; driverless tram operation is not yet covered in the same way as road vehicles and may require accompanying personnel or specific test arrangements (Federal Ministry of Justice, 2022; Kraftfahrt-Bundesamt, n.d.; United Nations Economic Commission for Europe, 2024).

3.2.7.2 Finland

In Finland, national data protection requirements and guidance from the Data Protection Ombudsman should be considered alongside the GDPR. Camera surveillance constitutes processing of personal data and should therefore be assessed accordingly when used in passenger-aware services (Data Protection Ombudsman's Office, n.d.).

For automated vehicles, Finland currently follows a flexible testing-oriented approach rather than a dedicated framework for regular Level 4 public transport operation. The Road Traffic Act and Vehicle Act allow automated test drives, with Traficom issuing test plate certificates. Applicants must provide documentation such as a description of the automated driving function, vehicle modifications, insurance and a risk assessment. Finnish law requires a responsible driver but does not necessarily require them to be inside the vehicle, enabling remote supervision concepts. Legislative amendments are being prepared to allow broader use of automated driving systems on public roads and to clarify the shift of responsibilities from the human driver towards the organisation operating the automated driving system (Connected Automated Driving Europe, 2024; Finnish Government, 2024; Finnish Transport and Communications Agency, 2023).

3.2.7.3 Spain

In Spain, the GDPR is complemented by national data protection requirements and guidance from the Spanish Data Protection Agency (AEPD). Its guidance on video surveillance is relevant to passenger-aware services using video or audio monitoring (Agencia Española de Protección de Datos, 2023). The AEPD provides dedicated guidance on video surveillance and also identifies material concerning the proportionality of image and voice recording.

Spain is also transitioning toward a permanent framework for automated vehicles. Testing on public roads is regulated through DGT procedures such as Instruction VEH 2022/07 and subsequent national testing frameworks. Applicants generally need to provide insurance, vehicle and system documentation, a description of the test, risk assessments and evidence of safety validation; event data recording or comparable data-storage functions may also be required. Automated operation must remain supervised by a defined operator, either on board or remotely, while fully unattended operation is not currently treated as a regular deployment model. Future mobility legislation is expected to provide a broader legal framework for innovative mobility,

including controlled testing environments, accessibility and integration with public transport systems (Connected Automated Driving Europe, 2026; Dirección General de Tráfico, 2022, 2026).

3.2.7.4 Austria

In Austria, national data protection requirements should be considered alongside the GDPR. Guidance from the Austrian Data Protection Authority on video surveillance is relevant to passenger-aware monitoring, particularly regarding necessity, proportionality and transparency (Austrian Data Protection Authority, n.d.). The authority's guidance emphasises case-by-case assessment, limiting surveillance to what is necessary in terms of area and time, and appropriate notification of video surveillance.

Austria has regulated automated driving primarily through the Automated Driving Ordinance, based on the Motor Vehicle Act. The framework allows defined automated-driving use cases and testing on public roads where specific requirements are met, including insurance, documentation, compliance with road traffic rules and safety measures. Permitted use cases include automated vehicles for passenger transport, automated parking, motorway pilot functions and other defined test scenarios. For highly automated public-road tests, a trained safety driver or a comparable immediate intervention concept is generally required. For regular public transport deployment, general EU and Austrian road-traffic, vehicle and operator rules continue to apply; accessibility is mainly reflected through EU type-approval requirements such as UNECE R107 for buses (Austrian Federal Chancellery, 2024; Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, 2022; oesterreich.gv.at, n.d.).

3.2.8 Implications for in-cabin monitoring in OptiPEx

The regulatory review provides practical guidance for the design and deployment of passenger-aware monitoring functions. Rather than determining whether monitoring technologies can be used, the identified requirements help define the conditions under which they can be implemented responsibly and lawfully.

The regulatory analysis leads to a layered implementation approach for in-cabin monitoring. Passenger density, occupancy and abstracted posture indicators are comparatively more acceptable when implemented as aggregated or anonymised analytics. Emergency detection, fall detection, blocked-area detection and collision-related risk support are more sensitive but can be justified when they are strictly purpose-limited, safety-oriented and supported by human escalation. Audio processing should be limited to event-based acoustic detection wherever possible. Emotion recognition, group-emotion inference, biometric identification and biometric categorisation should be avoided unless a separate legal assessment demonstrates a clear necessity, lawful basis and proportionality.

In addition, the analysis shows that in-cabin monitoring cannot be assessed only as a data-processing or AI function. Its deployment also depends on whether the service interacts with vehicle safety functions, automated-driving operation, passenger information systems, accessibility obligations or national approval procedures. Therefore, each OptiPEx service concept should be assessed according to its concrete function, operational role and deployment country. This includes checking whether the function remains an information or assistance service, becomes part of a safety-relevant vehicle function, or requires specific operator procedures, authority involvement or national permissions for automated public transport operation.

Overall, the relevant norms and laws do not prevent AI-based in-cabin monitoring, but they strongly shape its acceptable design. A legally robust OptiPEx approach should prioritise local processing, event-based recording, abstracted outputs, limited retention, transparent passenger information, data protection impact assessment, cybersecurity-by-design, validation across realistic operating conditions, documented fallback procedures and human oversight for escalation and intervention (European Data Protection Board, 2020; European Parliament and Council of the European Union, 2016, 2024a, 2024b; United Nations Economic Commission for Europe, 2021a, 2021b).

3.3 Ethical and societal considerations

Regulatory compliance provides the legal basis for deploying passenger-aware services, but responsible deployment also requires consideration of broader ethical and societal implications. Ethical principles can help ensure that passenger-aware technologies respect individual rights, support inclusion and maintain public trust. This section summarises the key ethical principles relevant to OptiPEx and discusses their implications for human oversight and passenger acceptance.

3.3.1 Ethical considerations

The deployment of passenger-aware AI services raises ethical questions related to privacy, fairness, transparency, human autonomy and accountability. These considerations are particularly important when services collect, analyse or act upon passenger-related information. While legal compliance establishes the minimum requirements for deployment, ethical principles help ensure that technology is developed and used in ways that respect individuals, support societal well-being and maintain public trust.

OptiPEx follows the principles of the Ethics Guidelines for Trustworthy AI (European Commission, Directorate-General for Communications Networks, Content and Technology, & High-Level Expert Group on Artificial Intelligence, 2019), which state that AI systems should be lawful, ethical and robust throughout their lifecycle. In practice, this means that passenger-aware services should respect human autonomy, prevent harm, promote fairness and remain understandable to users and stakeholders. Particular attention should be given to vulnerable groups, including passengers with disabilities, older adults and other users who may face barriers when using public transport services.

Several of the OptiPEx service concepts use sensing and analytics to improve passenger experience, accessibility or safety. Ethical deployment therefore requires careful consideration of privacy, data governance, transparency and accountability. Passengers should understand the purpose of the service, the type of information being processed and the intended benefits. Technologies should avoid unnecessary collection of personal data, minimise risks of discrimination or bias and support equitable treatment of different passenger groups.

The Ethics of Connected and Automated Vehicles (European Commission, Directorate-General for Research and Innovation, 2020) recommendations further emphasise privacy protection, informed consent, transparency, accountability and the prevention of discriminatory outcomes. Similarly, the Institute of Electrical and Electronics Engineers (IEEE) Global Initiative on Ethics of Autonomous and Intelligent Systems (IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems, 2017) highlights human rights, well-being, accountability, transparency and minimisation of misuse as important principles for the responsible development of intelligent systems.

Several OptiPEx design decisions were guided by privacy, fairness and societal acceptance considerations. For example, the project prioritises aggregated, event-based and privacy-preserving approaches over detailed monitoring of identifiable individuals. Certain technically feasible capabilities, such as individual emotion recognition, passenger profiling or other forms of intrusive passenger monitoring, were intentionally not included in the OptiPEx service concepts due to ethical, privacy and societal acceptance considerations. These ethical principles and design choices provide the foundation for the discussion of human oversight and passenger acceptance presented in the following sections.

