



D5.1 Adaptive Service Framework and Implementation Guidelines

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation acronym	Definition
AI	Artificial Intelligence
API	Application Programming Interface
CAN bus	Controller Area Network bus
CCAM	Connected, Cooperative and Automated Mobility
CCTV	Closed-Circuit Television
CI/CD	Continuous integration and continuous deployment
DTDL	Digital Twin Definition Language
EU	European Union
GDPR	General Data Protection Regulation
GPU	Graphics Processing Unit
HMI	Human-machine interface
HTTPS	Hypertext Transfer Protocol Secure
HVAC	Heating Ventilation and Air Condition
IDS	Intrusion Detection System
IEC	International Electrotechnical Commission
iOS	iPhone Operating System
IoT	Internet of Things
ISO	International Organization for Standardization (ISO)
ITxPT	Information Technology Standards for Public Transport
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
MFA	Multi-Factor Authentication
MQTT	Message Queuing Telemetry Transport
PA	Public Address
PIS	Passenger Information System
PT	Public Transport
RBAC	Role-Based Access Control
RTO	Recovery Time Objectives
SDK	Software Development Kit
SIL	Safety Integrity Level
SOP	Standard Operating Procedure

UC	Use Case
VMS	Video Management System
WCAG	Web Content Accessibility Guidelines

Executive Summary

OptiPEX project aims to improve the comfort and safety of public transport passengers as well as the security and ease of travelling by co-creating ethical and passenger-aware public transport services together with specific target user groups, such as wheelchair users, passengers with large objects, fragile passengers with limited mobility, tourists, and students. To achieve this, OptiPEX is built on three fundamental development pillars: measurement, analytics, and interaction. OptiPEX will develop perception technologies to measure passenger behaviour and situations. Trustworthy analytics is essential in recognising real-time passenger experiences and situations, enabling interaction with services and vehicles. Moreover, OptiPEX will develop adaptive and interactive vehicle technologies and digital services in collaboration with target groups that are suitable for various public transport modes. These services will optimise the onboard experience, promoting safety, inclusiveness, and trust. Ultimately, improved passenger satisfaction will drive the adoption of automated public transport technologies and enhance the sustainability of mobility services by contributing to the modal shift.

Deliverable D5.1, “Adaptive Service Framework and Implementation Guidelines,” supports the development of adaptive and interactive passenger services across various public transport modes, including railways, buses, and trams. The aim of D5.1 is to provide a framework and implementation guidelines that facilitate real-time, AI-driven service adaptation based on identified stakeholder needs, ensure cross-platform compatibility and scalability across different PT modes, while considering a privacy-preserving data governance aligned with EU regulations and transport policies.

D5.1 describes the constraints and requirements for the OptiPEX adaptive service framework, including passenger needs identified through focus group workshops. It presents the general design principles that guide the specification of the adaptive service framework. D5.1 also defines the OptiPEX Adaptive Service Framework, including building blocks for service governance, service definition and implementation, decision-making procedures, as well as considerations of privacy and ethics. Additionally, interfaces for data inputs, including insights from data analytics, and data outputs, such as actuator actions, vehicle adaptations and interaction channels, are introduced. Finally, implementation and operational guidelines, as well as the next steps towards deployment, are presented. For future work, the software specification and implementation of the OptiPEX Adaptive Service Framework, which enables real-time services and adapts vehicle controls, will be documented in Deliverable D5.2, “Integrated service framework”.

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Introduction

The OptiPEX project aims to improve the comfort and safety of public transport passengers, as well as the security and ease of travel, by co-creating ethical and passenger-aware public transport services in collaboration with specific target user groups, including wheelchair users, passengers with large objects, fragile passengers with limited mobility, tourists, and students. To achieve this, OptiPEX is built on three fundamental development pillars: measurement, analytics, and interaction. OptiPEX will develop perception technologies to measure passenger behaviour and situations. Trustworthy analytics is essential in recognising real-time passenger experiences and situations, enabling interaction with services and vehicles. Moreover, OptiPEX will develop adaptive and interactive vehicle technologies and digital services in collaboration with target groups that are suitable for various public transport modes. These services will optimise the onboard experience, promoting safety, inclusiveness, and trust. Ultimately, improved passenger satisfaction will drive the adoption of automated public transport technologies and enhance the sustainability of mobility services by contributing to the modal shift.

Deliverable D5.1, “Adaptive Service Framework and Implementation Guidelines,” facilitates the development of adaptive and interactive passenger services for various public transport modes, including railways, buses, and trams. The objective of D5.1 is to provide a framework and implementation guidelines that enable real-time AI-driven service adaptation, ensure cross-platform compatibility and PT mode scalability, and consider a privacy-preserving data governance aligned with EU regulations and transport policies.

D5.1 begins by outlining the constraints and requirements for the OptiPEX adaptive service framework in Section 1. This includes defining services relevant to the OptiPEX project that are targeted for development, along with the scope of the adaptive service framework. Furthermore, D5.1 compiles the passenger needs identified through focus group workshops, which included representatives from the target passenger groups (wheelchair users, passengers with large objects, passengers with limited mobility and visual impairments, tourists, and students), as well as other public transport stakeholders, and functional requirements derived from the service concept development work. Additionally, technical constraints for the adaptive service framework are introduced. Section 2 presents the general design principles that guide the specification of the adaptive service framework. The focus is on inclusive design, privacy and ethics, modularity and scalability, interoperability, responsiveness and edge intelligence, as well as safety, resilience, and service governance.

Section 3 defines the OptiPEX Adaptive Service Framework, covering four main building blocks. These building blocks describe service governance, service definition and implementation, decision-making procedures, as well as considerations of privacy and ethics. Section 4 specifies interfaces for data inputs, including insights from data analytics, and data outputs, such as actuator actions, vehicle adaptations and interaction channels.

Finally, implementation and operational guidelines are presented in Section 5, while Section 6 provides a summary of the deliverable and the next steps towards deployment.

1 Constraints and Requirements for OptiPEX Adaptive Service Framework

1.1 Definition of OptiPEX services

OptiPEX will co-create ethical passenger-aware public transport service solutions with user groups and other stakeholders to improve passenger experience, promote inclusivity, and build public trust in Connected, Cooperative and Automated Mobility (CCAM) systems. The passenger user groups include wheelchair users, passengers with large objects, fragile passengers with limited mobility or visual impairment, tourists and passengers without special needs, such as students, as depicted in Figure 1.



Figure 1. OptiPEX passenger user groups.

OptiPEX defines an ethical passenger-aware public transport service as a connected service that actively recognises and responds to the needs and preferences of passengers while considering inclusivity, privacy, safety, and trust. The OptiPEX services will be built on advanced vehicle technologies that assess passenger experience in real-time and adjust the conditions to enhance the sense of comfort and safety of the passengers, as well as ease of travelling.

The OptiPEX services will concentrate on four pre-defined Use Cases (UC) during the phases of boarding (transfer from stop/station to the seat/place in the vehicle), off-boarding (transfer from the vehicle to the stop/station) and while on-board (travelling seated/standing, i.e., time between boarding and off-boarding):

- UC1: **Automatic assistance for passengers with special needs** focuses on recognising user groups, understanding their expectations and requirements, and delivering timely services tailored to their individual needs.
- UC2: **Improving on-board safety with anomaly detection** involves identifying anomalies in passenger behaviour, such as panic, fear, or discomfort, as well as in the indoor environment of the vehicle, like

temperature or stiffness. The services are designed to adapt the vehicle to manage unexpected situations or call for help.

- UC3: **Pedestrian-to-vehicle communication** aims at estimating potential collisions between pedestrians and trams. The communication services between pedestrians and vehicles help prevent accidents and ensure safer interactions.
- UC4: **Passenger distribution optimisation** aims to enhance the passenger experience by identifying and directing passengers to less crowded areas and available seats.

