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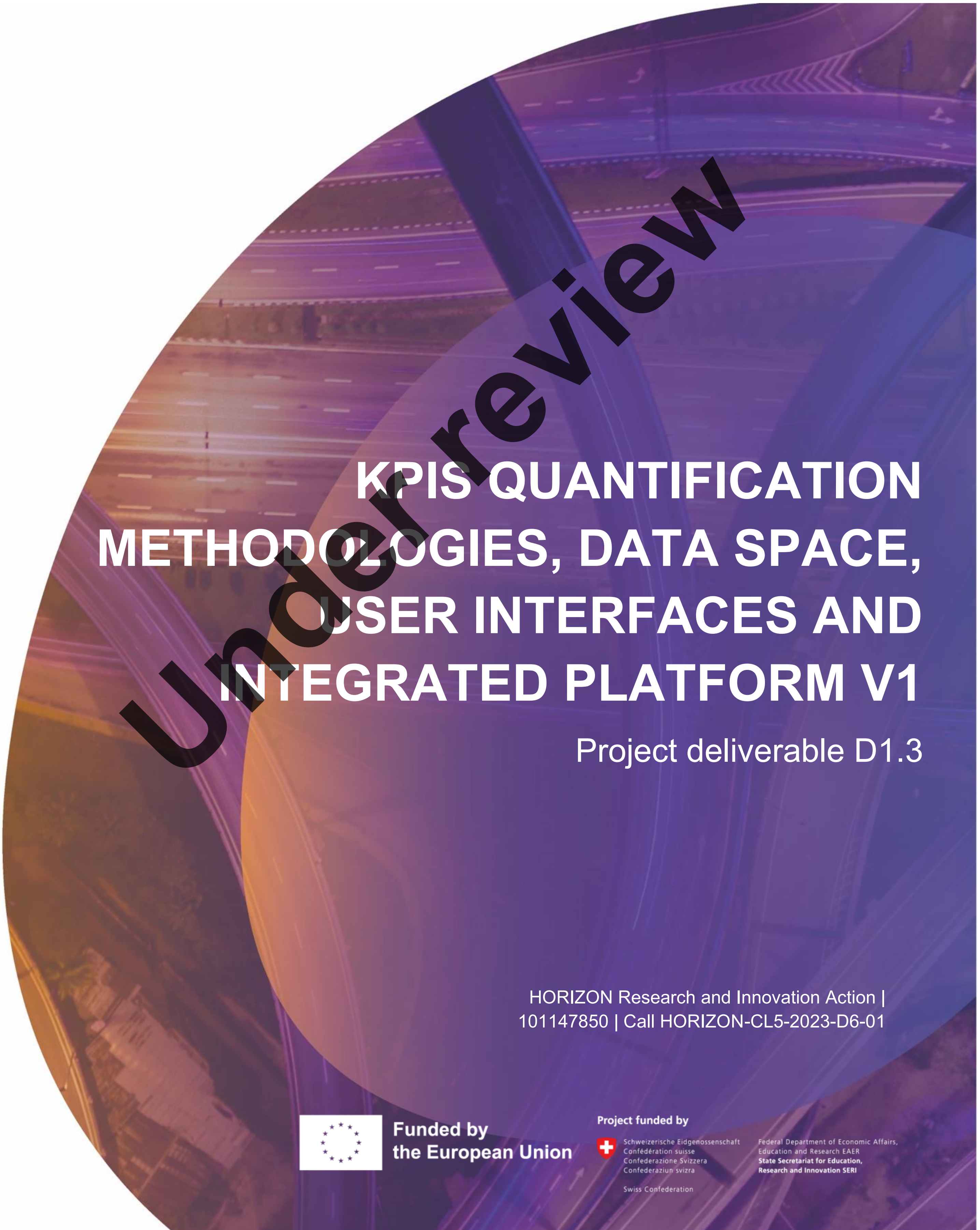
EVOROADS



KPIS QUANTIFICATION METHODOLOGIES, DATA SPACE, USER INTERFACES AND INTEGRATED PLATFORM V1

Project deliverable D1.3

HORIZON Research and Innovation Action | 101147850 | Call HORIZON-CL5-2023-D6-01

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Disclaimer and acknowledgement

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Version	Date	Author	Summary of changes
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0.3	16.09.2025	FRONT	Draft of Chapter 2: User Experience design methodology and Strategy Plane.
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0.11	23.10.2025	VTI	Finalisation of Chapter 3 conclusions and transition to platform architecture.
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0.15	08.11.2025	FRONT	Draft of Development and Physical Views, including deployment assumptions and security foundations (Sections 4.4–4.5.
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0.18	19.11.2025	FRONT	Draft of Chapter 5: State-of-the-art analysis and design of the Safe Mobility Data Space.

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0.21	23.12.2025	FRONT	Updated and consolidated final version
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1.0	30.12.2025	ERT	Final submission to the EC Portal.

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LIST OF ABBREVIATIONS AND ACRONYMS

Acronym	Meaning
AADT	Annual Average Daily Traffic
ADT	Average Daily Traffic
AI	Artificial Intelligence
API	Application Programming Interface
CAV	Connected and Automated Vehicle
CCAM	Connected, Cooperative and Automated Mobility
CKAN	Comprehensive Knowledge Archive Network
CNN	Convolutional Neural Network
CRS	Coordinate Reference System
CSV	Comma Separated Values
DATEX II	Data Exchange Standard for Traffic and Travel Information
DCAT-AP	Data Catalogue Application Profile (profile for data portals in Europe)
DIOD	Digital Infrastructure Observation Device/Drone
DFRS	Data for Road Safety
DMP	Data Management Plan
DOI	Digital Object Identifier
EDC	Eclipse Data Connector
EMDS	European Mobility Data Space
ETA	Estimated Time of Arrival
ETSI TC ITS	European Telecommunications Standards Institute, Technical Committee on Intelligent Transport Systems
EU	European Union
FR	Functional Requirement
FSI	Fatal Serious Injury
GDPR	General Data Protection Regulation

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GeoJSON	Geographic JSON
GeoTIFF	Georeferenced Tagged Image File Format
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
Hz	Hertz
HSM	Highway Safety Manual
IDSA	International Data Spaces Association
InSAR	Interferometric Synthetic Aperture Radar
iPerf	Internet Performance
IPR	Intellectual Property Rights
IRI	International Roughness Index
ISA	Intelligent Speed Assistance
ISAD	Infrastructure Support for Automated Driving
ITS	Intelligent Transport Systems
JSON	JavaScript Object Notation
JSON-LD	JavaScript Object Notation for Linked Data
KSI	Killed or Seriously Injured
KPI	Key Performance Indicator
LL	Living Lab(s)
LLM	Large Language Model
ML	Machine Learning
MLR	Multiple Linear Regression
NAP	National Access Point
NB	Negative Binomial (Regression Model)
NCO	Network Control Office
NOC	Network Operations Centre

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NVDB	Swedish National Road Database
NWRSA	Network-Wide Road Safety Assessment
OBU	On-Board Unit
ODRL	Open Digital Rights Language
OpenVOC	Open-Vocabulary Object Classification/Detection
OR	Odds Ratio
OSM	Open Street Map
PII	Personally Identifiable Information
PDF	Portable Document Format
PMSv4	Pavement Management System version 4
PNG	Portable Network Graphics
POSIX	Portable Operating System Interface
RFID	Radio-Frequency Identification
QA	Quality Assurance
QoS	Quality of Service
RF	Radio Frequency
RF	Random Forest
RIA	Research and Innovation Action
RMS	Root Mean Square
RMSE	Root Mean Square Error
RNN	Recurrent Neural Networks
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSU	Roadside Unit
SA2	Statistical Area Level 2
SAR	Synthetic Aperture Radar
SCB	Statistics Sweden

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SINR	Signal-to-Interference-plus-Noise Ratio
SLA	Service Level Agreement
SMDS	Safe Mobility Data Space
SOP	Standard Operating Procedure
STRADA	Swedish Traffic Accident Data Acquisition
TEN-T	Trans-European Transport Network
TN-ITS	Traffic and Navigation Information Services
UAV	Unmanned Aerial Vehicle
UPS	Uninterruptible Power Supply
UR	User Requirement
V2X	Vehicle-to-Everything
VMS	Variable Message Sign
VRU	Vulnerable Road User
WCAG 2.1 AA	Web Content Accessibility Guidelines, Level AA
WP	Work Package

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PROJECT EXECUTIVE SUMMARY

The EC-funded project EvoRoads (Evolutionary Solutions for Realising a Holistic Safe System Approach for All Road Users) is committed to advancing the European Union's Vision Zero initiative by implementing a comprehensive framework that integrates innovative models, tools, and services for data-driven safety assessments.

The project focuses on developing of a connectivity platform that digitalises transport infrastructure assets while enabling the seamless integration of safety assessment services. By leveraging advanced artificial intelligence (AI), EvoRoads analyses infrastructure monitoring data at various geospatial levels, enabling proactive risk warnings and supporting road operators in managing maintenance more effectively, enhancing safety and operational efficiency. It also defines safety criteria and quantification methods for key performance indicators (KPIs) to monitor safety performance as part of the "Safe System" approach.