3.3.2 Human oversight

Human oversight is a core principle in both trustworthy AI and public transport operations. It influences passenger trust, acceptance and perceptions of safety, particularly when AI systems support decision-making or operational responses. The findings from the passenger survey and focus groups reported in OptiPEx Deliverable D2.1 provide valuable insights into how passengers perceive the role of human oversight in AI-enabled public transport services (Lucas-Alba et al., 2025).

The issue of human oversight is strongly supported by the convergence between the two types of data: the quantitative survey and the focus groups (see OptiPEx deliverable D2.1 (Lucas-Alba et al., 2025)). The central idea is that participants do not necessarily reject technology, or even partial automation, but they do express clear reservations about the complete replacement of human supervision, especially when that absence affects safety, assistance, accessibility, conflict management and responsiveness.

Human oversight: synthesis of findings

The data suggest that autonomous public transport without a human driver is perceived cautiously or moderately negatively. In the survey, the four dimensions linked to autonomous transport — comfort, accessibility, safety/security and responsiveness — do not receive clearly positive evaluations. After reversing the negatively worded items so that all items point in the same direction, accessibility emerges as the least problematic dimension, whereas the weakest dimensions are comfort, safety and, particularly according to the net balance, responsiveness.

This indicates that the main concern does not appear to be purely technological. The issue is not only whether the vehicle can operate without a driver, but what happens when a human figure disappears whom passengers associate with supervision, assistance and situational control. In this sense, the driver or on-board staff are not perceived merely as vehicle operators, but also as a source of safety, guidance, assistance and capacity for intervention.

In quantitative terms, the survey shows that acceptance of autonomous transport is limited. The aggregate acceptance index for autonomous transport was below the neutral point, and the net balances were negative across the four dimensions. The pattern was particularly clear for safety and responsiveness: participants do not seem to expect a driverless system to be safer or to respond better to their needs. This is important because it connects directly with the idea of human oversight: the absence of a responsible person raises doubts about who detects, interprets and resolves problematic situations.

The focus groups reinforce this interpretation. The report shows that fully autonomous vehicles were not generally perceived favourably. Many participants considered that they could reduce their sense of safety, both because of the risk of accidents or technical failures and because of the difficulty of managing conflicts, emergencies or unexpected situations inside the vehicle.

The demand for human supervision appears across the different use cases. In the case of automatic assistance for passengers with special needs, some participants positively valued potential automated improvements, such as automatic ramps, door opening or passenger detection. However, these improvements do not remove concerns about the absence of human help. Among vulnerable users, especially older adults and people with visual impairments, reduced mobility or wheelchair users, the central issue is whether they will be able to board, orient themselves, find a seat or receive help when something does not work properly.

In the case of anomaly detection and on-board safety, participants are more accepting of AI when it operates as support for human staff. Cameras, surveillance systems, detection of altercations and automatic alerts are perceived positively if they serve to notify drivers, security staff or supervision centres. However, the focus groups show a clear condition: AI should not have ultimate responsibility for intervening or managing emergency protocols. Technology is accepted as a detection and alert system, not as a full substitute for human intervention.

In the case of vehicle-to-pedestrian communication and collision prevention, participants, especially students, are relatively receptive to sensors, automatic braking and warning systems. However, the same condition appears here as well: automation should complement, not replace, human supervision. Acceptance increases when automated systems are understood as an additional layer of safety but decreases if they are presented as a complete transfer of responsibility to the machine.

In the case of passenger distribution optimisation, cameras, sensors and intelligent systems are perceived quite positively because they respond to everyday problems: occupancy, access to reserved spaces, seat availability and management of the interior space. Nevertheless, even here, human staff remain important for

organising the space, assisting vulnerable passengers and dealing with uncivil behaviour. The report shows that some participants associate the presence of a supervising person with greater respect for reserved spaces, more order and better attention to those who need help.

Therefore, the results support a clear conclusion: acceptance of automation depends largely on the presence of meaningful human supervision. Participants are not necessarily opposed to cameras, sensors, apps, detection systems, automatic alerts or even automated accessibility functions. What generates greater resistance is the idea of a fully autonomous public transport system in which no human figure is available to supervise, assist, interpret ambiguous situations or intervene in conflicts and emergencies.

Summing up: human oversight

The results indicate that human oversight remains a central condition for the acceptability of autonomous and AI-supported public transport services. Survey data show that autonomous public transport is not perceived as clearly more comfortable, safer, or more responsive to users' needs. Focus group findings reinforce this pattern: participants were generally more willing to accept AI-based systems when they operated as support tools for detection, information, accessibility or safety, but they expressed reservations when automation implied the removal of human staff. The driver or onboard staff appear to be valued not only for vehicle operation, but also for reassurance, assistance, conflict management, emergency response and the supervision of shared spaces. Therefore, the main issue is not automation per se, but the perceived loss of human responsibility and situational responsiveness in fully driverless services. All in all, the main idea is *AI as support is acceptable; automation as human replacement is problematic*.

3.3.3 Passenger acceptance

The successful deployment of passenger-aware services depends not only on technical performance but also on passenger acceptance. Perceptions of usefulness, trust, privacy, safety and accessibility all influence how new technologies are received by different user groups. This section summarises the main acceptance-related findings from the passenger survey and focus groups conducted within OptiPEx and reported in Deliverable D2.1 (Lucas-Alba et al., 2025).

Passenger acceptance: synthesis of findings

The results suggest that passenger acceptance is selective, conditional, and use-case dependent. Participants do not appear to reject technological innovation in public transport as such. On the contrary, many digital or AI-supported services are positively received when they provide practical benefits, such as better information, improved safety, assistance for passengers with specific needs, or better management of crowding. However, acceptance decreases when technology is associated with full automation, loss of human presence, reduced control, or uncertain responsibility in emergencies.

The survey and focus group findings therefore point to a clear distinction: *Passengers are more accepting of AI-enabled support services than of fully autonomous public transport.*

This distinction is important. Technologies such as mobile applications, occupancy information, alerts for pedestrians, anomaly detection, cameras, sensors, or assistance systems are generally easier to accept when they are framed as tools that improve the service. By contrast, fully driverless public transport raises more reservations because it affects passengers' expectations about safety, assistance, comfort, accessibility and responsiveness.

1. Digital and AI-enabled services are relatively well accepted

The survey results show comparatively positive attitudes toward digital and information-based services. Participants were especially favourable toward services that provide information about the occupancy level of the next vehicle, mobile applications that help users navigate the public transport system, and alerts informing pedestrians about the proximity of a vehicle. These services are not described explicitly as "AI" in the survey, but they can reasonably be interpreted as digital, data-driven or potentially AI-enabled services. The survey includes these items in the comfort, accessibility and responsiveness sections.

This pattern is consistent with the focus groups. Participants often accepted AI-based systems when they were connected to a concrete and understandable function: detecting incidents, supporting boarding and alighting, estimating occupancy, identifying available spaces, preventing collisions, or improving passenger distribution. The key point is that acceptance increases when the technology has a specific practical purpose and when its benefits are easy to understand.

A concise interpretation would be *Passenger acceptance is higher when AI-enabled systems are perceived as practical service improvements rather than as abstract technological innovation.*

2. Acceptance depends strongly on perceived usefulness

Across both the survey and focus groups, acceptance appears to be strongly linked to perceived usefulness. Services that solve concrete passenger problems are better received. This is particularly clear for occupancy management, passenger distribution, information about crowded vehicles, assistance for boarding, and safety-related alerts.