1.2 The Scope of the Adaptive Service Framework

The OptiPEX Adaptive Service Framework makes the specification and implementation of passenger-aware services more efficient and effective, providing access to OptiPEX tools for measuring passenger behaviour and the surrounding environment, as well as the ability to control the vehicle and different digital services in it. Using the modular digital vehicle infrastructure and the Adaptive Service Framework, third-party service providers will have the opportunity to benefit from OptiPEX results in their service development activities. **Error! Not a valid bookmark self-reference.** depicts the role of the OptiPEX Adaptive Service Framework in relation to other parts of OptiPEX architecture. This deliverable provides a high-level definition of the interfaces to and from the OptiPEX Adaptive Service Framework, as well as a specification of the OptiPEX Adaptive Service Framework components.

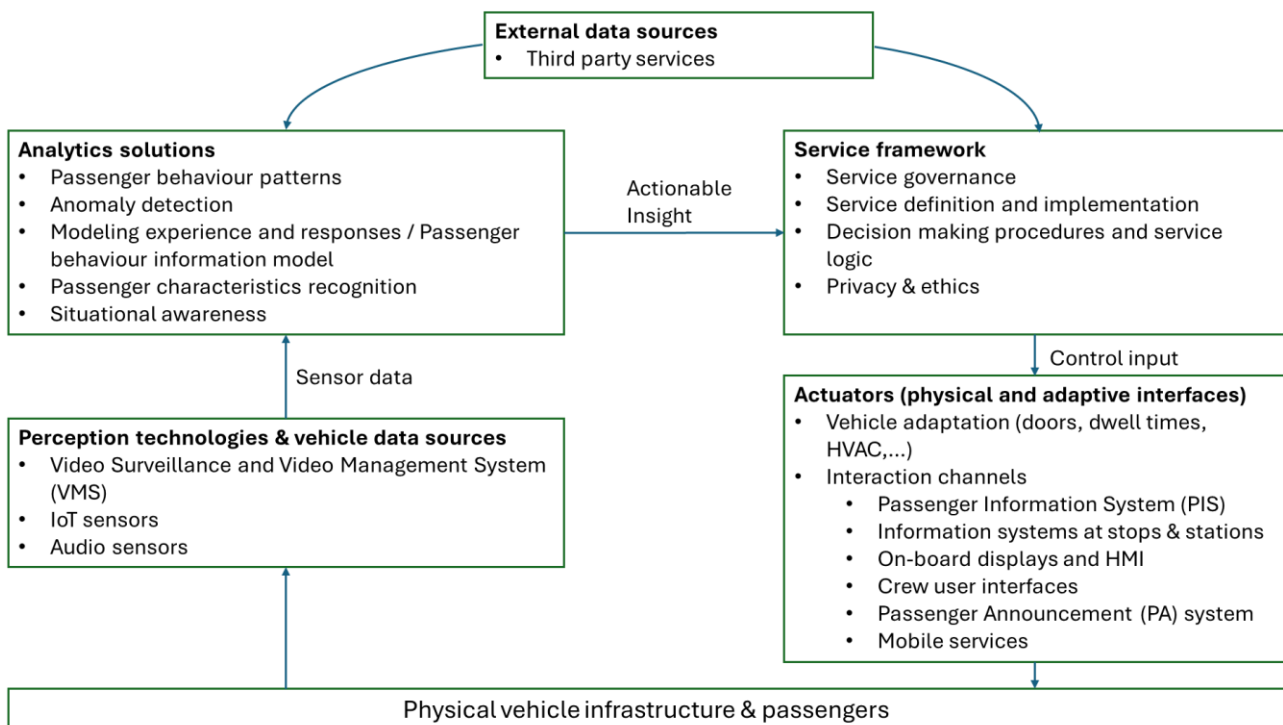


Figure 2. The role of the OptiPEX Adaptive Service Framework.

1.3 Results from the Requirement Analysis

1.3.1 Focus Group Interview Results

The OptiPEX project aims to improve public transport (PT) through a co-creation process. The fundamental tool for co-creation is the focus group, which involves gathering six to twelve people for one or two hours to ask them questions, in this case related to potential problems, solutions, and alternatives in PT (trams and buses). Topics addressed included accessibility, safety, and technological adaptation for different user groups in four countries: fragile users (visually impaired, physically impaired, older people) in Finland, Germany and Spain; students in Austria and Spain; passengers with large objects in Finland, and tourists in Finland and Germany. In each workshop, focus groups addressed questions related to the four possible use cases: automatic on-board assistance for passengers with special needs (UC1); improving on-board safety with anomaly detection (UC2); pedestrian-to-vehicle communication (UC3); and passenger distribution optimisation (UC4).

Key themes emerging across countries included:

- Accessibility (addressing physical and sensory challenges through inclusive design and technology),
- Safety (enhancing on-board protection and addressing concerns in autonomous scenarios),
- Technological adaptation (integrating apps and assistive tools for navigation and distribution optimisation), and
- Privacy (balancing the use of technology with robust data protection measures).

The suggestions, questions, concerns, and preferences of users from each group in each country form the basis for the proposed service concepts and mock-ups to be developed in the subsequent phases of the OptiPEX project (see Lucas-Alba, 2024).

1.3.2 Service Concept Requirements

The requirements derived from the service concept definitions exhibited significant variability in parameters such as timeliness, accuracy, and data type. However, the available data sources were limited and often shared across multiple service concepts. The most common data sources across the service concepts are video and data from the vehicle systems, with some specific cases requiring environmental sensors, audio, and lidar data. The required timeliness ranges from real-time edge processing to delayed batch processing, depending on the specific demands of each service concept.

Similarly, the required accuracy of sensors and resulting detections after processing (including behavioural indicators) varies from moderate to high, depending on the specific service being developed. Most service concepts require some form of human-machine interface to interact with the user. In some cases, a digital one (such as a Smartphone application, webpage, display, or audio announcement) or a physical one (such as buttons, or light controls).

1.3.2.1 [UC1 - Automatic Assistance for Passengers with Special Needs](#)

Key functionalities include real-time detection of passengers requiring additional assistance, such as wheelchair users, individuals with physical impairments, and those with large items like baby strollers. The system must monitor the boarding and off-boarding processes, providing necessary notifications to the driver and vehicle systems that manage doors and ramps, to facilitate smooth access.

Audio and visual aids should be integrated to support passengers with diverse needs, including announcements tailored to varying noise levels, multilingual support, and adjustable lighting. Tactile feedback and navigation aids should be included to improve accessibility for individuals with visual and physical impairments, while occupancy detection should be implemented to prioritise seating and allocate spaces for special objects. Additionally, the system should provide real-time route information, schedule updates, and seat availability through mobile and web applications.

1.3.2.2 UC2 - Improving On-board safety with Anomaly Detection

The key functionalities include monitoring anomalies in passenger behaviour, postural changes, and environmental factors. In such cases, the system must alert a vehicle driver or notify relevant stakeholders by providing accurate information, such as location and event, to enable prompt intervention. Additionally, the system must have protocols for issuing announcements to guide passengers during emergencies. The system should offer options, including audio, video, and chat connections, via an onboard interface or mobile application, to facilitate communication with passengers.

The system must assess deviations in environmental conditions, such as vibration, temperature, humidity, lighting, and noise levels, to adjust the climate control and prevent discomfort or motion sickness when necessary. Ambient noise levels inside the tram must be monitored, with automatic announcements triggered if thresholds are exceeded. The service must also track seating occupancy and provide real-time updates on quieter or crowded areas through passenger apps and station screens. Emergency assistance buttons and protocols for handling inappropriate behaviour must be supported, with connections to central control and security services, as required.