The results are developed alongside five axes: (1) an **Evolutionary Safety Assessment Framework** setting the basis by defining how to measure road safety in a multilayered catalogue; (2) a **Road Asset & Safety Management Digital Twin** collecting and distributing safety data; (3) **Advanced Monitoring Safety Systems** that leverage data to provide infrastructure owners with clear insights into the safety levels of their roads; (4) **Proactive Safety Warning Systems** ensuring that critical safety issues are raised pro-actively and in real-time to prevent safety hazards; and finally, all these results are combined in (5) **Solutions Integration, Augmentation and Impact Assessment tools** and **products** allowing for take-up of the results in the wider market. These axes converge into a **Safe Mobility Data Space** where all data related to EvoRoads' safety criteria and solutions are combined.

EvoRoads' methodologies and technologies will be validated in four Living Labs (LLs) addressing diverse road user scenarios across urban and rural environments to ensure broad applicability and effectiveness. EvoRoads LLs are situated in **Spain** (focusing on **Hazard-aware assets for better infrastructure safety level for existing and future roads users**), **Italy** (focusing on **Dynamic Road infrastructure safety diagnosis enhanced by emerging vehicle and digital technologies**), **Latvia** (focusing on **Automated (advanced) low-cost infrastructure monitoring and diagnostics: road hot spots, bridges, tunnels**), and **Romania** (focusing on **Remote sensing and warning technologies for better infrastructure and road conditions**).

The EvoRoads project runs from May 2024 until April 2027. A scale-up event is foreseen towards the end of the project to allow for the wider market to consider EvoRoads' results and to help provide ways forward.

Social Media link:

@evoroads-project

For further information please visit evoroads-project.eu

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DELIVERABLE EXECUTIVE SUMMARY

Deliverable *"D1.3: KPIs quantification methodologies, data space, user interfaces and integrated platform V1"* presents the first consolidated architectural and methodological baseline of the EvoRoads project. It documents how user needs, safety criteria, data analytics and system architecture are brought together into a coherent, integrated platform that supports evidence-based road infrastructure safety management across diverse European contexts. The deliverable establishes a structured framework for transforming safety-related observations into actionable knowledge. It begins by grounding the work in a clear methodological approach, ensuring traceability between project objectives, user needs and technical design choices. Particular emphasis is placed on avoiding siloed development, instead promoting cross-work-package alignment and architectural discipline from the outset.

A central contribution of D1.3 is the definition of **dynamic Key Performance Indicator (KPI) quantification methodologies**. These methodologies translate safety criteria into measurable indicators capable of supporting decisions at different temporal and organisational levels, from near-real-time operational awareness to longer-term planning and evaluation. By explicitly addressing time sensitivity, comparability and interpretability, the KPI framework enables authorities to prioritise interventions, assess impact and justify investments based on consistent evidence.

The deliverable also documents the **design of user interfaces and interaction concepts**, structured through the five planes of user experience (UX). This work ensures that the platform responds to the needs of multiple personas, including road safety operators, maintenance managers, planners, policy stakeholders and researchers. Rather than treating interfaces as an afterthought, EvoRoads positions UX as a core design driver, shaping how analytical outputs and KPIs are presented and acted upon.

At architectural level, D1.3 presents the EvoRoads **Integrated Platform Architecture** (Version 1) using the 4+1 architectural model. The Logical, Process, Development and Physical Views collectively describe component responsibilities, runtime interaction patterns, integration practices and deployment assumptions. An additional operational perspective demonstrates how the architecture supports safety decision workflows across pilots. The architecture explicitly accommodates heterogeneity across pilot sites while preserving a common backbone, ensuring that the platform operates as a single system rather than a collection of bespoke solutions.

A key enabling element documented in this deliverable is the **Safe Mobility Data Space (SMDS)**. The SMDS provides mechanisms for data integration, interoperability, governance and controlled sharing, aligned with European mobility data space principles. By embedding data sovereignty, metadata harmonisation and secure data exchange into the platform design, EvoRoads ensures that data can be reused across organisational and national boundaries without compromising trust or compliance.

D1.3 does not claim final system maturity. Instead, it transparently documents assumptions, constraints and areas scheduled for refinement in subsequent project phases. In conclusion, D1.3 demonstrates that EvoRoads has established a robust, coherent and policy-aligned foundation for its integrated platform. It confirms the project's capacity to translate European road safety goals into concrete technical and operational solutions, setting the stage for full integration, pilot validation and scalable impact in the next phases of the project.

Disclaimer

This document has utilised a large language model (LLM) exclusively for grammar, syntax, and stylistic refinement. Under no circumstances was the LLM employed to generate, modify, or substitute original research content. To the fullest extent permitted by applicable law, responsibility for the accuracy, validity, and integrity of the research and its conclusions rests entirely with the authors.

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1 INTRODUCTION

This chapter provides a general introduction to the deliverable, outlining its objectives, scope, and relevance within the EvoRoads Horizon Europe project (evoroads-project.eu, Grant agreement ID: 101147850). It situates the work in the broader context of data-driven transport safety and infrastructure monitoring, thereby preparing the ground for the more detailed analyses presented in subsequent sections.

1.1. OVERVIEW AND PURPOSE

Road traffic incidents remain a pressing societal challenge in Europe. In 2023, 20,400 fatalities were recorded across the European Union, corresponding to 46 deaths per million inhabitants, with vulnerable road users accounting for almost 70% of urban road deaths. Despite incremental progress, the current decline in accident rates falls short of the reduction trajectory needed to achieve the European Commission's Vision Zero target of halving road fatalities by 2030. Meeting that target requires sustained annual decreases of approximately 4.5% - a pace that has not yet been realised [1]. Preliminary data for 2024 indicate a modest improvement, with around 19,800 road deaths across the EU, representing a 3% drop compared to the previous year [2]. These statistics highlight a clear research and policy problem: the safety of Europe's transport systems cannot be adequately ensured through traditional monitoring practices and static evaluation methods alone.

This deliverable responds to that challenge by consolidating the first generation of tools and frameworks that will enable a new form of road safety intelligence. Rather than relying solely on historical data and retrospective crash statistics, the work presented here introduces methodologies for quantifying safety through dynamic indicators. These indicators, or KPIs, are designed not only to reflect static infrastructure attributes, such as road geometry or signage, but also to incorporate dynamic conditions - traffic density, weather influences, user behaviours, and evolving infrastructure states - that fluctuate over time and space. By doing so, the deliverable moves beyond conventional assessments and establishes the foundations of a system able to adapt in real-time, enhancing both precision and relevance.

At the core of this release lies the first version of a European **Mobility Data Space** tailored to safety applications. The data space is envisaged as a federated environment in which heterogeneous sources - ranging from connected vehicles, drones and roadside sensors to satellite interferometry and user-generated reports - can be harmonised, integrated and accessed securely. Unlike traditional siloed repositories, this environment emphasises interoperability, data quality, and trust. To that end, it adopts semantic models and pre-processing mechanisms that allow very different types of information to be fused into coherent streams. This enables both the enrichment of individual datasets and the creation of composite indicators that capture safety phenomena otherwise hidden when sources remain isolated.

Another central feature of this first release is the **Deployment of Prototype Applications** (including their mobile and web interfaces) through which stakeholders can access and act upon the generated intelligence. These applications embody the principle that advanced analytics only gain value when translated into usable insights for end-users, whether they are road operators, city planners, maintenance contractors, or policy makers. By offering visualisations, alerts, and configurable dashboards, the applications serve as the entry point to the wider platform, ensuring that complex data streams are transformed into actionable knowledge. Importantly, they also provide a mechanism for stakeholder feedback, allowing the system to evolve in response to real operational needs.

The integrated platform presented in this deliverable brings together contributions from several technological domains developed within the project's development-oriented work packages (WPs) (mostly WP2 and WP3). These include advanced monitoring tools capable of identifying infrastructure deterioration, predictive maintenance modules that

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prioritise interventions based on risk, and behavioural analysis instruments that capture patterns of unsafe user behaviour. The platform functions as the connective tissue between these components, providing the architecture through which data are ingested, harmonised, processed and exposed via secure interfaces. This integration is essential: only by combining hardware, software, and analytical innovations can a comprehensive and scalable approach to road safety be achieved.

The significance of this deliverable lies not only in the novelty of the individual outputs, but also in the way they collectively reframe how safety is understood, measured, and acted upon. By releasing the first set of quantification methodologies, the initial deployment of the data space, and the prototype applications, the project delivers a tangible step toward a European ecosystem for road safety intelligence. The solutions are designed with transferability in mind, ensuring applicability across **diverse road types**, from congested urban networks to rural secondary roads, and across different governance levels, from municipal operators to national transport agencies. In broader research terms, the deliverable lays the foundation for longitudinal assessment and iterative refinement. The methods and tools released here are not static end-products; they are the initial iteration of a living framework that will be enriched as new data become available and as subsequent project activities expand their scope. This adaptability is vital for addressing the inherently dynamic nature of transport systems. It also ensures that the outputs remain aligned with evolving regulatory frameworks and emerging mobility technologies, such as cooperative connected and automated mobility services.

Ultimately, the purpose of this deliverable is twofold. First, it demonstrates the **feasibility of integrating** heterogeneous safety-related data into a coherent analytical environment that yields meaningful indicators and services. Second, it provides stakeholders with the **first operational prototypes** of applications and interfaces that will form the basis of evidence-driven interventions. In this way, the deliverable makes an essential contribution to the overarching goal of EvoRoads: to accelerate Europe's transition toward safer, more resilient, and more transparent road networks in support of the Vision Zero strategy.