For example, in the focus groups, systems using cameras, sensors or AI to improve passenger distribution were often perceived positively because crowding, access to seats, and the management of reserved areas are everyday concerns. Similarly, anomaly detection systems were accepted when they were seen as tools for improving safety on board.

However, not all digital assistance is equally accepted. In the survey, the item concerning guidance to find a free seat on board was less favourably evaluated than other digital services. This suggests that acceptance is not automatic; it depends on whether users perceive the service as useful, necessary, non-intrusive and compatible with their actual travel experience.

3. Autonomous public transport receives more cautious acceptance

Passenger acceptance is clearly weaker for autonomous public transport than for digital support services. In the survey, the autonomous transport items were not positively evaluated overall. After recoding the negatively worded items so that higher values indicated more favourable attitudes, the four dimensions — comfort, accessibility, safety/security and responsiveness— remained below a clearly favourable level.

The pattern is especially informative. Autonomous public transport was not perceived as clearly more comfortable, safer, more responsive to users' needs or better able to aid without human staff.

The least problematic dimension was accessibility, but even this did not become clearly positive. The most problematic dimensions were comfort, safety/security and responsiveness. This suggests that passenger acceptance is not only about the technical feasibility of autonomous vehicles. It is also about whether passengers believe that the service can still provide care, reassurance, assistance and situational response without a human driver.

The focus groups reinforce this interpretation. Fully autonomous, driverless vehicles were generally not perceived favourably. Participants expressed concerns about accidents, technical failures, emergency situations, conflicts inside the vehicle, and the absence of human assistance.

A concise formulation would be *Passenger acceptance decreases when automation is perceived as removing human support rather than improving the service*.

4. Privacy is not rejected absolutely, but acceptance is conditional

Privacy-related acceptance is also conditional. The survey included one clearly relevant privacy item: willingness to allow the mobile phone to share location with public transport providers, under the condition that personal information would not be misused, to improve road safety for passengers and pedestrians.

The results suggest a moderate and cautious attitude: participants are not categorically opposed to sharing data, but acceptance depends on the purpose and safeguards. This is consistent with the focus groups, where many participants were willing to accept certain forms of data use, cameras or monitoring when these were

clearly linked to safety, accessibility or service improvement. However, concerns remained about constant surveillance, misuse of personal data, excessive monitoring and the need for anonymity or regulation.

The key idea is *Privacy concerns do not necessarily block passenger acceptance, but they make acceptance conditional on transparency, proportionality, anonymity, regulation and clear service benefits.*

5. Passenger acceptance varies by profile, but country and age matter most

The survey results suggest passenger acceptance varies across groups. The strongest differences appear by country, followed by age, then gender, while educational level plays a more limited role. The main patterns are summarised in Table 3.

Table 3. Passenger acceptance by profile.

Profile variable	Main acceptance pattern
Country	The strongest differentiating factor. Spain shows the highest acceptance of digital services; Germany is comparatively more open to autonomous public transport; Finland is the most reluctant toward autonomous public transport.
Age	Younger participants are more open to autonomous public transport and report more prior experience and greater app use. Older participants are more reluctant.
Gender	Men are more open to autonomous public transport and more willing to share location data. Women show more reservations, especially toward autonomous public transport.
Educational level	University education is associated with greater digital familiarity and higher use of transport apps, but it does not produce a clear linear increase in acceptance of autonomous public transport.

This suggests that passenger acceptance is shaped by both technology-related factors and social or contextual factors. Greater digital familiarity may support acceptance of digital services, but it does not automatically translate into strong acceptance of fully autonomous public transport.

6. Overall interpretation

The evidence points to a layered model of passenger acceptance. At the most acceptable level are digital and AI-enabled services that support passengers without replacing human responsibility. These include information apps, occupancy information, pedestrian alerts, anomaly detection, collision-prevention systems and passenger distribution tools. At an intermediate level are privacy-sensitive services, such as geolocation sharing or video-based monitoring. These can be accepted, but only if the purpose is clear, the data use is limited, and safeguards are credible. At the least accepted level is fully autonomous public transport, especially when driverless operation is perceived as removing human oversight, assistance and responsibility.

3.4 Safety and security contexts

Passenger-aware public transport services are deployed in environments where safety, security and operational reliability are critical. While many AI-enabled services primarily provide information, accessibility support, or comfort improvements, others support safety-related monitoring, situational awareness, or incident response. As a result, the potential consequences of system failures, incorrect detections or delayed responses vary considerably across service concepts.

Safety-related functions require confidence that systems perform reliably under realistic operating conditions and that potential failures can be detected and managed appropriately. Particular attention should be given to false alarms, missed detections, degraded operation, cybersecurity threats and the availability of

appropriate human oversight and intervention mechanisms. These considerations become increasingly important as AI-enabled services move closer to operational decision-making and safety-critical contexts.

Across the OptiPEx service concepts, safety and security considerations influence deployment readiness alongside regulatory compliance, ethical acceptability and technical feasibility. The closer a service is integrated with passenger protection, vehicle operations or incident management, the greater the need for validation, operational procedures, cybersecurity measures and clearly defined responsibilities. These considerations form an important part of the enabler and barrier analysis presented in Section 4.

4 Enablers and barriers for passenger-aware public transport services

This section presents the recurring enablers and barriers identified across the eight OptiPEx service concepts using the five-dimensional assessment framework. The analysis identified a combination of regulatory, ethical, technical, safety-related and organisational factors that may influence the future deployment of passenger-aware public transport services. Across the analysed service concepts, recurring enablers included clear passenger benefits, human oversight, accessible and inclusive design, privacy-preserving approaches, and the use of existing infrastructure and standards. At the same time, several recurring barriers emerged, particularly related to privacy and data protection, passenger trust, technical validation, system reliability, and organisational readiness. Together, these findings highlight both the opportunities and constraints associated with the deployment of AI-enabled passenger-aware public transport services.

The significance of individual enablers and barriers varies between service concepts. Safety-related services generally require higher levels of reliability, validation, cybersecurity, human oversight and organisational preparedness than services primarily aimed at improving passenger information, accessibility or comfort. Consequently, the same factor may have different implications depending on the purpose, technical implementation and operational context of the service

4.1 Common enablers and barriers for OptiPEx service concepts

The findings are presented according to the five dimensions of the analysis framework. Table 4 to 8 summarise the recurring enablers and barriers identified across the analysed service concepts. Detailed service-concept-specific findings are presented in Appendix 1.

4.1.1 Regulatory and compliance

Regulatory and compliance factors influence how passenger-aware services can be designed, implemented and deployed in public transport environments. Across the analysed service concepts, common enablers were related to privacy-preserving design approaches, accessibility requirements and the possibility of incorporating regulatory requirements into the system design from an early stage. The most common barriers were associated with personal data protection, evolving AI regulations, uncertainties regarding legal responsibilities and requirements related to data sharing and third-party approvals. Table 4 summarises the key regulatory and compliance-related findings.

Table 4. Common enablers and barriers related to regulation and compliance.

Common enablers	Common barriers
Data minimisation: The solution can avoid collecting personal data and use event-triggered, non-identifiable recording instead of continuous monitoring. This limits unnecessary data processing and reduces data retention, storage requirements and data-governance challenges.	**Privacy and personal data restrictions:** Restrictions on identifying and profiling passengers under GDPR may limit implementation options. Ambiguities in GDPR interpretation, uncertainty regarding applicable legislation and potential gaps in safety-related regulations may further hinder deployment.
Compliance-by-design: Regulatory and legal requirements can often be identified and incorporated during system design. Addressing compliance early reduces deployment risks and supports implementation and future operation.	**Regulatory uncertainty**: Unclear AI Act requirements, certification processes, future regulation, and approval procedures may delay service implementation and increase deployment risks.