1.3.2.3 UC3 - Pedestrian to Vehicle Communication

The system must be capable of predicting potential collisions between public transport vehicles and pedestrians in real time, with detection occurring at least 2 seconds before the potential impact. The collision prediction model must achieve an accuracy greater than 99% and maintain a false positive rate below 5%. It must also assess the severity of each potential collision, using indicators such as kinetic energy and angle of collision, and determine the geolocation of the event with a precision of within 2 meters. The system must identify the smartphones of the pedestrians involved. Once a potential collision is detected, the system must alert the pedestrian through both visual and audio warnings via the mobile app within 0.5 seconds. Simultaneously, a warning must also be communicated to the vehicle driver via a visual or audio signal displayed on a tablet inside the driver's cabin, also within 0.5 seconds. Additionally, the system must transmit the location and severity details of the potential collision to the public transport service provider for monitoring and response purposes.

1.3.2.4 UC4 - Passenger Distribution Optimisation

The functional requirements focus on three key areas: detection, communication, and visualisation. The system must reliably detect passenger occupancy within the tram, including designated areas for buggies and wheelchairs, with a model accuracy of at least 80-90%. This ensures accurate real-time tracking of space usage, both in general seating and special use areas. Detected occupancy data must then be reliably communicated to both a smartphone application and tram stops, enabling timely updates and integration across platforms. Visualisation plays a critical role in informing passengers: visual indicators at tram stops will display the occupancy status of various areas within the tram, helping passengers make informed boarding decisions. Similar indicators will be placed on tram doors to inform those boarding of space availability. In-app indicators will also provide real-time occupancy information. However, the exact functional requirements of these visual

indicators, whether on the app, tram doors, or tram stops, will be determined through the creation and evaluation of mockups.

1.4 Technical Constraints

The Adaptive Service Framework defined in this deliverable complies with the technical constraints derived from the vehicle infrastructure and system architecture specified in OptiPEX Work Package 4, “Vehicle technologies for an optimised passenger experience”.

1.4.1 Edge Computing

The framework is deployed on edge computing platforms embedded within public transport vehicles. These platforms are typically resource-constrained in terms of processing power, memory, and energy consumption. Therefore, all services must be optimised for low-latency execution and lightweight resource usage to ensure smooth operation under real-time conditions.

The system must support high-throughput processing of video and sensor data, enabling simultaneous execution of multiple AI tasks such as emotion detection, occupancy estimation, and anomaly recognition. Compatibility with embedded AI hardware like NVIDIA Jetson (NVIDIA, n.d.) modules is essential, and orchestration environments such as Kubernetes K3s (Veeam, n.d.) are used to manage service containers efficiently. These platforms must also support remote updates and diagnostics to facilitate maintenance and scalability across different vehicle fleets.

1.4.2 Data Integration

The framework must interface with a wide range of onboard and external data sources, including CAN bus signals, IoT sensors, CCTV systems, and Passenger Information and Video Management Systems (PIS/VMS). These data streams vary in format, frequency, and precision, requiring robust data handling capabilities. To ensure consistent and reliable operation, all data must be synchronised in time, harmonised in format, and tagged with location and context metadata.

This enables accurate fusion of behavioural, environmental, and operational data for real-time analytics and service logic. The system must also support dynamic data routing and buffering to handle intermittent connectivity and variable data loads, especially during peak hours or in complex urban environments.

1.4.3 Privacy and Security

Given the sensitive nature of behavioural and emotional data, the framework is designed to operate in full compliance with General Data Protection Regulation (GDPR, European Parliament and Council of the European Union, 2016) and other relevant data protection regulations, such as EU Artificial Intelligence Act (EU AI Act, European Parliament and Council of the European Union, 2024) and Ethics for guidelines Trustworthy AI (European Commission, 2019). All personal data is processed locally within the vehicle, and no raw video or audio is transmitted externally unless explicitly authorised by the operator or required for legal purposes.

Security mechanisms include end-to-end encryption (IBM, 2021), role-based access control (RBAC), and anonymisation of identifiable features (Irisity, 2022). These safeguards are embedded into the data pipeline and enforced at both the hardware and software levels. Additionally, the framework supports audit logging (Datadog, 2025), secure boot processes (Microsoft, 2023), and real-time threat detection (Darktrace, n.d.) to protect against unauthorised access and ensure system integrity throughout its lifecycle.

1.4.4 Vehicle Control Interfaces

The framework must interact with various vehicle subsystems to enable adaptive services. These include the Passenger Information System (PIS), CCTV and Video Management Systems (VMS), door control, lighting, heating, ventilation, and air conditioning (HVAC), audio announcements, and anti-collision systems. Interfaces are implemented via standardised APIs that support real-time bidirectional communication, allowing services to both monitor and influence vehicle behaviour.

For systems considered safety-critical, such as door actuation or emergency alerts, the framework must ensure fail-safe operation, redundancy, and compliance with transportation safety standards. This includes deterministic response times (University at Buffalo, 2000), watchdog mechanisms (IBM, n.d.), and fallback routines (Startup House, n.d.) that activate in case of hardware or software failure. The system must also support priority-based task scheduling (Sharif et al., 2023) to ensure that non-essential processes never delay critical functions.

1.4.5 Modularity and Interoperability

To support deployment across different vehicle types and transport networks, the framework is designed to be modular and interoperable. Each service component—such as emotion detection (ScienceDirect, n.d.), crowd monitoring (Neoma, n.d.), or environmental sensing (Darcena et al., 2022)—can be independently deployed, updated, or replaced without affecting the rest of the system.

The architecture supports plug-and-play integration with existing digital infrastructure, including legacy systems and third-party platforms, such as OpenCV (OpenCV, n.d.). It adheres to open data and interface standards, enabling collaboration with external vendors and future-proofing the system for upcoming innovations. The modular design also facilitates rapid prototyping and testing of new services, allowing transport operators to tailor solutions to specific operational needs and passenger demographics.

2 Framework Design Principles

The OptiPEX Adaptive Service Framework is designed to enable real-time, inclusive, and privacy-conscious interaction between passengers and public transport (PT) systems. Its architecture is grounded in the project’s foundational pillars (see Figure 3)—Measure, Analyse, and Interact—and is informed by the research and development activities carried out in Work Package 3 “Passenger Behaviour Analytics and Situational Awareness” and Work Package 4 “Adaptive Vehicle Technologies and Infrastructure”. The framework is designed to provide a flexible, scalable, and ethically aligned foundation for deploying AI-driven services in diverse PT environments.

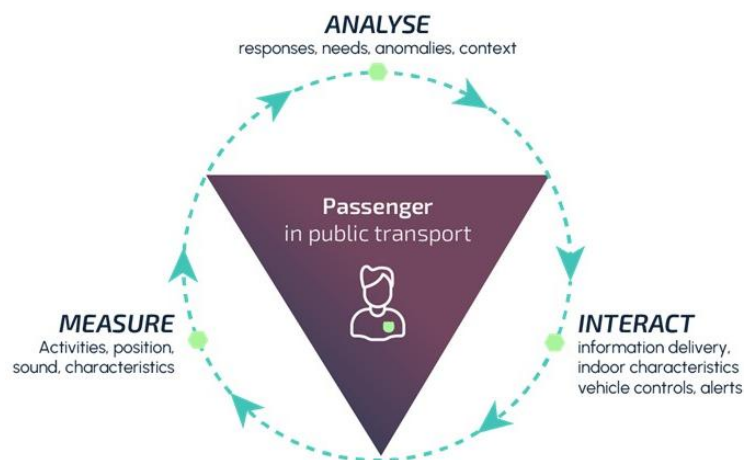


Figure 3. OptiPEX approach for real-time analysis and improvement of passenger experience in public transport.

2.1 Human-Centric and Inclusive Design

The framework is fundamentally designed around the principle of inclusivity, ensuring that public transport systems are accessible and responsive to the needs of all passengers. This includes individuals with reduced mobility, such as wheelchair users and elderly passengers, as well as those with situational needs—tourists unfamiliar with the system, passengers carrying large items, or those experiencing stress or discomfort.