1.2. DELIVERABLE IN CONTEXT

This subsection positions the deliverable within the overall structure of the EvoRoads project. Its purpose is to consolidate the outputs of preceding technical work into an integrated release that demonstrates how the different strands of research and development converge. Since it addresses integration, the deliverable brings together results from all technology development–oriented tasks, ensuring that methodologies, tools, and components produced elsewhere in the project are combined into a coherent platform.

1.2.1. RELATIONSHIP TO OTHER DELIVERABLES

The present deliverable does not stand in isolation but forms part of a continuum of outputs developed across several WPs. Its immediate predecessor is "*D1.2: Requirements, conceptual architecture and augmented safety criteria catalogue*" (May 2025). That earlier report established the foundation by capturing requirements from the perspective of end users and by proposing a conceptual architecture to frame the project's technical developments. Building upon this groundwork, the current deliverable advances to the definition of a technical architecture, moving a level deeper into detail by consolidating the outputs of multiple tasks into an integrated release of the platform.

Earlier work also shaped the safety framework that underpins the present results. Both "*D1.1: Best practices and baseline catalogue of safety criteria*" (October 2024) and the aforementioned *D1.2* concentrated on safety criteria as a research subject, forming the outcome of Task 1.1. That task performed a state-of-the-art analysis and gap assessment, leading to the creation of a baseline catalogue. By contrast, the current deliverable corresponds to Task 1.3, which develops methodologies for the quantification of these criteria into measurable KPIs. The methodological dimension therefore represents a progression from conceptual exploration to operational quantification, providing the first release of tools that can be applied dynamically to evolving road safety contexts.

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The integration described here is also closely connected with the technological developments undertaken in subsequent WPs. Outputs from *"D2.1: Infrastructure monitoring tools V1"* and *"D2.2: Predictive maintenance and on-the-edge safety tools V1"* will be incorporated into the platform. Similarly, results from *"D3.1: Digital twin and smart road equipment V1"* and *"D3.2: Behavioural models, CAVs infrastructure readiness and micro-mobility services V1"* are assimilated. In this way, the deliverable serves as the first junction where diverse streams of innovation converge, demonstrating how distinct monitoring, predictive, digital twin, and behavioural modelling tools can operate within a coherent and extensible platform.

Looking ahead, the deliverable also has a defined role in the project's broader lifecycle. *"D4.1: Demonstrations Planning Guidelines"* (October 2025) will rely on the platform presented here to outline the specific pilot use cases to be tested in each site. The present deliverable therefore provides the technical backbone against which the planning of demonstrations will be aligned. It will also serve as the reference point for *"D4.2: Evaluation of the first round of demonstrations"* (March 2026), where initial feedback from pilot deployments will be assessed. Further into the project, *"D1.4: KPIs quantification methodologies, data space, user interfaces and integrated platform V2"* (February 2027) will extend and refine the work introduced here, providing a more advanced release that incorporates lessons learned from pilot testing and stakeholder engagement.

Finally, it is important to note the relationship with the *Data Management Plan (DMP)* (all versions), which contains the analytical descriptions of the datasets used in the project, structured in line with the **DCAT Application Profile** tailored to EvoRoads [3]. The data governance principles set out in the DMP form an essential complement to the integration activities described here, ensuring that the datasets feeding the platform are appropriately catalogued, harmonised, and managed throughout the project's lifecycle.

1.2.2. MAPPING EVOROADS OUTPUTS

The present deliverable fulfils the project's commitment to provide the first release of the KPIs quantification methodologies, the mobility data space, the mobile and web applications, and the integrated platform that connects components from the technology-oriented work packages. Its objectives are firmly aligned with the commitments set out in the Grant Agreement. The work builds directly on the foundation of earlier requirements gathering and conceptual design, while translating these into technical outputs that demonstrate integration and operability.

The link to **Task 1.3** is visible in the methodologies developed for dynamic KPI quantification, where the safety criteria identified in earlier activities are operationalised into measurable indicators. The outputs are designed to capture the influence of both static and dynamic road attributes, ensuring that the resulting KPIs can be updated in real time to reflect changes in traffic conditions, user behaviour, and infrastructure quality. These methods rely on mathematical, statistical, and machine learning techniques to enhance predictive capacity, thus enabling evidence-based safety monitoring and crash risk estimation.

Task 1.4 commitments are reflected in the establishment of the Safe Mobility Data Space, which integrates heterogeneous data sources into a harmonised environment that ensures interoperability, trustworthiness, and secure sharing. By extending the work of the International Data Spaces association and embedding quality assurance mechanisms, the data space provides the backbone for reliable KPI calculation and service deployment. Complementing this, **Task 1.5** objectives are met through the integration of solutions from WP2 and WP3 within a coherent platform architecture. This encompasses the specification of roles and processes, the design of service interfaces, and the provision of mobile and web clients that serve as entry points for end users. Through systematic testing and evaluation, the deliverable verifies that these combined outputs operate effectively as a unified system.

For reasons of space and clarity, a **detailed table** mapping the Grant Agreement mandates against the deliverable outputs has been omitted here; it may instead be accessed in Annex II.

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1.3. METHODOLOGY

The methodological approach that underpins this deliverable, summarised in ***Figure 1*** below, combines established design frameworks with participatory processes to ensure that the resulting platform is both technically robust and aligned with user needs. At the architectural level, **the 4+1 view model** was adopted to capture the system from multiple perspectives, covering logical, process, development, physical, and scenario views. This provided a structured means to define how the data space, dashboards, and integrations should operate and interact. Complementing this, the **five planes user experience methodology** was employed to guide the design of interfaces and client applications. By progressing from strategy and scope through to structure, skeleton, and surface, the project was able to ensure that the technical outputs were directly anchored in user requirements and resulted in coherent and accessible experiences.

The requirements collection phase combined **co-creation with stakeholders** and **iterative internal validation**. Living Labs (LLs) were organised at the pilot sites to engage municipalities, road operators, technology providers, and end-users, creating a participatory environment for gathering needs and identifying barriers. These activities were complemented by six internal workshops held in March and April 2025, where project partners synthesised the stakeholder inputs into a consolidated set of functional and non-functional requirements. The outcomes of this process were documented in D1.2, which defined user-oriented requirements and introduced a conceptual architecture. The present deliverable builds upon that foundation, translating requirements into detailed technical specifications for the first release of the integrated platform.

Technical refinement was achieved through **sustained engagement** with the consortium's technology providers. Inputs were gathered via dedicated bilateral calls, presentations at General Assemblies, monthly WP meetings, and regular task-level discussions. These exchanges ensured consistency across the parallel developments reported in D2.1, D2.2, D3.1 and D3.2, which each contributed tools to be incorporated within the platform. Particular emphasis was also placed on the digital twin and deployment infrastructure, with Task 3.1 leading detailed design sessions that included the leaders of Tasks 1.5 and 2.1 to guarantee alignment between the data integration backbone and the infrastructure monitoring solutions. To secure seamless platform integration, the project adopted an incremental validation strategy: individual modules were first tested in isolation, then progressively combined in controlled environments before being incorporated into the shared platform environment. This staged approach allowed potential incompatibilities to be detected early and resolved collaboratively, reducing risks of fragmentation and ensuring that the integrated release operates as a coherent whole.

An additional methodological strand concerned the **development of safety-related KPIs**. The process emphasised the importance of maintaining a clear link between outcome indicators, such as fatalities and serious injuries, and supporting indicators that capture contributing factors. Once this relationship was established, specific KPIs were defined, relevant data sources identified, and temporal resolutions determined to enable either real-time, periodic, or long-term monitoring. While the application of countermeasures lies formally outside the project scope, the KPIs were designed with practical use in mind, ensuring that they can guide interventions ranging from immediate warnings to longer-term infrastructure improvements. In this way, the KPI methodology complements the technical architecture and integration strategy, ensuring that the platform outputs are measurable in terms of their contribution to safer transport systems.

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Figure 1: Methodology summarisation for Deliverable 1.3

1.4. DELIVERABLE STRUCTURE

The present document is organised into six chapters that together provide a coherent account of the first release of the EvoRoads integrated platform.

Chapter 1 introduces the purpose and scope of the deliverable, situates it within the broader project, and outlines the methodological approach that has guided the work. **Chapter 2** presents the design of the user-facing elements through the five planes of UX, showing how the interfaces were shaped from strategic intent to final surface design. **Chapter 3** addresses the development of dynamic KPIs, detailing the process through which safety-related criteria are transformed into measurable indicators capable of supporting interventions at different temporal resolutions. **Chapter 4** then turns to the technical architecture of the platform, adopting the 4+1 methodology to present the system from multiple perspectives and including a discussion of access control and security mechanisms. **Chapter 5** focuses on the safe mobility data space, describing its design principles, data models, and role in ensuring interoperability and trust across heterogeneous sources. Finally, **Chapter 6** draws together the main findings, highlighting conclusions, lessons learnt, challenges encountered, and the alignment of the deliverable with European transport safety goals, while outlining the steps foreseen for the next project phases.