Common enablers	Common barriers
Accessibility regulations supporting design and requirements: Established accessibility frameworks, including Technical Specification for Interoperability relating to Persons with Reduced Mobility (TSI PRM) and the European Accessibility Act, provide guidance and requirements for designing inclusive passenger services.	**Third-party approvals**: Unclear data owner responsibilities and permissions for sharing sensitive data with third parties may hinder deployment.

4.1.2 Ethical and societal aspects

Passenger acceptance and societal legitimacy are essential prerequisites for the successful deployment of AI-enabled public transport services. Across the analysed service concepts, common ethical and societal enablers were linked to clear passenger benefits, inclusive service design and the maintenance of meaningful human oversight. The corresponding barriers were primarily related to trust, transparency, concerns regarding surveillance and privacy, risks of unequal treatment, and challenges associated with technology adoption among different passenger groups. Table 5 presents the common ethical and societal findings.

Table 5. Common enablers and barriers related to ethical and societal aspects.

Common enablers	Common barriers
Clear passenger benefit: Use cases that provide clear improvements in safety, accessibility, and passenger comfort are more likely to achieve broad user acceptance and stakeholder support.	**Passenger trust:** Concerns about AI, potential bias, limited transparency and misconceptions about data use may reduce trust and create resistance to adoption. Continuous monitoring or surveillance may further negatively affect the passenger experience.
Human control is maintained in the system: AI functions support rather than replace human decision-making. Maintaining driver, operator or passenger control over important actions increases trust, supports accountability and enables intervention when needed.	**Risk of highlighting individual vulnerabilities and fairness risk:** Identifying disabilities and making special needs visible may unnecessarily expose certain passenger groups. This may also lead to unequal treatment of passenger groups.
Inclusive design: Support for passengers with diverse accessibility needs beyond existing solutions improves the user experience. Accessible interaction methods and support for multiple languages further benefit passengers.	**Technology adoption issues**: Deployment may be constrained when services require smartphone ownership or specific devices. If the system requires additional user effort (e.g., installing an app and registering for service), it may further reduce adoption of new services.

4.1.3 Safety and security

Safety and security considerations are particularly important for passenger-aware systems that provide situational awareness, support operational decision-making or contribute to passenger protection. The analysis identified several recurring enablers related to human oversight, cybersecurity measures and improved awareness of potentially hazardous situations. At the same time, concerns regarding misclassification, system failures and time-critical operational requirements emerged as recurring challenges. Table 6 summarises the common safety and security-related findings.

Table 6. Common enablers and barriers related to safety and security

Common enablers	Common barriers
Human-centred safety architecture: Systems designed with continuous human supervision and manual override capabilities, ensuring that automated functions enhance rather than replace human decision-making and safety management. Different operator escalation procedures and safe-stop mechanisms support this as well.	**AI (or pattern-recognition) classification errors**: Missed detections (e.g., false negatives), false alarms (e.g., false positives), or delayed detection can lead to late warnings and hazardous situations, depending on the safety level of the use case.
Cybersecurity implementation: Secure communication, encryption protocols and established standards support safe implementation. Compliance with cybersecurity requirements from the design phase and continuous monitoring during operation further strengthen system resilience.	**System failure consequences:** Safety-critical failures can result in operational disruptions, delayed reactions, and inappropriate interventions, increasing risks for passengers and operators.
Real-time awareness to improve operational safety: Real-time awareness, supported by early warning capabilities, situational awareness, and continuous condition monitoring, enhances operational safety by enabling timely interventions and improving passenger safety and security.	**Time-critical performance requirements**: Services depend on real-time responses, reliable communication and timely operator intervention. Time-critical situations may leave control-centre personnel with limited time to react, increasing the risk of delayed or ineffective interventions.

4.1.4 Technical validation and interoperability

Deploying passenger-aware services depends not only on regulatory compliance and passenger acceptance but also on technical feasibility and interoperability within existing public transport ecosystems. Common technical enablers identified in the analysis included scalable architectures, the use of existing standards and infrastructure, and opportunities provided by evolving AI technologies. The most significant barriers were related to data availability and quality, validation under realistic operating conditions, integration complexity and dependencies on external technologies and infrastructure. Table 7 presents the common technical validation and interoperability findings.

Table 7. Common enablers and barriers related to technical validation and interoperability

Common enablers	Common barriers
Scalability: The solution can be deployed across multiple vehicles and operating environments, increasing its potential impact and commercial viability. Modular architectures and standardised interfaces further facilitate integration and interoperability.	**Data limitations**: Lack of training and real-world data, limited dataset diversity, and data ownership constraints may reduce model performance, complicate validation activities, and slow the deployment of AI-enabled services.
Use of standards and infrastructure: Existing transport infrastructure and vehicle data systems reduce implementation effort and facilitate integration into public transport ecosystems. Standardised communication interfaces (e.g. Auracast) further support interoperability between vehicles, infrastructure and passenger devices.	**Real-world variability**: Lighting conditions, vehicle occupancy levels, and environmental factors (e.g., acoustic conditions) may reduce system performance compared to controlled testing environments.
AI-supported data generation and augmentation: Synthetic data generation, data augmentation techniques and the availability of open-access datasets can support	**Technology dependencies and system complexity**: Integration with vehicle systems may require significant customisation efforts and may vary across vehicle types and operators.

Common enablers	Common barriers
AI model development and validation when real-world data are limited.	Dependencies on network connectivity, external technologies, infrastructure, third-party systems and passenger-owned devices may further increase implementation complexity.
	Validation challenges: Limited detection accuracy for rare safety-related events and other difficult classification cases can reduce overall accuracy. Validating rare cases and extensive multi-scenario testing can create significant challenges for service validation.

4.1.5 Organisational and operational readiness

Even technically feasible and legally compliant services require organisational preparedness to achieve successful deployment and long-term operation. Across the analysed service concepts, common organisational enablers were associated with compatibility with existing operational practices, support from established ecosystem actors and manageable maintenance requirements. Recurring barriers included capability gaps, lifecycle management burdens and dependencies on suppliers, third-party systems and cross-organisational coordination. Table 8 summarises the common organisational and operational readiness findings.

Table 8. Common enablers and barriers related to organisational and operational readiness

Common enablers	Common barriers
Low operational burden: Compatibility with existing operational roles, minimal training requirements, intuitive functionality, and limited intervention needs facilitate efficient deployment and long-term service operation.	**Operational capability gaps**: In complex services, insufficient staff training, limited technical expertise, lack of established procedures, and control-centre readiness challenges may reduce deployment and operational readiness.
Existing ecosystem: Trusted partnerships and vendor support increase deployment readiness by providing technical expertise and operational support.	**Lifecycle management burden**: Continuous software updates to maintain functionality, security, regulatory compliance, and compatibility with evolving technologies. Additional maintenance activities, including diagnostics, performance monitoring, and system health management, may increase operational workload and lifecycle costs.
Easy maintenance and updates: Built-in diagnostics and remote software updates support efficient lifecycle management and continuous service improvement. Configurable user-interface content can also facilitate the reuse of existing operational materials.	**Ecosystem dependencies**: Service implementation may be constrained by ecosystem dependencies, including supplier reliance, third-party integrations, contractual requirements, and cross-organisational collaboration needs.

4.1.6 Key enablers and critical barriers

The synthesis of the findings presented in Section 4.1 and the service-concept analyses identified several recurring themes that appear particularly important for the successful deployment of passenger-aware public transport services. Factors were considered key or critical when they recurred across multiple service concepts and were assessed as having a substantial expected influence on service deployment or acceptance. Table 9 presents the key enablers and Table 10 critical barriers identified across OptiPEx service concepts.