To support this, the framework incorporates behavioural indicators, such as body posture, facial expressions, and vocal cues, which are used to infer passenger states in real-time. These indicators were identified and validated through studies conducted in Work Package 3, “Passenger behaviour analytics and situational awareness”. The framework supports multimodal interaction, allowing passengers to receive feedback and assistance through visual, auditory, and tactile channels. This ensures that services are not only technically effective but also socially and emotionally attuned to the people they serve.

Moreover, the framework is designed to adapt to group dynamics and contextual factors, such as time of day, crowding levels, and environmental conditions. This adaptability enhances the overall passenger experience and supports the broader goal of making public transport more attractive and equitable.

2.2 Privacy and Ethical Compliance

Respecting passenger privacy and ensuring the ethical use of data are core principles of the framework. All data processing related to behavioural and emotional analytics is performed locally on edge devices, minimising the risk of data leakage and ensuring compliance with GDPR (European Parliament and Council of the European Union, 2016), the EU AI Act (European Parliament and Council of the European Union, 2024), Ethics of Connected and Automated Vehicles (European Commission, Directorate-General for Research and Innovation, 2020) and IEEE Global Initiative on Ethics and Autonomous and Intelligent Systems (IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems, 2019). The edge-based implementation approach also reduces latency and improves system responsiveness.

OptiPEX aims to align the work with ethical guidelines and technical safeguards, including data minimisation strategies, anonymisation techniques, and secure communication protocols. For example, video and audio data are processed in real-time to extract non-identifiable features (e.g., emotion scores, posture vectors), which are then used for service logic without storing the raw media.

The framework also supports transparency and accountability through audit logs, consent management interfaces, and explainable AI components. These features allow operators and stakeholders to understand how decisions are made and to intervene when necessary. Ethical risk assessments are integrated into the service lifecycle, ensuring that new features are evaluated for fairness, bias, and societal impact before deployment.

2.3 Modularity and Scalability

To accommodate the diverse operational contexts of public transport systems across Europe, the framework is built with a modular and scalable architecture. Each service component—whether it's emotion detection, occupancy estimation, or environmental monitoring—can be deployed independently or in combination, depending on the vehicle type, available hardware, and use case requirements.

OptiPEX aims to define a flexible edge computing infrastructure that supports containerised services orchestrated via lightweight platforms such as Kubernetes K3S. This enables dynamic service deployment, updates, and scaling, even in resource-constrained environments such as trams or shuttles. The framework also supports integration of different sensors and actuators, enabling rapid adaptation to new vehicle configurations or pilot sites.

Scalability is further supported by a layered architecture that separates data acquisition, processing, and service logic. This separation allows for efficient resource allocation and simplifies maintenance and upgrades. The framework is designed to grow with the system, whether that means adding new AI models, integrating additional sensors, or expanding to new cities.

2.4 Interoperability and Standards Alignment

Interoperability is essential for ensuring that the framework can integrate seamlessly with existing PT infrastructure and third-party systems. To this end, the framework adheres to widely accepted standards, including ITxPT (ITxPT, n.d.) for transport interoperability, Transmodel (Transmodel, n.d.) for data exchange, and DTDL (Microsoft Azure, n.d.) for digital twin representations.

OptiPEX aims to define APIs and data models that enable communication between the framework and vehicle subsystems, including Passenger Information Systems (PIS), Video Management Systems (VMS), and control units for doors, lighting, and HVAC. These interfaces are designed to be vendor-neutral and extensible, allowing for seamless integration with both legacy systems and emerging technologies.

The framework also includes alignment of data provided by different sensors, such as audio sensors and cameras. This is critical for accurate situational awareness and coordinated service responses. By aligning with standards, and promoting interoperability via open APIs, the framework supports cross-site deployment, vendor collaboration, and long-term sustainability.

2.5 Real-Time Responsiveness and Edge Intelligence

One of the defining features of the framework is its ability to respond to passenger needs in real time. This is achieved using edge AI, which processes sensor data locally to detect behavioural patterns, emotional states, and environmental changes. The system supports GPU-accelerated processing, e.g. NVIDIA (NVIDIA, n.d.), for high-throughput tasks such as video analytics, enabling it to handle multiple concurrent services without compromising performance.

OptiPEX aims to develop a suite of AI models optimised for edge deployment, including emotion recognition from facial and vocal cues, activity and motion sickness detection based on body postures and movement, and occupancy estimation using video-based density mapping. These models are lightweight, robust, and capable of operating under varying lighting, noise, and crowding conditions.

The framework's real-time capabilities are essential for enabling adaptive services, such as adjusting lighting or audio/visual announcements based on passenger mood or alerting operators to potential safety issues. These features not only enhance the passenger experience but also support operational efficiency and incident prevention.

2.6 Safety, Resilience, and Service Governance

Safety and reliability are non-negotiable in public transport systems. The framework includes built-in mechanisms to ensure that services operate safely and can recover gracefully from failures. Interfaces with safety-critical systems—such as door control, HVAC, and anti-collision systems—are designed to comply with EN 50126 SIL2 standards (EN-STANDARD, n.d.), ensuring that they meet rigorous safety and reliability requirements.

OptiPEX aims to define a comprehensive governance model for managing the lifecycle of adaptive services. This includes tools for monitoring system health, logging service activity, and managing updates and rollbacks. The framework also supports redundancy and failover strategies to maintain service continuity in the event of hardware or software faults.

In addition, the framework includes policy enforcement mechanisms to ensure that services operate within defined ethical and operational boundaries. These include access controls, usage limits, and automated alerts for anomalous behaviour. Together, these features provide a robust foundation for deploying AI-driven services in complex, real-world PT environments.

3 Definition of OptiPEX Adaptive Service Framework

OptiPEX Adaptive Service Framework guides the design and implementation of services that optimise the passenger experience in public transport. The framework includes tools and procedures that facilitate the development of passenger-aware services across different public transport modes and instruct in coordinating service governance and complying with issues related to privacy and ethics. The framework is further divided into modules, each of them covering a specific area of service design and implementation.

OptiPEX Adaptive Service Framework, depicted in Figure 4, has interfaces with Vehicle technologies and Passenger behaviour Data models & AI Algorithms. In addition, requirements are provided as input to the OptiPEX Adaptive Service Framework. The OptiPEX Adaptive Service Framework is further divided into the following modules: Service Definition and Implementation, Service Governance, and Privacy and Ethics.