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2 EVOROADS PLATFORM USER EXPERIENCE

This chapter will present the user experience (UX) approach for the EvoRoads platform, detailing the methodology, strategy, and design principles that shape user interactions. It will cover user profiling and success criteria, define user and content data requirements, and outline interaction design through use cases and information architecture. Additionally, it will describe user journeys through information delivery and navigation design, concluding with visual representations such as mock-ups and wireframes to illustrate the platform's intended look and feel.

2.1. USER EXPERIENCE DESIGN METHODOLOGY

The design of the EvoRoads platform is grounded in a user-centred methodology that places the needs, expectations, and behaviours of end-users at the forefront of development. User-centred design as a discipline emerged in the late twentieth century, influenced by research in human–computer interaction, ergonomics, and cognitive psychology. It emphasised that systems should be intuitive and accessible, not merely technologically sophisticated. As digital products became more complex, practitioners sought structured frameworks to align technical development with user requirements. Among the most influential of these is **the five planes of UX methodology**, first articulated by Jesse James Garrett in the early 2000s. This framework, visualised in ***Figure 2***, has since become widely adopted in both industry and academia as a way of ensuring that digital systems progress coherently from abstract goals to concrete interfaces [4].

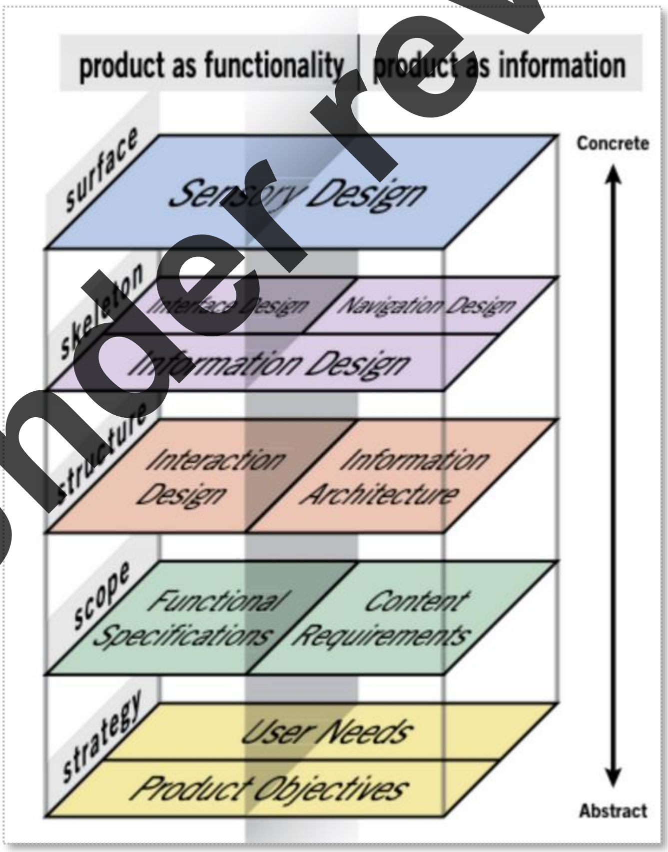

Figure 2: Official Visualisation of the 5 Planes of UX Design by J.J. Garrett [4]

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The strength of the five planes lies in its layered approach. Each plane represents a level of decision-making, from the most conceptual to the most tangible. While the planes can be followed sequentially, the methodology also encourages iteration: insights gained at a later stage may prompt refinements to earlier decisions. This flexibility ensures that design outputs remain responsive to evolving contexts and stakeholder feedback, while maintaining overall coherence.

The first plane, **strategy**, establishes the purpose of the system. It requires identifying the objectives of the organisation or project and aligning them with the goals of the users. This step prevents design efforts from drifting into features that may be technically interesting but irrelevant to actual user needs. It also ensures that the project's wider ambitions, such as improving safety or efficiency, are embedded from the outset in the design process.

The second plane, **scope**, translates the high-level goals into concrete requirements. Functional requirements specify what capabilities the system must deliver, while content requirements define the information that must be made available. Scope acts as a boundary-setting exercise, making explicit decisions about what the system will and will not do. By clarifying expectations early, it reduces the risk of scope creep and helps teams allocate resources effectively.

The third plane, **structure**, is concerned with organisation. It encompasses two complementary dimensions: information architecture and interaction design. Information architecture ensures that content is logically categorised and easy to retrieve, while interaction design determines how users navigate and interact with system functions. Together, these aspects create a blueprint of the UX, describing how different elements fit together and how users move through them to achieve their goals.

The fourth plane, **skeleton**, refines the structure into a concrete layout. Wireframes, schematics, and interface diagrams are produced to show how information and controls will be arranged on the screen. At this level, decisions about navigation menus, button placement, and data visualisation modules are made, with the primary aim of ensuring clarity and usability. The skeleton provides a tangible reference that developers, designers, and stakeholders can review and iterate upon before committing to full-scale implementation.

The fifth and final plane, **surface**, represents the visual design of the system. Here, the focus shifts to the look and feel of the interface: typography, colour palettes, iconography, and other aesthetic choices. Although the surface is the most visible part of the design to end-users, it is effective only when supported by the careful groundwork of the preceding planes. The surface reinforces usability by guiding attention, reducing cognitive load, and fostering trust through consistency and clarity.

In practice, the five planes are rarely traversed in a strictly linear fashion. Instead, they function as reference layers that interact with one another. A visual design choice at the surface may reveal flaws in the skeleton, just as user testing of interaction flows may highlight shortcomings in the scope or strategy. This iterative nature ensures that design evolves dynamically, rather than being fixed prematurely. Taken together, the five planes of UX provide a systematic yet flexible methodology for bridging the gap between user needs and technological solutions. They ensure that design decisions are grounded in purpose, translated into clear requirements, organised into coherent structures, refined through layout, and expressed through visual form. By adopting this framework, the EvoRoads project aligned itself with a well-established tradition in UX design, ensuring that its platform interfaces are not only functional but also accessible, comprehensible, and responsive to the diverse range of users who will rely upon them.

2.2. USER EXPERIENCE STRATEGY PLANE

At the foundation of the five planes of UX lies the **strategy plane**, which defines the purpose of the platform by answering two principal questions: **how the builders of EvoRoads expect to benefit from the platform, and what end-users will gain in terms of value**. For EvoRoads, these questions must be understood in relation to both the project's role within the Horizon Europe framework and the wider ambitions of the EU for road safety. The EU's Vision Zero strategy, which aims to halve road fatalities by 2030 and eliminate them by 2050, frames the collective purpose of our work [5]. Within this context, EvoRoads partners not only pursue technological and commercial opportunities but also recognise their responsibility to contribute to measurable societal progress. End-users - including municipalities, infrastructure operators,

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and citizens - expect the platform to deliver business value by providing actionable intelligence, enabling efficient maintenance, and fostering safer mobility. The strategy plane thus anchors the UX design in the dual pursuit of innovation and impact, ensuring that platform development is guided by both societal and stakeholder objectives.

2.2.1 BUSINESS GOALS FROM DEVELOPERS' VIEWPOINT

In defining the strategy for the EvoRoads platform, it is important to reflect on the benefits expected by its builders, who are not only researchers and innovators, but also European citizens committed to safer mobility.

2.2.1.1 SOCIETAL AND SAFETY-RELATED BUSINESS GOALS

These expectations encompass social, technical, and operational outcomes that together guide the development of the platform.

- **Enhanced road safety outcomes:** Provide actionable intelligence that supports measurable reductions in collisions, fatalities, and serious injuries, contributing directly to the EU target of halving road deaths by 2030.
- **Dynamic KPI quantification:** Enable continuous monitoring of infrastructure and user behaviour through real-time KPIs, supporting fast adaptation of the traffic system to evolving risks.
- **Predictive maintenance:** Improve asset management efficiency by allowing operators to anticipate infrastructure failures, aiming to reduce downtime and maintenance-related incidents by at least 20%.
- **Digital twin integration:** Deliver a live digital representation of road networks that strengthens resilience, optimises operations, and enhances situational awareness for municipalities and operators.
- **Protection of vulnerable road users:** Prioritise the safety of pedestrians, cyclists, elderly citizens, people with disabilities, and micro-mobility users, targeting a 20% reduction in their exposure to hazardous conditions.
- **Safer rural and secondary roads:** Extend advanced monitoring and KPI quantification to less supported road categories, helping reduce risks on rural and non-trunk roads where accidents remain disproportionately high.
- **Efficient decision-making:** Provide evidence-based insights for local authorities, enabling better allocation of resources and supporting investment decisions with clear safety returns.
- **Transparency and trust:** Demonstrate secure and privacy-preserving data governance, ensuring that citizens and stakeholders can trust the platform as a neutral and reliable safety tool.
- **Cross-country scalability:** Validate a solution that functions across varied traffic environments and road types, ensuring replicability and broader European adoption beyond the initial pilots.
- **Citizen engagement:** Strengthen public awareness and confidence by incorporating nudging tools and transparent feedback mechanisms that foster safer behaviours.
- **Alignment with Vision Zero:** Anchor the platform within the EU's long-term strategy of eliminating road fatalities by 2050, positioning it as a tangible step toward this collective ambition.