Table 9. Key enablers identified across OptiPEx service concepts

Key enablers	Main contributing service concepts							
	SC1 	SC2 	SC3 	SC4 	SC5 	SC6 	SC7 	SC8 
Clear passenger value and practical usefulness	x		x		x	x		x
Human oversight and access to human support				x		x	x	
Accessible and inclusive service design	x	x	x					x
Timely and reliable passenger information		x		x				x
Reliable and accurate system performance	x		x			x	x	x

Table 10. Critical barriers identified across OptiPEx service concepts

Critical barrier	Main contributing service concepts							
	SC1 	SC2 	SC3 	SC4 	SC5 	SC6 	SC7 	SC8 
Privacy and data protection concerns	x					x		x
Trust and acceptance of AI-driven decisions	x					x	x	
False positives and detection errors	x					x	x	
Dependence on passenger behaviour and compliance			x					x
Real-world implementation and operational feasibility			x	x		x	x	x

The most frequently recurring enabler across the analysed concepts was the ability to provide clear and tangible passenger benefits, particularly in terms of safety, accessibility, comfort and travel convenience. Human oversight and access to human support also emerged as important factors supporting trust and acceptance. In addition, accessibility, timely information and reliable system performance were consistently identified as important prerequisites for successful deployment. Privacy and data protection concerns emerged as the most common barriers, particularly for concepts involving passenger monitoring or automated detection. Trust in AI-supported functions and concerns about incorrect detections also recurred. Several concepts depended on passenger behaviour and cooperation, while operational procedures, system integration and organisational readiness created practical implementation challenges.

Overall, the findings indicate that successful deployment depends on balancing passenger value, accessibility, trust, privacy, technical reliability and operational feasibility. Concepts that provide clear user benefits, maintain appropriate human oversight and deliver reliable information appear better positioned for acceptance and deployment. Conversely, unresolved privacy concerns, insufficient trust, unreliable detection and unclear implementation responsibilities may constrain future deployment. These findings provide the basis for the implications presented in Section 5.

4.2 Cross-use-case barrier and enabler landscape

While Section 4.1 identified the main recurring enablers and barriers, it does not show their relative importance across service concepts. To support comparison, the identified factors were assessed according to their expected influence on deployment, adoption, operation and long-term sustainability. The recurring enablers and barriers were assessed using a three-level significance rating comprising low, medium and high significance. The rating reflects the expected influence of each factor on the deployment, adoption, operation or long-term sustainability of the service. The assessment criteria are presented in Table 11.

Where multiple enablers or barriers were identified within the same service concept and assessment dimension, the highest significance rating was used in the landscape visualisations. This approach highlights the most influential factor identified within each service concept and dimension and therefore provides a criticality-oriented rather than cumulative overview.

Table 11. Significance ranking classes

Significance	Enabler classes	Barrier classes
Low	Helpful but not essential. The service could still be implemented successfully without it.	Unlikely to have a significant effect on deployment or operation.
Medium	An important facilitating factor that improves feasibility, acceptance, performance, or operational efficiency.	May affect implementation, adoption, validation, or operational performance.
High	Strongly contributes to service viability, adoption, safety, scalability, inclusion, or operational readiness.	May prevent implementation, reduce service effectiveness, has effect on safety if fails.

The significance ratings were used to visualise the relative influence of identified enablers and barriers across the eight service concepts and five assessment dimensions. Darker colours indicate higher significance, while lighter colours indicate lower significance. The landscapes in Figure 1 and Figure 2 represent expert judgement of the expected influence of identified factors on future deployment readiness rather than measured system performance.

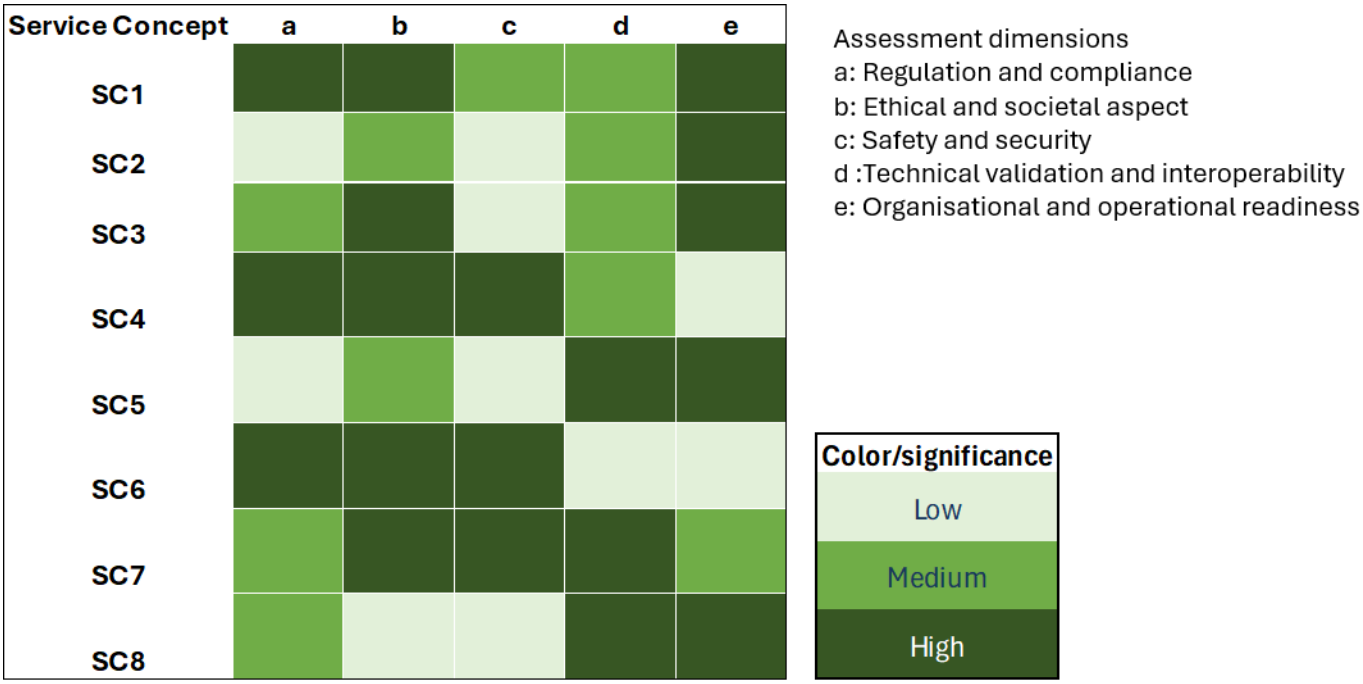


Figure 1. Enabler landscape

The enabler landscape highlights dimensions in which identified design choices, regulatory requirements, operational arrangements or technical solutions support successful deployment across multiple service concepts. Strong enablers are particularly visible in the areas of passenger value, accessibility, human oversight and scalable technical approaches.