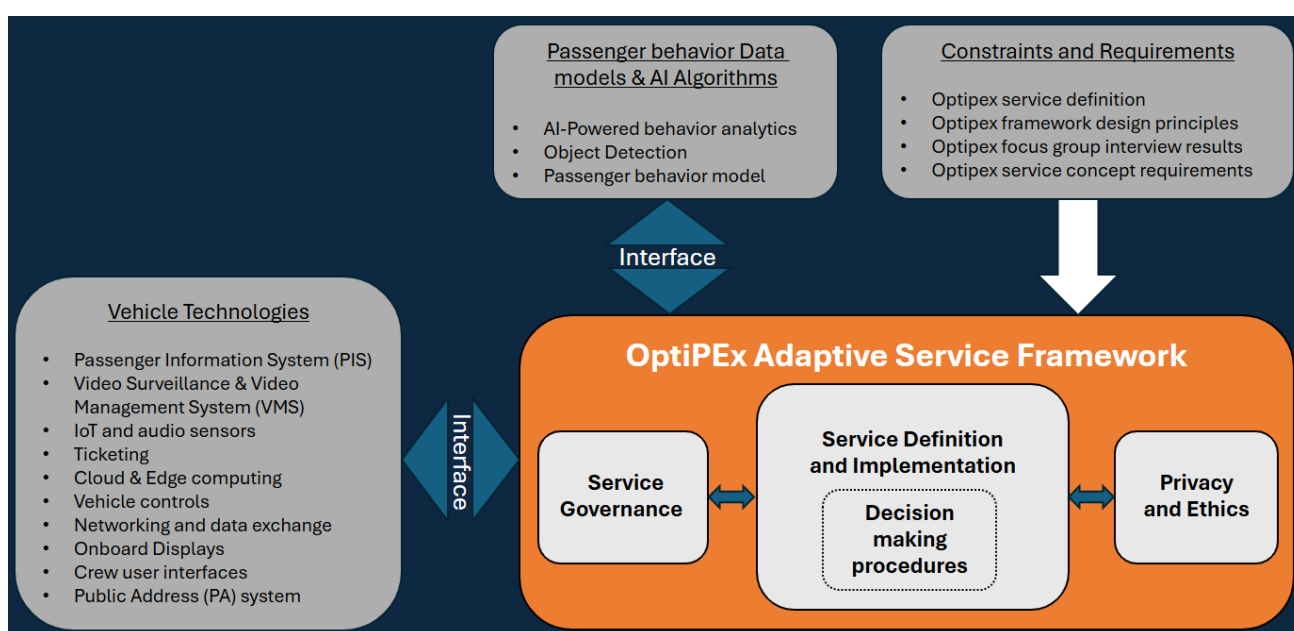


Figure 4. OptiPEX Adaptive Service Framework.

3.1 Service Definition and Implementation

As public transport ecosystems are becoming increasingly complex, the ability to translate data and analytics into services is critical. This translation requires careful consideration of technical constraints, system architecture, and regulatory compliance, underscoring the need for modular, adaptable approaches to service implementation.

Service Definition and Implementation module (see Figure 5) provides a structured approach for developing and deploying high-quality services in complex PT environments. The module outlines the procedures and tools for defining and implementing OptiPEX services effectively, ensuring that they meet the needs of the passengers while maintaining efficiency and reliability, and compliancy with regulatory and ethical aspects. With the procedures and tools provided by this module, a service is implemented into software, transforming the outputs of analytics solutions into actual OptiPEX services.

The decision-making procedures are embedded within this module, while privacy and ethical standards compliance and service governance are provided by the other modules in the OptiPEX Adaptive Service Framework. Building on the outcomes of the co-creation process, this sub-module enables the deployment of use-case-specific services.

The service definition and implementation module outlines the process in which the service requirements are implemented into software that transforms actionable insight (see Section 4.1) into visible, audible and/or tactile outputs, e.g., on vehicle controls or passenger information displays. The process is illustrated in Figure 5. It includes:

- assessing the requirements of the service together with the technical constraints from the vehicle infrastructure and system architecture (see Section 1.4 for technical constraints)
- selecting which actionable insight(s) to use from the analytics solution (see Section 4.1 for a detailed description of actionable insights)
- defining what kind of decision-making procedures are used
- defining how the outcome of the decision-making procedures modifies the actuators so that the requirements of the service are met.

The process also includes a continuous check with the service governance module and privacy and ethics module to ensure compliance with data privacy and ethical guidelines.

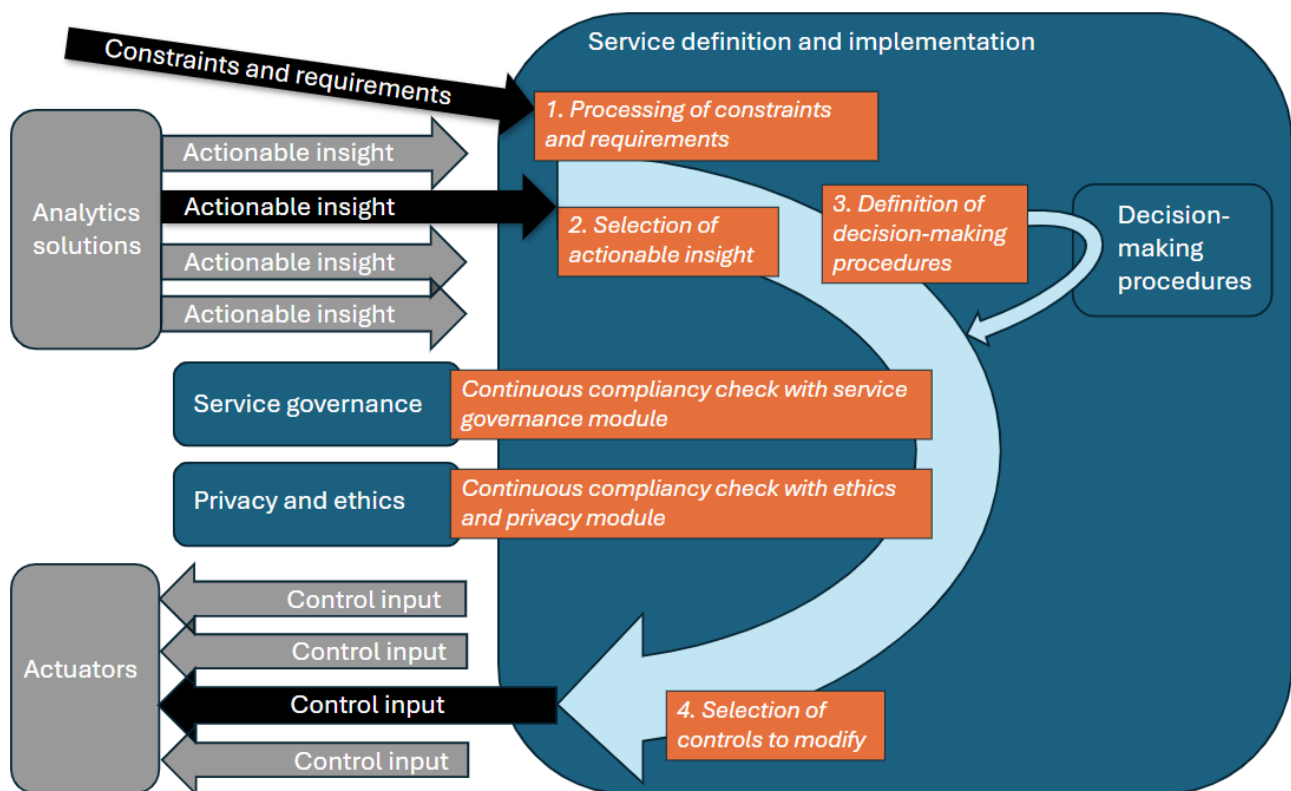


Figure 5. Service definition and implementation.

3.1.1 Decision-making Procedures

The decision-making procedures sub-module provides means for defining consistent logic for decision-making across different services (see Figure 6). This consistency is crucial for maintaining service reliability and ensuring the predictability and transparency of the service logic.

The sub-module defines tools and policies for developing efficient and reliable algorithms for services, e.g., by defining data validations and feasibility checks. These are essential to ensure that the decisions made by the algorithms are not only logically sound but also practically implementable within the constraints of the PT ecosystem. Algorithm outputs need to be checked also against policies defined in Service governance module and Privacy and ethics module.

As described in Section 3.1, the decision-making is not done directly based on data from different sensors and vehicle systems but based on actionable insights formed by the Analytics solutions. Actionable insights are discussed in detail in Section 4.1.

The key points addressed by the decision-making procedures sub-module are illustrated in Figure 6. They include:

- Defining and implementing input data validation.
- Development of decision-making algorithm(s) defined in the Service definition and implementation module.
- Definition of privacy-preserving mechanisms based on input from Privacy and ethics module.
- Defining compliancy checks against rules for safety, privacy, and ethics provided by Service governance and Privacy and ethics modules. Also, feasibility checks such as checking against boundary conditions are done to ensure that the decision is reasonable.
- Defining and implementing fallback mechanisms to ensure service continuity in case the provided decision is not feasible or otherwise valid.