Taken together, these expectations demonstrate the breadth of benefits that the EvoRoads platform seeks to deliver, from measurable safety improvements to greater inclusivity and trust. They highlight a vision of mobility where data and technology underpin not only efficiency but also social responsibility, extending protection to the most vulnerable and addressing long-neglected road environments. At the same time, project partners will syntax individual exploitation plans for their contributions, to be elaborated further in Deliverable "*D5.2: IPR and innovation management, Exploitation Roadmap*".

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2.2.1.2 TECHNOLOGY-LEVEL BUSINESS GOALS

In addition to the wider societal and safety-related benefits anticipated from the EvoRoads platform, there are also clear business goals at the technological level. These address the usability, performance, and operational qualities of the system, ensuring that the platform is not only impactful in its outcomes but also practical and dependable in everyday use.

- **Intuitive user interfaces**: Ensure that web and mobile applications are easy to use, with a minimal learning curve for both expert operators and occasional users.
- **Low-latency performance**: Deliver near real-time updates of safety KPIs and alerts, with end-to-end latency not exceeding a few seconds for critical events.
- **Scalability**: Design the architecture to handle large volumes of heterogeneous data streams, enabling future extension beyond the initial pilots.
- **Reliability and resilience**: Maintain high system availability, with redundancy and fallback mechanisms to ensure continuous service in case of network or hardware failures.
- **Interoperability**: Provide open interfaces and data models that support seamless integration with existing ITS platforms, municipal systems, and European data initiatives.
- **Security and privacy**: Guarantee compliance with General Data Protection Regulation (GDPR) and cybersecurity best practices, ensuring secure data exchange, encryption of sensitive information, and role-based access control.
- **Lightweight applications**: Develop mobile and web clients optimised for low bandwidth and limited device resources, ensuring smooth performance across diverse environments.
- **Configurability**: Allow different user groups (e.g., operators, policymakers, citizens) to adapt dashboards and visualisations to their specific needs.
- **Maintainability**: Employ modular and containerised components to simplify updates, bug fixes, and the integration of new features during and beyond the project.
- **Cross-platform consistency**: Ensure that interactions and design principles remain coherent across desktop, mobile, and in-vehicle contexts.

These goals reflect the need for a platform that is not only ambitious in scope but also robust in technical execution. They highlight qualities that determine user trust, adoption, and long-term sustainability, complementing the broader social impact described earlier. An observant reader will note that many of these goals correspond closely to the non-functional requirements of the platform, though at a higher level of abstraction. While not a one-to-one mapping, they provide a consistent framework for ensuring that usability and performance considerations remain integral throughout the development process.

2.2.1.3 BRAND IDENTITY GOALS FOR THE EVOROADS PLATFORM

Beyond societal and technological objectives, the EvoRoads platform must also project a clear and consistent brand identity. This ensures that its visual and communicative presence resonates with stakeholders and conveys trust, innovation, and European collaboration.

- **Clarity and professionalism:** Present a visual identity that is modern, consistent, and authoritative, reinforcing confidence in the platform's reliability and scientific basis.
- **European alignment:** Reflect the shared values of the European Union and the Vision Zero strategy through colours, symbols, and narratives that emphasise collaboration and inclusivity.
- **Accessibility and inclusivity:** Ensure that branding and design choices, including typography and colour contrast, support accessibility standards so that all users feel represented and considered.

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- **Memorability:** Create a recognisable and coherent look-and-feel across web, mobile, and dissemination materials that makes the EvoRoads platform immediately identifiable in the broader landscape of mobility initiatives.

These brand goals complement the technical and social objectives by shaping how the platform is perceived and remembered. They demonstrate that trustworthiness and usability extend beyond system performance into communication and design. While less measurable than performance indicators, they provide the visual and emotional coherence necessary for user adoption.

2.2.1.4 MEASURING THE SUCCESS AND IMPACT OF THE INTEGRATED PLATFORM

The success of the EvoRoads platform can only be meaningfully assessed if its achievements are measured against the goals set for it. These goals, as defined in the strategy plane, operate at three complementary levels: societal and safety outcomes, technology-level performance, and brand identity. Together, they provide a structured framework for evaluating the platform's contribution, not only as a technical system but also as a tool for social good and a recognisable EU initiative.

At the societal level, success is tied directly to the platform's ability to reduce risks for road users and support progress towards Vision Zero. Quantifiable outcomes such as reductions in collisions, fatalities, and near-miss incidents, alongside greater protection of vulnerable users and safer rural roads, serve as primary benchmarks. Additional evidence will come from municipalities adopting the system for evidence-based decision-making, as well as from improvements in transparency and citizen trust. These measures reflect the platform's contribution to the overarching ambition of safer, more inclusive mobility across Europe.

Technological goals demand a different set of metrics. Success here can be demonstrated by measuring interface usability (task completion rates, user satisfaction), performance (system latency for alerts and KPI updates), reliability (uptime and resilience under load), and scalability (capacity to process heterogeneous data sources across pilot and non-pilot sites). Security compliance and data privacy protections, such as GDPR adherence [6], also provide tangible measures. These criteria ensure that the platform not only functions but does so in a way that is efficient, dependable, and adaptable across diverse contexts.

Finally, brand identity goals shape how the platform is perceived and trusted. Success in this dimension can be observed through stakeholder recognition of EvoRoads as a consistent, professional, and inclusive initiative. Accessibility of visual design, coherence across dissemination materials, and memorability of its interfaces are qualitative but vital measures of impact. While harder to quantify, they reinforce adoption and long-term engagement, linking directly to user trust and inclusivity.

Evaluation across these three dimensions will ultimately demonstrate whether the platform has delivered on its promises. A dedicated future deliverable, "*D4.3: Solutions impact assessment*", will expand on this by providing a comprehensive methodology that combines quantitative and qualitative measures. In this way, EvoRoads ensures that its success is not judged narrowly by technical performance alone, but by its holistic contribution to safer, more transparent, and more resilient European transport systems.

2.2.2 BUSINESS GOALS FROM END-USERS' VIEWPOINT

Designing EvoRoads requires us to look beyond institutional objectives and our own technical ambitions, and to attend carefully to the everyday realities of its intended users. After clarifying the platform's strategic goals from the perspectives of the developers and the European policy framework, the next step is to ground the experience in lived practices: how road operators diagnose issues on a Monday morning, how municipal planners weigh interventions across constrained budgets, how maintenance crews act under time pressure, how emergency services navigate risky locations, and how citizens - especially vulnerable road users - perceive and respond to safety information. Good design is not conjecture; it is an evidence-informed synthesis of needs, constraints, and behaviours. To avoid the myopia and vanity that often accompany developer-centric thinking, we adopt a user-centred approach that privileges field observations, co-creation,

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and iterative validation over abstract assumptions. This entails recognising varied contexts of use (urban and rural), different levels of digital literacy, accessibility requirements, multilingual needs, and strict expectations around privacy and transparency. It also means defining measurable success criteria - task efficiency, error reduction, comprehension of risk signals - before we design interfaces. The following subsections therefore articulate user perspectives and crystallise them into personas that guide concrete, testable design decisions.

This section marks a deliberate pivot: from **business value defined by the builders** to **business value experienced by the end-users**. We have already gathered requirements and completed the first pass of business analysis; now we translate those inputs into human-centred artefacts that will steer the platform's navigation, interaction patterns, and content priorities. By making this bridge explicit, we reduce the risk of building technically impressive features that do not land in day-to-day work.

Personas are the tool we use to keep that bridge intact. As Alan Cooper famously argued in *The Inmates Are Running the Asylum* [7], well-crafted personas prevent design from being captured by edge cases or internal opinions; they anchor decisions in representative user goals rather than in the loudest voice in the room. Steve Krug's *Don't Make Me Think* [8] adds the complementary principle of obviousness: if an interaction is not self-evident to the people who must rely on it under pressure, the design has failed - no matter how advanced the underlying technology. Together, these ideas frame personas as more than biographies; they are design constraints that improve clarity, reduce rework, and make trade-offs explicit.

Figure 3: The EvoRoads end-user personas resulting from the Living Labs analysis

Our personas, illustrated in ***Figure 3***, are not invented in a vacuum. They are distilled from the **LLs** that took off during the first year of EvoRoads, where stakeholders co-created scenarios and described the frictions and workarounds in their daily routines. Insights from interviews, pilot workshops, and internal sessions in March-April 2025 were consolidated in *D1.2*, and they underpin the profiles that follow. Each persona below is presented with a consistent structure - goals, decisions and time horizons, pain points, user stories, accessibility considerations, core data, constraints, and essential UX features. This uniformity lets us map requirements to views and derive acceptance criteria without ambiguity. It also

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helps us spot gaps: if a critical decision does not appear in any persona, we can address the omission before it becomes costly.

2.2.2.1 ROAD SAFETY OPERATOR (TRAFFIC CONTROL CENTRE ANALYST)

Applicable Living Labs: Madrid; Galicia; Santa Oliva; Turin; Riga; Alba Iulia.

Job description:
Monitors live safety conditions and KPIs across the network, triaging alerts and coordinating the right responses. Works under time pressure to prevent incidents, protect vulnerable users, and keep traffic flowing safely.