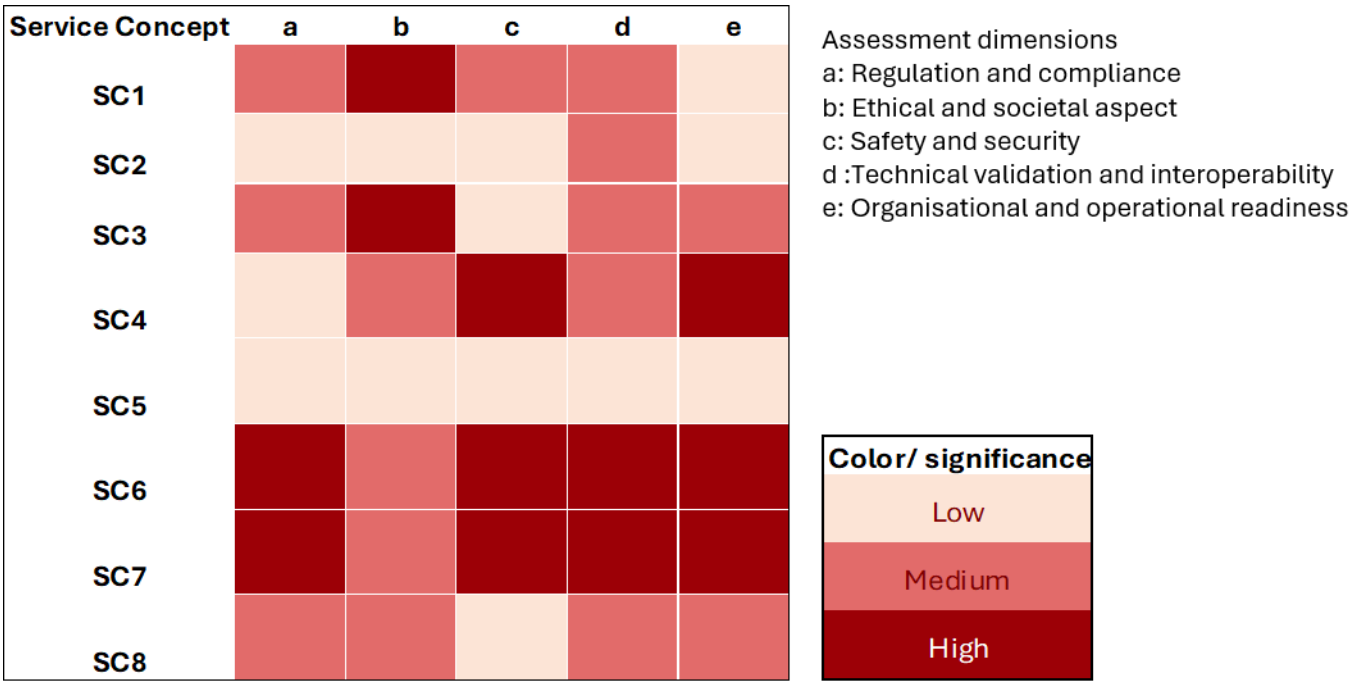


Figure 2. Barrier landscape

The barrier landscape highlights areas that require additional mitigation, validation, or organisational preparation. High-significance barriers are most frequently associated with regulatory uncertainty, privacy and

data protection concerns, availability of training and validation data, system reliability, and operational readiness.

The landscapes also indicate a clear distinction between comfort-oriented and safety-oriented services. Services aimed at passenger information, accessibility or comfort generally face fewer safety and validation challenges and can often leverage existing operational processes and infrastructure. In contrast, safety-related services require higher levels of reliability, validation, cybersecurity, human oversight and organisational readiness. As the potential consequences of incorrect or delayed system outputs increase, so does the need for testing, monitoring and operational governance.

Service concepts that can utilise existing vehicle systems, communication technologies, data sources and operational processes appear easier to deploy and scale. Standardised interfaces and modular architectures support interoperability and reduce integration complexity across different vehicles, operators and service environments.

Regulatory compliance remains a fundamental prerequisite for deployment, and uncertainty about how AI legislation, data protection requirements, and other regulatory obligations will be interpreted may slow implementation and increase development costs. In general, the complexity and evolving nature of legislation can be a significant barrier to introducing AI-enabled services. Another widely recognised barrier is the lack of training data for vulnerable road users and rare cases, which limits many use cases. Rapid advances in Generative AI (GenAI), Vision-Language Models (VLMs), and Large Multimodal Models (LMMs) create new opportunities for synthetic data generation and data augmentation, enabling more targeted model training and improved accuracy in recognising events and behaviour.

Across the service concepts, software maintenance and lifecycle management emerged as recurring considerations. Continuous updates, cybersecurity management, diagnostics, monitoring and evolving operational requirements may create long-term obligations for service providers and operators. Clear governance structures, responsibilities and operational procedures are therefore important for the sustainable deployment of passenger-aware public transport services.

5 Implications for AI-enabled public transport service design

The identified enablers and barriers provide insights into how passenger-aware public transport services can be designed, deployed and governed successfully. Although the analysed service concepts differ in their objectives and implementation approaches, several common lessons emerged regarding passenger value, privacy, trust, accessibility, reliability and operational readiness. This section synthesises these lessons and translates them into practical implications for future AI-enabled public transport services and their stakeholders.

5.1 Design implications

Deliver clear passenger value. Passenger acceptance depends strongly on perceived usefulness. Services should address tangible needs related to accessibility, safety, comfort or travel convenience, and these benefits should be clearly communicated to users. Concepts whose benefits are less visible to passengers or operators are likely to face lower acceptance and deployment readiness. Therefore, clear value creation should remain a primary design objective throughout service development.

Minimise personal data collection and use privacy-preserving approaches. Personal data processing should be limited to what is necessary for the intended purpose, and less intrusive sensing and monitoring approaches should be preferred whenever they can deliver the required functionality. Privacy-sensitive design is particularly important for services involving passenger detection or behavioural monitoring, as concerns regarding surveillance and data handling may reduce passenger acceptance.

Ensure reliable AI outputs and proportionate alerting. Reliability, accuracy and appropriate alert thresholds are essential for maintaining trust. False positives, excessive notifications and inaccurate predictions may reduce system credibility, contribute to alert fatigue and increase operator workload. AI-enabled services should therefore prioritise relevant events and keep notifications as precise and non-intrusive as possible.

Keep humans in the loop for alerts and interventions. Across the analysed service concepts, AI was generally perceived as most acceptable when supporting rather than replacing human judgement and intervention. Human oversight remains particularly important for safety-related functions, passenger assistance and incident management.

Provide actionable information at the right time and place. Passenger information should be accurate, easy to interpret and delivered sufficiently early for users to act on it. Where relevant, information should be provided before boarding rather than only inside the vehicle, and services should avoid increasing passenger or operator information load unnecessarily.

Design accessible, understandable and non-stigmatising passenger interfaces. Services should be accessible and inclusive for diverse passenger groups, including people with visual or mobility impairments, older users and passengers with varying levels of digital literacy. Multimodal interaction, simple language and clear visual or auditory presentation can improve both usability and acceptance. At the same time, services should avoid unnecessarily highlighting individual vulnerabilities or creating situations that could lead to stigma or unequal treatment.

Integrate AI services into existing operational workflows. New services should fit existing driver, control-centre and passenger workflows without introducing unnecessary responsibilities, distraction or operational disruption. Several analysed concepts demonstrated that perceived passenger value alone is insufficient if implementation requires substantial changes to operational practices. Services that integrate smoothly into existing procedures, responsibilities and infrastructure are likely to encounter fewer deployment barriers and achieve greater long-term sustainability.

5.2 Stakeholder implications

Technology developers and service providers. Technology developers should integrate privacy, accessibility, safety and cybersecurity requirements throughout the development lifecycle. Particular attention should be given to transparency, real-world validation, system robustness, reliable AI outputs and mechanisms supporting human oversight. Solutions that minimise unnecessary personal data processing, use proportionate sensing approaches and build on existing standards and infrastructure are likely to facilitate integration and reduce deployment barriers. The evaluation also indicates that technical performance alone is insufficient: systems must deliver clear passenger value and remain understandable and trustworthy in real use contexts.

Public transport operators. Successful deployment depends on organisational readiness as well as technical performance. Staff training, operational procedures, incident-management processes and lifecycle maintenance capabilities are important prerequisites for sustainable deployment. Attention should be given to how AI-enabled services fit existing workflows and affect driver and control-centre workload. Human oversight remains especially important for safety-related functions and passenger assistance, and new services should avoid unnecessary alerts, distraction or additional operational responsibilities. The tram-driver evaluation provides particularly strong evidence for the importance of these real-world operational constraints.