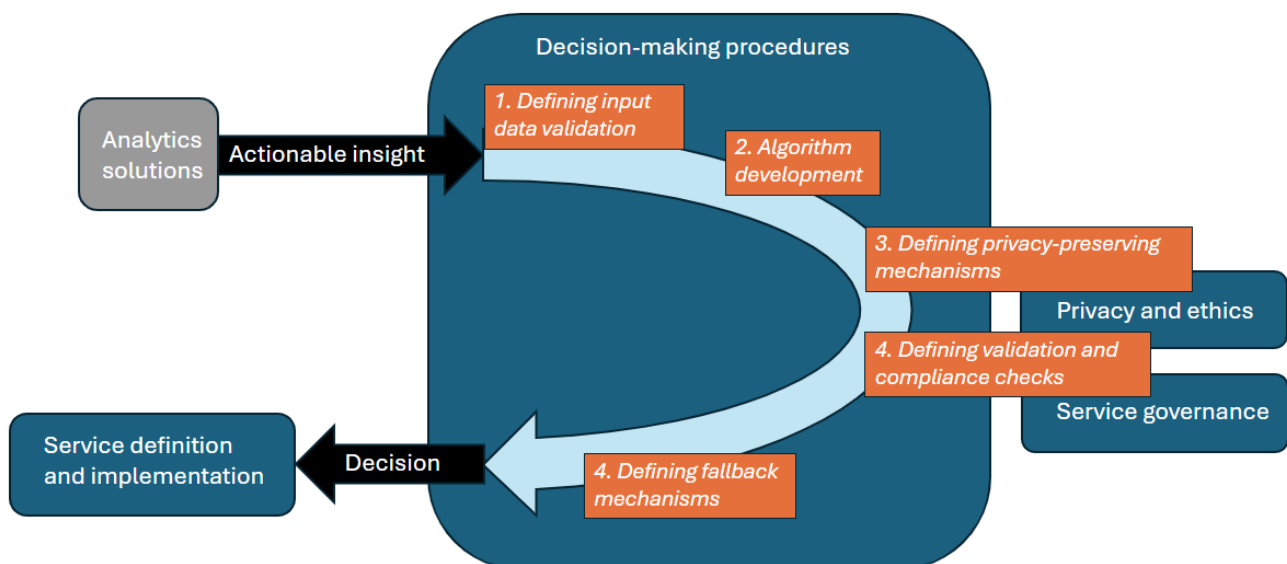


Figure 6. Decision-making procedures.

3.2 Service Governance

The service governance module provides governing function in the OptiPEX Adaptive Service Framework. It is composed of set of tools, policies, and procedures that guide the service definition and implementation. It ensures that the services that are designed and developed within the framework comply with the design guidelines described in Section 5. Service governance module outlines, for example, how audit logging and access control should be managed.

Since the OptiPEX Adaptive Service Framework is designed to facilitate the collaborative development of services, the service governance module also clarifies roles and responsibilities, ensuring that the ownership of services and liability issues are specified.

3.3 Privacy and Ethics

Privacy and ethics are central to the OptiPEX Adaptive Service Framework. All services are designed to comply with the GDPR (European Parliament and Council of the European Union, 2016) and the EU AI Act (European Parliament and Council of the European Union, 2024), ensuring that personal data is handled responsibly and transparently. The framework incorporates privacy-preserving mechanisms such as data anonymisation and local (edge) processing to reduce data exposure.

Ethical considerations are embedded throughout the service lifecycle—from co-creation to deployment—guided by the EU’s Ethics Guidelines for Trustworthy AI (European Commission, 2019). Special attention is given to inclusiveness, fairness, and the protection of vulnerable user groups. Data collection and service interactions are subject to ethical oversight and informed consent when required.

A concrete part of privacy and ethics is to ensure secure transmission of data within the OptiPEX Adaptive Service Framework. Privacy and ethics module instructs the use of secure transmission protocols for relaying the framework inputs from the data models and AI algorithms and outputs to the vehicle controls, passenger information displays, etc.

4 Interfaces for Analytics and Actuators

4.1 Actionable Insights

An actionable insight refers to a refined piece of knowledge derived from data analysis that possesses attributes enabling direct, effective intervention or strategic adjustment to achieve a predefined objective. It transcends raw data or mere descriptive statistics by integrating contextual understanding, predictive power, and prescriptive guidance. Critically, an actionable insight not only delineates what is occurring within a system but also elucidates the underlying causal mechanisms ('why') and explicitly outlines how specific modifications or interventions can yield a desired outcome. This prescriptive quality distinguishes it from a simple observation, transforming passive information into a catalyst for informed decision-making and operational optimisation. Actionable insight can be defined in the following manner: “A cohesive set of understandings about the problem situation based on prognostic insights derived from synergic understanding of analytical results, which enables the user to make an informed decision to solve the problem” (Tan & Chan, 2016). In the context of OptiPEX, the purpose of actionable insights is to interpret the results of analytics tools to support decision-making processes for adaptive and interactive services. The actionable insight for adaptive physical spaces includes (Järvinen et al., 2024):

- Trigger: What has been detected?
- Target: What should be accomplished?
- Temporal aspects: How fast the service should react or how long the service should react?
- Intensity: How strong the service response should be?

The service concepts co-created in collaboration with target passenger groups and stakeholders provide requirements for actionable insight input towards the OptiPEX service framework. The categories for actionable insights in OptiPEX are Passenger detection, Passenger movement, Passenger behaviour and Event detection (including events related to passengers, vehicle performance and indoor environmental characteristics).

Passenger detection refers to the system’s ability to detect on a specific moment the existence of a passenger or a specific type of passenger (e.g. wheelchair user, physically impaired, visually impaired, travelling with a large object or in a group) in a known location at the stop or on-board the vehicle. This insight is used on the service level to build services able to assist passengers boarding and off-boarding the vehicle, to improve the passenger comfort with more even distribution of passengers on the vehicle and between vehicles, and to enhance the safety in the vicinity of a vehicle at stops.

Passenger movement refers to the system’s ability to continuously monitor the movement of passengers boarding, travelling and off-boarding. Passenger movement insights are needed, e.g., to ensure successful boarding and off-boarding, to recognise a need for special assistance, or to detect abnormalities.

Passenger behaviour refers to the analysis of clearly visible or more subtle actions and activities related to passengers’ emotional or physical responses to different stimuli or situations. For example, the system should be able to detect abnormal movement on board (restlessness or changing of seats), abnormal speech or noises, or to predict passenger’s intention to off-board.

Event detection refers to the detection of abnormal vehicle performance or indoor environmental characteristics, which might either cause discomfort on-board or risk passenger safety. For example, a reckless driving style or the changes in CO2 and temperature levels should be detected.

The requirements derived from the service concept work provide current information on the trigger for actionable insights. The future OptiPEX activities on service concept development and use case demonstration will finalise the actionable insight details on target, temporal aspects and intensity contributing to the final version of the actionable insight in the context of the OptiPEX service framework.

4.2 AI-Vehicle Adaptation

Services defined in OptiPEX Adaptive Service Framework can be adapted into different vehicle systems and technologies through APIs and SDKs provided by the system/technology providers. Typically, such APIs and SDKs are proprietary, yet compliant with most common protocols and file formats, such as MQTT (MQTT.org, n.d.) and JSON (JSON.org, n.d.).

The main systems and components of the vehicle technologies in the OptiPEX Adaptive Service Framework are shown below in Table 1.

Table 1. The main systems and components of vehicle technologies within the OptiPEX Adaptive Service Framework.