Primary job to be done:

- Spot, prioritise, and confirm emerging risks quickly (near-misses, dangerous behaviours, infrastructure issues).
- Trigger proportionate mitigations (e.g., advisory messages, local rule adjustments, hotspot watchlists).
- Keep a reliable operating picture for colleagues and shift changeovers.
- Review outcomes and tune thresholds/rules to reduce noise and improve hit rate.
- Pay special attention to Vulnerable Road User (VRU) hotspots and rural/secondary roads where data or coverage may be weaker.

Decisions & time horizon:
Real-time (seconds–minutes) for alert triage and actions; hourly for status checks; daily/weekly for hotspot reviews and rule tuning; periodic for governance reports.

Pain points:

- Too many alerts and false positives hide the truly urgent ones.
- Data comes from many places; provenance isn't always clear or trusted.
- Latency and coverage gaps (especially on rural roads) slow reactions.
- Responsibilities and escalation routes can be unclear in fast-moving situations.
- High cognitive load during peaks; easy to miss context or repeat patterns.

User stories:

- *As a road safety operator, I need reliable, real-time hazard detection from roadside units, so as to react immediately and keep traffic safe.*
- *As a road safety operator, I need to fuse crowdsensed defects/signage issues from vehicles and micromobility, so as to escalate only validated hazards.*
- *As a road safety operator, I need strategic sensing (Unmanned Aerial Vehicle (UAV)/ Interferometric Synthetic Aperture Radar (InSAR)) to validate hard-to-see risks and protect major corridors.*
- *As a road safety operator, I need forward-looking risk intel, so as to prevent crashes and plan targeted interventions.*
- *As a road safety operator, I need to deploy targeted roadside warnings, so as to reduce risky behaviour before incidents occur.*
- *As a road safety operator, I need visibility on Connected, Cooperative and Automated Mobility (CCAM) communications health, so as to guarantee delivery of safety-critical alerts and nudges.*

Accessibility & language needs:
WCAG-compliant UI; high contrast and colour-blind safe palettes; keyboard shortcuts; screen-reader labels on critical controls; optional audio cues; large-text mode; plain English; multilingual support where needed.

Core data:

- **Dynamic safety KPIs** (near-miss proxies, speed variance, harsh braking, conflict indices).

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- **Infrastructure condition** from **UAV/drone imagery** (pavement, markings, signage) and **computer vision detections** (potholes, cracks, faded lines, obstructions).
- **Satellite InSAR time-series** for ground movement around roads and structures.
- **Vehicle-based telemetry** from **probe/maintenance vehicles** and **micro-vehicle kits** (Global Navigation Satellite System (GNSS), acceleration/vibration proxies for roughness) via a sensor-agnostic layer.
- **Roadside/edge sensing** and **smart equipment** status (RSUs, beacons, smart signs).
- **V2X / ETSI TC Intelligent Transport Systems (ITS) messages** relevant to hazards and local advisories.
- **Connectivity & Quality of Service (QoS)** (cellular and short-range): coverage, latency, throughput, packet loss; Infrastructure Support for Automated Driving (**ISAD) readiness** indicators.
- **Weather/visibility** feeds and **environmental context**.
- **Work-zone data**: planned/active works, lane closures, temporary traffic management states.
- **Digital twin outputs**: risk scores, black-spot probabilities, deterioration forecasts, recommended advisory speeds.
- **VRU & micro-mobility layers**: flows, parking compliance, conflict hotspots, school/event time windows.
- **Citizen/crowdsourced reports** (privacy-safe, with moderation).
- **Administrative/geospatial layers**: speed limits, geometry, crossings, schools, hospitals.
- **Audit & provenance**: source, timestamp, model/rule version.

Sensitivity: personal data are minimised/pseudonymised; imagery and telemetry handled with privacy safeguards (blurring/redaction where required), GDPR compliance, secure access and retention limits.

Constraints:
GDPR and duty-of-care; fixed SOPs and legal protocols; limited staffing at peaks; variable bandwidth/hardware; inter-agency coordination; limited direct enforcement authority.

Key UX needs/features:

- A clear list of alerts, ordered by importance.
- A short, plain explanation of each alert ("why flagged").
- One main map with easy on/off switches for layers.
- Big, safe action buttons (with confirmation) for common tasks.
- Mark alerts as seen/assigned/closed, with handover notes.
- A simple timeline to replay what happened.
- Easy controls to adjust local thresholds/profiles when needed.
- Works well even with poor connection (basic summaries available).
- Save favourite views for quick access.
- A clear badge when communications are degraded, and safer defaults apply.

2.2.2.2 MUNICIPAL MOBILITY PLANNER (POLICY & INVESTMENT)

Applicable Living Labs: Madrid; Galicia; Santa Oliva; Turin; Riga; Alba Iulia.

Job description:

Plans and prioritises mobility and road safety projects across urban and rural areas, balancing safety, equity, cost, and political feasibility. Translates long-term goals (e.g., Vision Zero) into annual programmes, corridor strategies, and investment plans.

Primary job to be done:

- Identify high-risk corridors and sites, including rural/secondary roads, and rank them for intervention.
- Build defensible project portfolios using KPI trends, before/after evidence, and cost–benefit views.
- Align proposals with policy targets (VRU protection, accessibility, emissions, resilience).

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- Coordinate with maintenance and operations to time works and minimise disruption.
- Communicate plans clearly to decision-makers and the public (briefings, maps, summaries).

Decisions & time horizon:

Quarterly to multi-annual; programme selection, corridor strategies, budget phasing; periodic monitoring and course correction based on evidence.

Pain points:

- Fragmented evidence makes it hard to compare sites fairly.
- Limited budget and political cycles force trade-offs that are hard to justify.
- Rural and secondary roads are under-measured, creating equity gaps.
- Before/after evidence is inconsistent or buried in separate reports.
- Complex data (technical, statistical) is hard to turn into plain, persuasive messages.

User stories:

- *As a municipal planner, I need long-term forecasts of road deformation and deterioration, so as to direct investments toward high-risk zones.*
- *As a municipal planner, I need harmonised safety criteria and KPI dashboards, so as to align with EU standards and monitor compliance.*
- *As a municipal planner, I need to evaluate behavioural interventions, so as to prioritise investments in VRU safety.*
- *As a municipal planner, I need to ensure road investments align with CCAM coverage and future mobility readiness.*
- *As a municipal planner, I need to provide transparency and engage citizens, so as to justify investments and build trust.*
- *As a municipal planner, I need to optimise maintenance budgets and prioritise high-value interventions.*

Accessibility & language needs:

Clear plain-language explanations; readable charts with high contrast; downloadable briefs and maps; bilingual or multilingual support where needed.

Core data:

- **Longitudinal safety KPIs** (fatal/serious injury proxies, near-miss indicators, VRU exposure, speed variance, conflict indices).
- **Crash histories and black-spot probabilities** (aggregated).
- **Infrastructure condition summaries from UAV/drone imagery and computer vision** (pavement, markings, signage).
- **Ground movement trends from InSAR for medium/long-term risk.**
- **Vehicle/probe and micro-vehicle kit signals** (aggregated roughness/ride quality, GNSS-based flows).
- **Smart equipment status (e.g., dynamic signs) and work-zone records** (planned/active).
- **Connectivity/ISAD readiness for corridor feasibility and digital services.**
- **Socio-demographic and land-use aggregates** (equity cuts, schools, hospitals).
- **Cost libraries and unit rates, programme constraints, and before/after impact datasets.**

Sensitivity: All personal data minimised/pseudonymised; outputs aggregated; strict access controls and GDPR-compliant handling.

Constraints:

Fixed budgets and procurement rules; election/policy cycles; inter-department coordination; statutory processes; limited high-quality data for some rural areas.

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Key UX needs/features:

- One fair ranking of corridors/sites with plain “why” notes.
- Filters for VRU focus, rural/secondary roads, equity, cost bands.
- Easy before/after impact cards and what-changed notes.
- Side-by-side cost / impact / risk comparison for portfolio building.
- Export maps and two-page briefs ready for committees and public pages.
- Simple targets tracker (progress to policy goals) with confidence indicators.

2.2.2.3 MAINTENANCE PROGRAMME LEAD (INFRASTRUCTURE OWNER/CONTRACTOR)

Applicable Living Labs: Madrid; Galicia; Santa Oliva; Turin; Riga; Alba Iulia.

Job description:
Plans and delivers preventive and corrective road works across urban and rural networks, balancing safety, cost, traffic impact, and programme deadlines. Coordinates contractors and approvals, sets up safe work zones, and verifies outcomes before closing works.

Primary job to be done:

- Build and maintain a risk-ranked backlog of assets/segments needing treatment.
- Choose what to fix and when using deterioration forecasts, safety risk, cost, and traffic disruption.
- Prepare work-zone plans and safety measures, with a focus on VRUs and sensitive sites (schools, hospitals).
- Coordinate timings and dependencies with operations, micro-mobility, and telecom (e.g., signage, comms readiness).
- Verify and document post-works results; update asset records and future forecasts.

Decisions & time horizon:
Weekly–annual (programme planning, scheduling windows, night vs day works, treatment selection); real-time for urgent defects and on-site changes due to weather/incidents.

Pain points:

- Condition data are fragmented or outdated; hard to compare sites fairly.
- Conflicting objectives: safety vs traffic flow vs budget vs political timing.
- Tight windows, permits, and constraints (noise, school hours, events, weather).
- Incomplete asset registers or “as-built” records complicate planning.
- Weak before/after evidence makes it hard to prove effectiveness.