Vehicle manufacturers and system integrators. Many passenger-aware services depend on integration with vehicle systems, sensing technologies, communication infrastructure and passenger information platforms. Vehicle manufacturers and system integrators play an important role in enabling interoperability, maintaining cybersecurity, reliable data exchange and supporting deployment across different operating environments. Integration should also support multimodal and accessible interfaces while allowing AI functions to complement, rather than disrupt, established safety and control mechanisms.

Regulators and public authorities. The findings indicate that regulatory frameworks can both enable and constrain innovation. Public authorities and regulators have an important role in providing a clear framework for the responsible deployment of passenger-aware AI services, particularly regarding AI governance, data protection, accessibility and safety. Early dialogue between developers, operators and authorities can help clarify requirements and reduce uncertainty before deployment. This is especially relevant for services involving passenger group detection, behavioural monitoring or safety-critical interventions, where proportionality, transparency and accountability need to be clearly established. This implication is consistent with concerns identified during the OptiPEx co-creation and evaluation activities.

Passengers and target user groups. Passenger acceptance is strongly influenced by perceived usefulness, accessibility, transparency, reliability and trust. Continuous involvement of passengers and representative user groups can help ensure that services address genuine needs and remain usable under real travel conditions. Different passenger groups contribute different perspectives. Younger users often emphasise innovation and information services, older users' safety and reliability, visually impaired passengers' accessibility and communication, and mobility-impaired users' predictability and spatial coordination. Their involvement should therefore continue throughout prototype development, validation, demonstration and service refinement.

Cross-stakeholder coordination. The findings demonstrate that no single stakeholder perspective is sufficient for the successful development of AI-enabled public transport services. Passenger value, technical feasibility and operational viability do not always coincide. Effective service development therefore requires continuous cooperation between passengers, operators, technology developers, system integrators and public authorities. Cross-stakeholder collaboration can help identify potential deployment barriers early, improve acceptance and ensure that technological innovation remains aligned with practical operational needs.

5.3 Transferability

Many of the identified enablers and barriers are not specific to the OptiPEx service concepts but are broadly relevant to passenger-aware AI services in public transport. In particular, the importance of clear passenger value, privacy-preserving design, human oversight, accessibility and organisational readiness is likely to extend to future services that utilise passenger sensing, adaptive passenger information, anomaly detection or AI-supported operational decision-making.

Although the detailed findings depend on the service context, the five-dimensional analysis framework proved useful for examining regulatory, ethical, safety, technical and organisational factors in a structured manner. The framework may therefore support the assessment of future AI-enabled mobility services beyond the specific applications analysed in OptiPEx.

6 Conclusions

This deliverable analysed the enablers and barriers associated with the future deployment of passenger-aware public transport services developed within OptiPEx. Using a multidimensional assessment framework covering regulatory, ethical, safety, technical and organisational perspectives, the study examined eight service concepts addressing accessibility, passenger information, comfort, safety and operational efficiency. The analysis provides a structured understanding of the factors that may support or constrain the development and deployment of AI-enabled public transport services.

The results demonstrate that successful deployment depends on more than technical feasibility alone. Across the analysed service concepts, clear passenger value, meaningful human oversight, accessible and inclusive design, privacy-preserving approaches and compatibility with existing transport systems emerged as important enabling factors. At the same time, recurring barriers were identified in relation to privacy and data protection requirements, passenger trust, validation of AI-based functions, availability of suitable training and testing data, system reliability and organisational readiness. These findings highlight the need to balance technological innovation with regulatory compliance, societal acceptance and operational feasibility. The findings support the OptiPEx objective of developing passenger-aware services that improve comfort, safety, accessibility and trust while remaining compatible with regulatory and operational requirements.

A clear distinction emerged between services primarily supporting passenger information, accessibility and comfort and those addressing safety-related situations. Comfort- and information-oriented services generally face fewer validation and operational challenges and can often build upon existing infrastructure and operational practices. In contrast, safety-related services require stronger evidence of reliability, validation under realistic operating conditions, cybersecurity measures, clearly defined responsibilities and appropriate human oversight. As the potential consequences of incorrect or delayed system outputs increase, so does the need for robust governance, operational procedures and lifecycle management.

The findings further indicate that future passenger-aware public transport services should be designed around tangible passenger benefits while ensuring transparency, privacy protection, accessibility and trustworthiness. The results highlight the importance of involving passengers, operators, technology providers and public authorities throughout service development and deployment. Such collaboration can help align technological capabilities with genuine user needs, regulatory requirements and operational realities, thereby improving both acceptance and deployment readiness.

As OptiPEx progresses toward implementation and validation, the findings in this deliverable provide a foundation for subsequent technical development, integration, and demonstration work. By identifying opportunities and constraints early, the analysis supports informed decision-making and contributes to developing passenger-aware public transport solutions that are technically feasible, socially acceptable, and operationally viable. More broadly, the results provide transferable lessons for the development of trustworthy, inclusive and human-centred AI-enabled mobility services and highlight the key factors that should be considered when introducing passenger-aware technologies into real-world public transport environments. Ultimately, the results contribute to the broader goal of enabling trustworthy, inclusive and human-centred AI-enabled mobility services.

Declaration of Generative AI in the writing process

During the preparation of this work, the authors have used Microsoft Copilot to improve structure, content, and spelling. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the document.

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Appendix 1: OptiPEx expert workshop findings on enablers and barriers for future deployment

Table 12. SC1 Notification about specific passenger types: Enablers and barriers

SC1 Notification about specific passenger types		
Dimension	**Enabler** (what supports deployment)	**Barrier** (what hinders / risks deployment)
Regulation and compliance	• TSI PRM supports accessibility-oriented assistance • Accessibility-by-design aligns with EU accessibility objectives	• Passenger recognition may involve personal/sensitive data • GDPR transparency and retention requirements • Automated actions may require additional safety approvals
Ethical and societal aspects	• Supports independent travel • Human oversight possible • Sense of safety should increase	• Possible delays caused by the system, may be viewed negatively • May expose invisible disabilities • Risk of misclassification
Safety and security	• Earlier awareness for the driver improves boarding safety • Manual override available	• False negatives may leave passenger unsupported
Technical validation and interoperability	• Easy integration with existing infrastructure	• Availability of datasets for algorithm development • Occlusions and crowding reduce accuracy
Organisational and operational readiness	• No changes in driver role • Clear operational value case	• Possible delays in the timetable • New procedures and contracts

Table 13. SC2 Audio information channel for tourists: Enablers and barriers

SC2 Audio information channel for tourists		
Dimension	**Enabler** (what supports deployment)	**Barrier** (what hinders / risks deployment)
Regulation and compliance	• Supports hearing aids, providing access for the hearing-impaired • No data is collected • No special legal approvals are needed	• With visual impairment, it might be difficult to get information about the service. It would also be needed in an audible format. • Auracast is not a fully mature standard yet
Ethical and societal aspects	• Support for multiple languages is available. Possibility to develop the service further to include automatic translation through AI services. • There is no personnel available at stations; this could provide the needed support • Voice guidance is a natural way of interaction and well accepted	• Smartphones and headphones/hearing aids with Auracast support are needed • The content is static, and there are no interaction possibilities, so the system doesn't necessarily give answers to the questions the user has. • Need to actively connect to the service
Safety and security	• Standard Bluetooth protocol • Technically consistent (no need for multiple sensorial inputs) • No data collected/needed	•
Technical validation and interoperability	• Easy to scale up • Easy to test and validate • Personal volume adjustment possible	• Smartphone and headphones/hearing aids with Auracast support is needed • Not many devices support Auracast at the moment
Organisational and operational readiness	• No training needed (personnel) • Information content easily updateable. • Additional system that augments normal vehicle audio system	• No easy way to get diagnostics, usage data or feedback of the service • Information consistency throughout all the channels. • Vehicle location needed for location-dependent information (integration to the vehicle location data needed)