System/component	Description
CCTV & Video Management System (VMS)	CCTV & Video Management System (VMS) consists of cameras and a storage and management system for the live and recorded video data. VMS can be further integrated with different sensors and video analytics system, such as emotional video analytics systems.
Passenger Information System (PIS)	PIS is used to manage and control passenger information within a vehicle system, as well as at bus stops and stations. PIS includes a plurality of sensors and devices (e.g. displays and PA systems), which are utilised to provide passenger information and for interaction with passengers.
Ticketing Systems	Ticketing systems are used to register passengers entering the vehicle. Ticket systems can also be utilised for collecting and recording passenger data.
IoT and audio sensors	IoT and audio sensors are used to collect audio and other data, which can be measured within the vehicle.
Vehicle controls	Vehicle controls include the controls of ramps, doors, heating, ventilation and other functions related to the physical infrastructure of the vehicle.
Onboard displays	Onboard displays can operate independently or can be part of PIS.
Crew user interfaces	Crew user interfaces are used to provide a dedicated interface between the onboard crew and subsystems within the vehicle.

System/component	Description
Public Address (PA) system	Public Address (PA) system is used to provide audio announcements in the vehicle. It can operate independently or be part of PIS.
Cloud-based systems	Cloud-based systems are used to reinforce data management, collection and orchestration of various subsystems within the vehicle in support to enable passenger service adaptation.
Edge computing	Edge computing for low-latency, real-time data processing is leveraged by large public transport systems, where space and capacity are sparse for storing data.
Guiding systems	Guiding systems provide a physical and adaptive interface for passengers boarding the tram.

4.3 Interaction Channels

The OptiPEX Adaptive Service Framework will act as the central orchestration layer, connecting analytics outputs, governance tools, and privacy mechanisms to the OptiPEX services that directly interact with end users. The integration between such framework and the different OptiPEX interaction channels will be designed to ensure seamless, real-time delivery of insights and actions, while maintaining security, scalability, and ethical compliance. Such OptiPEX interaction channels are as follows:

- Mobile services
- Passenger Information System (PIS)
- Public Address (PA)
- On-board displays
- Crew user interfaces

Essentially, the interaction will rely on standardised, well-documented APIs that allow the OptiPEX services to communicate efficiently with the service framework. These APIs, typically RESTful or gRPC-based, will expose the functionalities managed within the framework in a consistent and structured manner.

To ensure adaptability and scalability, a modular design of the OptiPEX Adaptive Service Framework will allow individual services to be added or modified without requiring full system overhauls. Each functionality to be provided by the framework should be encapsulated within its own self-contained module and so, ensuring that services can evolve independently, supporting the framework’s broader goals of scalability, adaptability, and resilience. For instance, if a new co-created service is introduced, it can be incorporated into the service framework as a new module, and the corresponding interaction channel could be activated or updated via remote configuration and incremental deployment.

From a development and operational perspective, the interaction will be supported by a shared CI/CD pipeline. This pipeline will ensure that updates to both the framework backend and the OptiPEX services will be tested against each other, maintaining compatibility and minimizing the risk of integration failures.

Therefore, the interaction between the OptiPEX Service Framework and the OptiPEX interaction channels will be structured around a secure, modular, and standards-based architecture.

4.3.1 Mobile Services

The mobile services to be developed in OptiPEX will play a central role in connecting passengers, operators, and system components through seamless, and real-time interaction. These services will act as the human-facing layer of the whole solution, translating the insights, recommendations, and alerts generated by analytics components into actionable, meaningful experiences for users.

To ensure broad reach and inclusivity, the mobile services will be designed for compatibility with widely used platforms, specifically recent versions of Android and iOS. The development approach will emphasize cross-platform consistency, enabling a uniform look, feel, and performance across different devices.

Additionally, user experience (UX) and usability considerations are deeply embedded in the design philosophy of mobile services. Thereby, the mobile-based interfaces will be developed following established design guidelines, such as Nielsen's Heuristics (Nielsen) to ensure intuitive navigation, visual clarity, and responsiveness across varying screen sizes and orientations.

Accessibility is also a core design requirement. By following international accessibility standards, the interfaces should accommodate a wide range of user needs and preferences, ensuring that individuals with disabilities can engage fully with the system's services. Features such as adaptable contrast, scalable text, and screen reader compatibility will be considered baseline expectations rather than optional enhancements.

Security and privacy are equally central to the implementation guidelines. User authentication and authorization will be designed to follow best practices, ensuring that users can securely manage their preferences, data, and service interactions. Privacy management will be integrated directly into the user interface, empowering users to exercise control over their data in line with legal and ethical obligations such as GDPR (European Parliament and Council of the European Union, 2016).

Therefore, the OptiPEX mobile services will be designed to balance technical robustness, user-centred design, and long-term adaptability. By prioritizing compatibility, modularity, usability, security, and maintainability, OptiPEX mobile services will be well-equipped to address the diverse and evolving needs of various stakeholders, ultimately enhancing both passenger experience and operational efficiency.

4.3.2 Passenger Information System (PIS)

The Passenger Information System is responsible for delivering real-time travel information to passengers both onboard and at stations. It includes displays, audio systems, and backend software that manage content such as route updates, next stops, service disruptions, and accessibility information. In the OptiPEX framework, the PIS also serves as a channel for adaptive content delivery, adjusting messages based on passenger needs or detected emotional states.

4.3.2.1 [Public Address \(PA\) System](#)

The Public Address (PA) System can be seen as part of passenger information system. It provides audio-based communication to passengers, typically through pre-recorded or live announcements. It is used to convey critical information such as stop names, safety instructions, or emergency alerts. Integrated with the adaptive service framework, PA can dynamically adjust tone, language, or content based on real-time passenger context or detected anomalies.

4.3.2.2 [Onboard Displays](#)

On-board displays are part of passenger information system. They are visual interfaces located inside the vehicle, used to present route information, service updates, and adaptive content. These interfaces may also

include touchscreens or gesture-based controls for passenger interaction. Within OptiPEX, these displays can be used to reflect emotional analytics (e.g., calming visuals during stressful situations) or to guide passengers to available seating or exits.

4.3.3 Crew User Interfaces

Crew user interfaces are dedicated terminals or control panels used by the vehicle operator or onboard staff. These interfaces provide access to system status, alerts, and manual overrides. In the OptiPEX framework, crew interfaces also display real-time behavioural insights and system recommendations, enabling staff to respond proactively to passenger needs or safety-critical events.

5 Implementation and Operational Guidelines

This section outlines the key operational and implementation requirements for deploying and maintaining adaptive services within public transport (PT) environments. These guidelines are intended for PT operators, technical integrators, and service providers to ensure safe, efficient, and user-centric operation of the OptiPEX Adaptive Service Framework.

5.1 Guidelines for Digital Infrastructure

5.1.1 Sensor Setup and Placement

Sensors used for behavioural analytics, environmental monitoring, and service adaptation shall be installed in locations that maximise coverage while preserving passenger privacy. Sensor placement shall be validated to ensure accurate detection of passenger states and environmental conditions. Sensors should be mounted in a way that avoids interference with passenger movement and accessibility features.

At stations and stops, sensors shall be positioned to monitor crowding, accessibility needs, and environmental factors. All sensor installations must comply with local safety and accessibility regulations.

5.1.2 Network and Connectivity

The system shall operate reliably under varying network conditions. Onboard services must be capable of functioning in offline or low-bandwidth scenarios by relying on edge computing. Connectivity to cloud-based systems should be used for non-critical data synchronisation, updates, and analytics aggregation.

Operators shall ensure that network infrastructure supports secure, encrypted communication between vehicle systems, edge nodes, and backend services. Redundancy and fallback mechanisms should be implemented to maintain service continuity during outages.

5.1.3 Sustainability and Energy Efficiency

The system shall be designed with sustainability in mind, minimizing energy consumption and environmental impact. Hardware components should support low-power operation modes and be selected based on energy efficiency ratings. Operators shall implement energy-saving policies for sensor operation, data transmission, and edge computing. Lifecycle assessments should be conducted for hardware to support responsible procurement and disposal practices.