User stories:

- *As a maintenance lead, I need detailed infrastructure condition data, so as to dispatch crews efficiently.*
- *As a maintenance lead, I need forecasts of asset deterioration, so as to plan proactive interventions.*
- *As a maintenance lead, I need efficient scheduling of works, so as to minimise cost and traffic disruption.*
- *As a maintenance lead, I need to verify the effectiveness of repairs, so as to ensure long-term quality.*
- *As a maintenance lead, I need to align resource allocation with budgets, so as to optimise limited funds.*
- *As a maintenance lead, I need to coordinate with telecoms, utilities, and road operators, so as to minimise disruption and ensure safety.*

Accessibility & language needs:
Clear, printable packs (method statements, maps); high-contrast charts; plain language summaries for briefings; mobile-friendly field mode; multilingual where needed.

Core data (sensitivity):

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- **Infrastructure condition** from **UAV/drone imagery** and **computer vision** (pavement distress, markings, signage).
- **Vehicle/probe and micro-vehicle kit signals** (GNSS, vibration/roughness proxies) via a sensor-agnostic layer.
- **InSAR ground-movement** trends for medium/long-term risk near corridors/structures.
- **Dynamic safety KPIs** and near-miss indicators (including VRU exposure/conflict).
- **Digital twin outputs:** deterioration forecasts, risk scores, suggested advisory speeds, black-spot probabilities.
- **Traffic data** (Annual Average Daily Traffic (AADT)/peaks), diversion risks, sensitive sites (schools, hospitals).
- **Connectivity & QoS** (cellular/short-range), **ISAD readiness** for work-zone comms and signage control.
- **Smart equipment status** (dynamic signs, beacons, RSUs) and **work-zone states** (planned/active).
- **Weather/visibility** forecasts; **events calendars**; **permit and constraint** datasets (noise windows, environmental limits).
- **Asset registry** and historical **maintenance records**; **cost libraries** and contractor performance metrics.

Sensitivity: Mostly aggregated/operational data; any personal data minimised/pseudonymised; contractor performance treated as confidential; GDPR-compliant handling and secure access.

Constraints:

Fixed budgets and procurement rules; permits and statutory notices; weather and seasonal restrictions; lane availability and traffic management capacity; coordination with utilities and telecom; supply-chain lead times.

Key UX needs/features:

- Backlog ranked by risk and benefit/cost.
- One map with condition, risk, traffic, and sensitivity layers (schools, hospitals).
- A compare-treatments screen (cost, duration, expected benefit).
- Work-zone planner with templates and clash warnings (events, school times, degraded comms).
- Built-in advisory signage and diversion setup (with confirmation).
- Checklists for work-zone safety; printable method statements and maps.
- Post-works verification: attach new imagery/sensor runs; automatic before/after KPIs.
- Automatic report to update the asset register and programme status.
- Offline field mode for low-connectivity areas.
- In-platform notifications when dependencies change (weather alerts, QoS degradation, new incidents).

2.2.2.4 MICRO-MOBILITY SERVICES MANAGER (E-SCOOTERS/CYCLING)

Applicable Living Labs: Madrid; Riga; Turin; Alba Iulia; Galicia.

Job description:

Runs shared micro-mobility services and coordinates with the city to keep riders and pedestrians safe. Adjusts operations (geofences, parking, fleet placement) based on demand, risks, and events.

Primary job to be done:

- Find and reduce conflict hotspots between riders, pedestrians, and traffic.
- Improve parking compliance and keep pavements, crossings, and ramps clear.
- Adjust geofences and speed limits by time and place (e.g., school hours, stadium events).
- Detect and report potholes and surface defects to the city for fast, trackable fixes.
- Balance fleet availability with safety rules and local regulations.

Decisions & time horizon:

Daily to weekly for geofences, parking zones, and fleet placement; hourly during events or peaks; monthly/quarterly for programme reviews with the city.

Pain points:

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- Conflicts cluster in time windows (school finish, events) and are hard to anticipate.
- Parking rules differ by street; signage and curb space change often.
- Data privacy rules limit raw trip data sharing with the city.
- Public perception turns quickly after incidents or viral photos of bad parking.
- Many dashboards; hard to see the whole picture in one place.

User stories:

- *As a micro-mobility manager, I need to know which cycle lanes and scooter paths are unsafe, so as to adapt operations.*
- *As a micro-mobility manager, I need to enforce parking rules, so as to reduce clutter and improve city relations.*
- *As a micro-mobility manager, I need to adapt fleet deployment to safe and well-maintained areas, so as to maximise rider satisfaction.*
- *As a micro-mobility manager, I need to correlate user incidents with infrastructure risks, so as to support accountability and safety improvements.*
- *As a micro-mobility manager, I need to comply with municipal reporting obligations, so as to retain operating licenses.*
- *As a micro-mobility manager, I need to inform riders about safe and unsafe zones, so as to improve safety and user trust.*

Accessibility & language needs:

Clear icons and wording; colour-blind safe palettes; mobile-friendly controls for on-street checks; bilingual or multilingual labels where needed.

Core data (sensitivity):

- **Aggregated trip traces** and **demand** heatmaps (pseudonymised).
- **Conflict/near-miss** indicators for VRUs at crossings, shared paths, and stations.
- **Parking complianc**e metrics (time to clear, on/off-pavement, no-park breaches).
- **Geofence logs** (speed caps, slow/stop zones, time windows).
- **Pavement distress signals**: computer vision pothole detections, rider roughness/vibration proxies from on-vehicle kits, and crowdsourced reports (privacy-safe).
- **Event and school schedules, land-use** and **curb** regulations.
- **Weather and visibility** (rain, wind) affecting rider behaviour.
- **Digital twin risk layers and advisory messages** available to public signage.

Sensitivity: Personal data minimised/pseudonymised; strict consent and retention controls; GDPR-compliant access; shared only as aggregates.

Constraints:

City permits and service SLAs; changing curb rules; media scrutiny; limited staff for on-street corrections; device/bandwidth limits for field teams.

Key UX needs/features (simple):

- Hotspot map with when and why (plain reasons).
- One screen for geofences (draw, schedule, preview effect).
- Clear parking compliance dashboard with “top 10” problem blocks.
- Event presets to switch rules quickly.
- Before/after cards to show impact.
- Exportable summaries for city meetings (privacy-safe).
- Mobile view for quick checks on the street.

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2.2.2.5 CITIZEN / VULNERABLE ROAD USER (GENERAL PUBLIC)

Applicable Living Labs: Madrid; Galicia; Santa Oliva (IDIADA site visitors/staff); Turin; Riga; Alba Iulia.

Job description:
Walks, cycles, drives, or uses a wheelchair or stroller for day-to-day trips. Wants simple, trustworthy safety information to choose safer routes and avoid hazards, without giving up privacy.

Primary job to be done:

- See a clear safety advisory for my current area and time of day.
- Choose a safer route for walking/cycling that avoids hazards and works.
- Get a timely heads-up about temporary risks (roadworks, events, bad weather).
- While driving, receive gentle, non-distracting nudges about hazards ahead (e.g., work zones, slippery road, school zone) with simple advice like recommended speed.
- Report a problem (pothole, blocked ramp, faded markings) quickly and track its status.

Decisions & time horizon:
Minutes to hours (route choice now or later today); quick, in-the-moment reactions while driving; occasional weekly checks for schools, hospitals, stations.

Pain points:

- Risk messages are vague or full of jargon.
- “Safer route” options are hidden or hard to compare.
- Temporary changes (roadworks, events, weather) catch me by surprise.
- Reporting an issue is slow, unclear, or disappears into a void.
- Worries about tracking, data sharing, and who sees what.

User stories:

- *As a citizen, I need clear advisories about unsafe road sections, so as to avoid danger when walking, cycling, or driving.*
- *As a citizen, I need reassurance that authorities are monitoring infrastructure risks, so as to trust daily mobility.*
- *As a vulnerable road user, I need accessible safety information, so as to make informed travel choices.*
- *As a citizen, I need safe detour options when roads are closed, so as to continue my journey without risk.*
- *As a citizen, I need evidence that interventions are happening, so as to believe authorities are acting on risks.*
- *As a citizen, I need to provide feedback on safety priorities, so as to participate in decision-making.*

Accessibility & language needs:
WCAG-compliant; large text mode; high contrast; colour-blind safe palettes; clear icons + plain wording; optional audio cues. **Driving mode:** big, glanceable cards; voice prompts or gentle haptics; no text entry while moving; multilingual labels.

Core data:

- **Aggregated risk/advisory layers** (VRU conflict indices, time-of-day patterns).
- **Safer-route options** using public risk layers, **work-zone/closure** data, and event windows.
- **Driving nudges feed:** geofenced hazards, recommended speed/advisories, weather/visibility alerts (low latency).
- **Weather/visibility** advisories.
- **Administrative/geospatial layers**: crossings, cycle routes/lanes, school and hospital zones.
- **Public signage advisories** (dynamic messages) when available.
- **Crowdsourced reports** (privacy-safe, moderated; status visible to the reporter).

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Sensitivity: No personal trip data required by default; optional location sharing with explicit consent; phone motion used only to enable driving mode; all data GDPR-compliant with minimisation and clear retention.