Table 14. SC3 Save the seat: Enablers and barriers

SC3 Save the seat		
Dimension	**Enabler** (what supports deployment)	**Barrier** (what hinders / risks deployment)
Regulation and compliance	• Accessibility Act; people with disabilities have the same rights and possibilities to use public transport as people without disabilities • AI and Data Act requires taking care of privacy, which decreases citizens' concerns about being identified	• Complexity of AI Act and other regulations can hinder implementation
Ethical and societal aspects	• Supports independent mobility • Improves accessibility and comfort	• Special characteristics recognised, which might make disabilities visible • Hidden disabilities may be missed • Relies heavily on passenger cooperation
Safety and security	• The Cybersecurity Act requires the system's vulnerabilities to be considered and the system to be updatable • Driver door control remains possible	• AI decision is false, and doors will close, and the driver accelerates too early • Crowded environments reduce safety performance
Technical validation and interoperability	• Scalability across multiple transport modes • Easy integration with existing infrastructure	• Object detection is difficult in crowded areas and vehicles • Many disability cases to validate • Multiple subsystems must interoperate
Organisational and operational readiness	• Minor training required for personnel	• Strict real-time requirements

Table 15. SC4 Communication system with central control: Enablers and barriers

SC4 Communication system with central control		
Dimension	**Enabler** (what supports deployment)	**Barrier** (what hinders / risks deployment)
Regulation and compliance	• Regulations for autonomous vehicles under development in the EU • Existing control centre procedures available	• Cybersecurity of communication system connection • Full provision of accessibility (button location)
Ethical and societal aspects	• Safety-critical events will not be handled by the avatar • Can reassure passengers during disruptions	• Passengers do not trust the avatar • Decision logic for avatar usage (No safety-critical events for avatars)
Safety and security	• System detects malfunctions and safe stop procedures start	• Loss of communication link (no human oversight present in the vehicle) • Potential misuse or misbehaviour of avatar
Technical validation and interoperability	• Flexibility of avatar • Easy interaction with avatar → Testing possibilities are very good	• Adaptability of existing living labs + future systems to integrate avatar • Reliable network connection needed • Usability of avatar in crowded vehicle (Noise and crowding affect usability) • Misbehaviour of avatar is difficult to test and understand the root cause
Organisational and operational readiness	• Existing control-centre infrastructure	• Avatar diagnostics / error states unclear • Operators require new skills and training

Table 16. SC5 Optimised in-vehicle conditions to avoid travel discomfort: Enablers and barriers

SC5 Optimised in-vehicle conditions to avoid travel discomfort		
Dimension	**Enabler** (what supports deployment)	**Barrier** (what hinders / risks deployment)
Regulation and compliance	• No sensitive data needed • Low cybersecurity risk • Easy to justify legally	• (Follows recommendations for healthy indoor conditions) • Heating, Ventilation and Air Conditioning (HVAC) supplier dependencies • Regulatory requirements differ across operators • Environmental monitoring governance
Ethical and societal aspects	• No ethical issues with sensor data. • Direct improvement to passenger experience • Solution doesn't decrease the human intervention possibilities	• Comfort preferences conflict • Optimisation may not satisfy everyone • Expectation management required
Safety and security	• Low-risk functionality • Existing HVAC safeguards • Gradual adjustments possible	• Sensor failure may create discomfort • HVAC cyberattacks possible • Poor control tuning may create instability
Technical validation and interoperability	• Simple environmental data, data size limited • Scalable solution • Strong simulation opportunities	• Occupancy inputs may be needed • Integration to HVAC suppliers • Vehicle differences complicate deployment
Organisational and operational readiness	• No training for personnel needed • Fits current maintenance process	• Additional maintenance effort • Supplier involvement required • Increased operational costs

Table 17. SC6 Passenger in-vehicle safety and security system: Enablers and barriers

SC6 Passenger in-vehicle safety and security system		
Dimension	**Enabler** (what supports deployment)	**Barrier** (what hinders / risks deployment)
Regulation and compliance	• Raw data processing at the edge; only event information sent out	• Restricted data collection (GDPR) • AI Act requirements
Ethical and societal aspects	• The service would improve the sense of safety • Emergency button available	• The service might cause the feeling of being watched • Limited audio processing (complete speech-to-text of every word/phrase is not allowed) • If the local detection system fails, the only second path is the button press option
Safety and security	• System safety monitoring • Human-centred decisions/escalation • Usage of latest cybersecurity measures & technologies	• Requirements based on the safety scope are higher than comfort functions (e.g. False alarms and missed detections need to be minimised)→ Validation / Certification needed incl. updates • Unreadiness/missing protocols of the control centre could cause delays/false or missing reactions
Technical validation and interoperability	• For validation purposes, acting out the situations is relatively easy • AI data generation (Video + Audio) • Open access data sets	• Model bias and limited performance caused by limited data • Data availability of real-world data • Technical limitations caused by e.g. camera types, positions. • Different vehicle types and environments, e.g. different acoustics
Organisational and operational readiness	• Technology provider with operators responsible for the service • Technology provider needs to provide information and support to use the system, incl. manuals, training, help desk	• Limited trained staff • Providing the information/protocols for the control centre so that they know quickly what and how to do it, while keeping the human focused.

Table 18. SC7 Tram collision warning system: Enablers and barriers

SC7 Tram collision warning system		
Dimension	**Enabler** (what supports deployment)	**Barrier** (what hinders / risks deployment)
Regulation and compliance	• Safety regulations support the service provisioning	• AI Act and other regulations can hinder implementation
Ethical and societal aspects	• Passengers feel more comfortable and safer • Improves pedestrian safety • Driver can oversight; it's just a warning • When people feel that the system helps, they trust it and use it (transparency)	• Different accessibility needs for warnings, for example • Disabled people might need a different warning type (e.g., vibration, …) • Privacy risks and data collection might not be accepted • People are afraid of AI systems
Safety and security	• Earlier hazard awareness • Makes situations safer, helping drivers and passengers to detect critical situations • Being distracted is an advantage in this case • It's a system working internally (edge), data processing happens in the tram and reduces latency	• If the passenger or driver does not get a warning in time • Alert fatigue possible • If technology does not work, it can create a critical situation
Technical validation and interoperability	• Existing collision systems (e.g., in cars) can speed up the adoption • Scalability: Localisation module, connection module and warning message can be installed in different vehicles	• Occlusions and weather effects • Complexity of the system: Multiple technologies, including smartphones, need to be interoperable • Testing different scenarios might be difficult • Difficult validation (unexpected people behaviour)
Organisational and operational readiness	• Safety procedures and frameworks exist • Operators are interested in this kind of service to avoid collision	• Liability questions remain • Reliability needs to be high

Table 19. SC8 Know before you go: Enablers and barriers

SC8 Know before you go		
Dimension	**Enabler** (what supports deployment)	**Barrier** (what hinders / risks deployment)
Regulation and compliance	• User consent • Transparency to stakeholders on how the data is used • Enabling text-to-speech for visually challenged • Follow GDPR compliance	• Regulatory approval from data owners • Misconceptions about data usage
Ethical and societal aspects	• User is the decision maker • Reduces travel uncertainty • Not a safety-critical system	• Inaccurate data can disadvantage users • Device accessibility issues
Safety and security	• Ensure safety practices – Encrypted communication/protocols • Appropriate information about the service in case of interruptions	• Incorrect guidance may create crowding • Users may over trust predictions
Technical validation and interoperability	• Data Augmentation • Real-world validation is straightforward • AI modules are general enough with various inputs	• Infrastructure interoperability (legacy systems) • Reliability of real-world occupancy data
Organisational and operational readiness	• Basic training for system maintenance • Operator-friendly – minimal daily intervention	• Adequate technical skills on the operator side • Requires relevant system updates