Where feasible, renewable energy sources should be used to power infrastructure components, particularly at fixed installations such as stations and depots.

5.2 Guidelines for Software Design

5.2.1 Interoperability and Standards Compliance

The system shall be designed to integrate seamlessly with existing public transport infrastructure and third-party services. All components must adhere to relevant industry standards.

Operators and integrators shall ensure that APIs are well-documented, version-controlled, and support secure, standards-based communication. Compatibility with legacy systems must be assessed during deployment planning to avoid service disruptions.

Interoperability testing shall be conducted prior to rollout and during major updates to ensure continued compliance and functionality.

5.2.2 Maintenance and Maintainability

The system shall be designed for maintainability, with modular components that can be updated or replaced independently. Maintenance schedules must be defined for hardware (e.g., sensors, edge devices) and software (e.g., AI models, orchestration layers).

Operators should implement remote diagnostics and update mechanisms to reduce downtime. Maintenance logs shall be kept and reviewed to ensure system reliability.

5.2.3 Ethical AI Use

All AI-driven components of the system must be developed and deployed in accordance with ethical AI principles. This includes ensuring fairness, transparency, accountability, and explainability in automated decision-making.

Bias mitigation strategies shall be applied during model training and validation. Operators must document AI model behaviour, limitations, and decision logic, especially for features that impact passenger experience or safety.

Users shall be informed when AI is used in service delivery, and mechanisms must be in place to allow human oversight and override where necessary.

5.2.4 Localisation and Cultural Sensitivity

The system shall support localisation to accommodate diverse passenger populations. This includes language support, cultural norms, and region-specific accessibility requirements.

User interfaces must be adaptable to local languages and symbols, and content should be culturally appropriate and inclusive. Operators shall engage with local communities and stakeholders to ensure services are aligned with user expectations and needs.

Localisation efforts must be reviewed periodically to reflect demographic changes and evolving cultural contexts.

5.3 Design Guidelines Related to Regulations and Cybersecurity

5.3.1 Regulatory Compliance and GDPR

The system must comply with the General Data Protection Regulation (European Parliament and Council of the European Union, 2016) and other relevant national and EU-level regulations. Personal data shall be anonymised or pseudonymised where feasible. Consent mechanisms must be implemented for data collection where required.

Operators shall maintain a data protection impact assessment (DPIA) and ensure that all data processing activities are documented and reviewed regularly. Data subjects must be informed of their rights and provided with accessible channels to exercise them.

5.3.2 Data Storage and Management

All data collected and processed by the system must be stored in accordance with applicable data protection laws. Sensitive data, including video and audio streams, shall be processed locally and shall not be stored unless explicitly required and authorised.

Storage systems shall support the secure, encrypted retention of logs and metadata for auditing and diagnostics purposes. Data retention periods must be defined and enforced, and data minimisation principles shall be applied wherever possible.

5.3.3 Cybersecurity Measures

All components of the system must be protected against cyber threats through a comprehensive security strategy. This includes securing data in transit and at rest, protecting system interfaces, and ensuring the integrity of software and firmware.

Operators shall implement role-based access control (RBAC), multi-factor authentication (MFA), and regular security audits. Intrusion detection systems (IDS) and endpoint protection must be deployed to monitor and respond to threats. All updates must be cryptographically signed and verified before deployment.

Incident response plans shall be established to address cybersecurity breaches, including containment, recovery, and notification procedures.

5.4 Operational Guidelines

5.4.1 Training and Capacity Building

All personnel involved in operating or maintaining the system must receive appropriate training. Training programs shall cover technical operation, privacy and ethics, emergency procedures, and passenger interaction.

Refresher training should be conducted periodically, and new features or updates must be accompanied by updated training materials.

5.4.2 Passenger Communication

Clear and accessible communication about the services provided by the system shall be made available to passengers. This includes information about adaptive features, accessibility support, and data privacy.

Information shall be delivered through multiple channels, including onboard displays, mobile applications, and station signage. Communication must adhere to accessibility standards, such as Web Content Accessibility Guidelines (WCAG) and be available in multiple languages where appropriate.

5.4.3 Access to First Responders and Crew Availability

In the event of an emergency, the system shall provide mechanisms for notifying first responders and enabling rapid crew intervention. Crew user interfaces must display real-time alerts and recommended actions.

Operators shall ensure that trained personnel are available during service hours to respond to any incidents that may arise. Crew members must be familiar with the system's capabilities and limitations.

5.4.4 User Feedback and Continuous Improvement

Mechanisms shall be established to collect and analyse feedback from passengers, crew, and technical staff. Feedback channels may include mobile apps, onboard interfaces, surveys, and customer service interactions.

Collected feedback shall be reviewed regularly and used to inform system updates, service enhancements, and training programs. Operators must ensure that feedback mechanisms are accessible, anonymous where appropriate, and responsive to user concerns.

A continuous improvement cycle shall be implemented, incorporating feedback into development roadmaps and operational planning.

5.4.5 Auditing and Review

Operators must implement regular auditing procedures to assess system performance, compliance, and user satisfaction. Audits shall include technical diagnostics, data protection reviews, and service quality assessments.

Review processes should involve feedback from passengers, crew, and technical staff. Findings from audits must be documented and used to inform continuous improvement.

5.4.6 Risk Mitigation and Incident Handling

Operators must establish standard operating procedures (SOPs) for identifying, reporting, and responding to incidents. These procedures shall include protocols for technical failures, safety-critical events, and passenger-reported issues.

The system shall include automated alerts for anomalies and predefined thresholds that trigger operator intervention. Incident logs must be maintained and reviewed periodically to identify patterns and improve response strategies.

5.4.7 Disaster Recovery and Business Continuity

Operators must develop and maintain a disaster recovery plan to ensure service continuity in the event of major disruptions, including natural disasters, cyberattacks, or system-wide failures.

The plan shall define recovery time objectives (RTO), backup procedures, and roles and responsibilities during recovery operations. Regular drills and simulations must be conducted to validate readiness.

Critical system components shall be backed up regularly, and redundant infrastructure should be deployed to support failover and rapid restoration of services.

6 Conclusions

Deliverable D5.1, “Adaptive Service Framework and Implementation Guidelines,” supports the development of adaptive and interactive passenger services across various public transport modes, including railways, buses, and trams. Its aim is to provide a framework and implementation guidelines that enable real-time AI-driven passenger service adaptation, ensure cross-platform compatibility and scalability across transport modes, and consider a privacy-preserving data governance aligned with EU regulations and transport policies.

D5.1 defined services relevant to the OptiPEX project that are targeted for development, along with the scope of the adaptive service framework. Furthermore, D5.1 compiled the passenger needs identified through focus group workshops, which included representatives from the target passenger groups (wheelchair users, passengers with large objects, passengers with limited mobility and visual impairments, tourists, and students), as well as other public transport stakeholders, and functional requirements derived from the service concept development work. Additionally, technical constraints for the adaptive service framework were introduced, together with general design principles that guide the specification of the framework.

D5.1 outlined the OptiPEX Adaptive Service Framework, consisting of four main components. These components define service governance, service definition and deployment, decision-making procedures, and considerations of privacy and ethics. Additionally, interfaces for data inputs, including insights from data analytics, and data outputs, such as actuator actions, vehicle adaptations, and interaction channels, were specified. Lastly, implementation and operational guidelines were provided.

Following the specification of the adaptive service framework, the next phase of the OptiPEX project will focus on transitioning from high-level framework design to software specification and actual implementation. The framework will establish tools and policies for service governance in future autonomous public transport vehicles, interfacing with the vehicle controls and services. The software specification and implementation of the OptiPEX Adaptive Service Framework will be documented in Deliverable D5.2, “Integrated service framework”.

Declaration of Generative AI in the writing process

During the preparation of this work, the authors used Microsoft Copilot in order to test ideas and improve the structuring of the content. 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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