Constraints:

Must **not distract drivers**; comply with phone-use laws; very low latency for driving nudges; variable bandwidth and battery; diverse devices; trust concerns about data use.

Key UX needs/features:

- A big, clear advisory for “here and now” with one-sentence reason.
- A Safer Route button (walk/cycle) with side-by-side compare (distance/time vs safety).
- Driving mode: automatic when moving; short voice/haptic nudges; large cards; quick “mute/snooze”; no typing.
- Heads-up banners for nearby works, events, or poor weather.
- A Report a problem button (auto-location, photo, type, send) with a reference/status.
- Privacy controls always visible (location use, data sharing, delete history).
- Offline map for my area with cached advisories.
- Simple filters (avoid busy roads, prefer crossings/ramps, avoid steep segments).
- Language toggle and large text switch on the first screen.

2.2.2.6 POLICY MAKER / REGULATOR (REGIONAL OR NATIONAL)

Applicable Living Labs: Madrid; Galicia; Santa Oliva (IDIADA); Turin (Piedmont); Riga; Alba Iulia.

Job description:

Sets safety targets, funding priorities, and programme rules across multiple cities or regions. Needs clear, comparable evidence to justify decisions, show progress, and stay aligned with national/EU goals (e.g., Vision Zero).

Primary job to be done:

- Set realistic targets for casualty reduction and VRU protection, urban and rural.
- Allocate funds to the best-value projects and programmes, based on evidence.
- Monitor progress with comparable KPIs and step in where delivery is off-track.
- Check equity (who benefits) and readiness (e.g., ISAD/connectivity) across corridors.
- Ensure methodological consistency and auditability for public scrutiny and reviews.

Decisions & time horizon:

Annual to multi-annual cycles (targets, budgets, regulations); quarterly/biannual reviews; occasional rapid guidance after major incidents or weather events.

Pain points:

- KPIs and definitions differ across jurisdictions; like-for-like comparison is hard.
- Evidence can be dense or technical; hard to explain to non-specialists.
- Political and budget pressures create short-term trade-offs.
- Rural and secondary roads are under-represented in monitoring.
- Uncertainty isn’t shown clearly, making targets risky to set or defend.

User stories:

- *As a policy maker, I need harmonised safety reports across regions, so as to enforce consistent standards.*
- *As a policy maker, I need evidence linking risks to costs, so as to justify funding allocations.*
- *As a policy maker, I need early warnings about critical risks on strategic corridors, so as to coordinate national responses.*
- *As a policy maker, I need to benchmark safety across regions, so as to enforce fair standards and track progress.*

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- *As a policy maker, I need to design fair, effective allocation of national funds, so as to maximise road safety benefits.*
- *As a policy maker, I need audit evidence of safety and funding actions, so as to ensure accountability.*

Accessibility & language needs:
Plain-language summaries; high-contrast charts; consistent colour keys; bilingual/multilingual labels; downloadable briefs in standard templates.

Core data:

- **Harmonised safety KPIs** (fatal/serious injury proxies, near-miss indicators, speed variance, VRU exposure), with **confidence/uncertainty**.
- **Black-spot probabilities** and **trend lines** (city, district, corridor).
- **Infrastructure condition aggregates** from **UAV/drone imagery** and **computer vision** (pavement, markings, signage) — summarised, not raw.
- **Ground movement trends** from **InSAR** for medium/long-term risk to roads/structures.
- **Behavioural/conflict metrics** (VRU and micro-mobility hotspots), privacy-safe.
- **Connectivity / QoS** summaries and **ISAD readiness** per corridor.
- **Programme data**: costs, unit rates, delivery status, before/after impact.
- **Socio-demographic and land-use aggregates** for equity/priority areas (schools, hospitals).
- **Methodology/provenance**: KPI definitions, data sources, timestamps, model/rule versions, audit trails.

Sensitivity: Policy-level use of **aggregated/anonymised** data; strict GDPR compliance; controlled access; clear retention and purpose limits.

Constraints:
Legal mandates and audit requirements; public/press scrutiny; fixed budgets and procurement rules; need for comparability across diverse regions; limited time and staff capacity.

Key UX needs/features:

- A comparable dashboard across regions with clear definitions.
- Progress-to-target bars with confidence ranges.
- Impact per euro cards to support funding choices.
- Equity filters (VRU, rural/urban, sensitive sites).
- Methodology cards beside each KPI (what it is, how it's made).
- One-click exports to official templates (PDF/Word/CSV).
- Alert badges when a programme drifts off-track or data quality drops.
- Notes and justification fields stored with each decision for audit.

2.2.2.7 ACADEMIC RESEARCHER (TRANSPORT SAFETY / URBAN ANALYTICS)

Applicable Living Labs: Madrid; Galicia; Santa Oliva; Turin; Riga; Alba Iulia.

Job description:
Designs studies to understand risk, evaluate measures, and improve models for road safety. Needs well-documented, privacy-safe datasets and clear methods to reproduce results and compare across sites.

Primary job to be done:

- Find, understand, and download versioned datasets with full metadata and KPI definitions.
- Build and benchmark models (risk prediction, deterioration, conflict detection) across pilots.
- Test before/aftereffects of measures and report statistical significance.
- Explore causal factors (infrastructure, behaviour, weather, connectivity) with uncertainty clearly shown.

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- Share reproducible pipelines (notebooks, parameters) and cite datasets properly.

Decisions & time horizon:

Project-based (weeks–months) for study design and modelling; periodic updates when new data drops or methods improve.

Pain points:

- Inconsistent schemas and KPI definitions across sources.
- Limited access to raw data; privacy rules unclear or slow approvals.
- Sparse or noisy labels (e.g., crashes are rare; near-miss proxies vary).
- Hard to track versions of data and models over time.
- Results are difficult to reproduce due to undocumented preprocessing.

User stories:

- *As a researcher, I need access to anonymised raw and processed datasets, so as to build models and validate findings.*
- *As a researcher, I need metadata and documentation, so as to reproduce and validate analyses.*
- *As a researcher, I need benchmarking datasets across pilots, so as to compare risk factors and validate methodologies.*
- *As a researcher, I need reproducibility support, so as to validate my studies.*
- *As a researcher, I need to compare EvoRoads data with external datasets, so as to strengthen evidence.*
- *As a researcher, I need to publish and share validated outputs, so as to contribute to scientific progress and policy debates.*

Accessibility & language needs:

Clear plain-English docs; consistent field names and units; examples in common tools (CSV, GeoJSON, Python notebooks); high-contrast charts; glossary of acronyms.

Core data:

- **Versioned KPI time series** (near-miss proxies, speed variance, harsh braking, VRU exposure, conflict indices) with definitions and confidence/uncertainty.
- **Crash/incident aggregates** and **black-spot probabilities** (spatially/temporally aggregated).
- **Infrastructure condition summaries** from **UAV/drone & computer vision** (pavement/markings/signage) as tiles or segment-level features (no raw PII).
- **InSAR displacement** rasters (downsampled/aggregated) for ground movement near corridors/structures.
- **Probe/micro-vehicle features** (roughness/vibration, GNSS-derived flow) aggregated to segments/grids.
- **Roadside/edge telemetry & smart equipment** status summaries (RSUs, dynamic signs), **V2X-relevant** hazard/advisory indicators.
- **Connectivity/QoS** metrics and **ISAD readiness** per corridor.
- **Weather/visibility** histories; **work-zone logs** (planned/active); **event calendars**.
- **Digital twin outputs**: risk scores, deterioration forecasts, recommended advisory speeds.
- **Crowdsourced reports** (privacy-safe, de-identified); **land-use & sensitive sites** (schools/hospitals).

<u>*Sensitivity:*</u> All data anonymised/aggregated; strict GDPR compliance; controlled access; licences and retention limits; suppression for low-count cells.

Constraints:

Ethics approvals and data-use agreements; compute/storage quotas; embargoes on sensitive layers; requirement to cite methods and datasets; cross-pilot comparability limits.

Key UX needs/features:

- Dataset browser with filters (pilot, time, theme) and clear licences.
- Versioned KPI catalogue with “how it’s made” pages.
- Query builder (time/place/segment type) with preview stats.
- Model cards & benchmarks (metrics, features, windows, baselines).
- Before/after tool with confidence intervals and matched cohorts.
- Application Programming Interface (APIs) & CSV exports with sample notebooks and rate-limit info.
- Provenance panel (sources, timestamps, rule/model versions).
- Reproducibility tags/DOIs for datasets and experiment runs.

2.2.2.8 TELECOMMUNICATIONS NETWORK MAINTENANCE ENGINEER (CELLULAR & ROADSIDE COMMS)

Applicable Living Labs: Madrid; Galicia; Santa Oliva; Turin; Riga; Alba Iulia.

Job description:
Keeps roadside and cellular communications working along key corridors so safety services, signage, and data flows don’t fail. Spots coverage/latency problems, finds the cause, and restores service quickly - urban and rural, day and night.

Primary job to be done:

- Detect connectivity degradations (coverage gaps, high latency, packet loss) on safety-critical routes.
- Localise faults to mast, RSU, backhaul, power, or configuration and decide next steps.
- Restore service within SLA and record what was done and when.
- Plan targeted improvements (antenna tilt, small cell/RSU placement, backhaul upgrades) for persistent weak spots.
- Coordinate timing with road works and events to avoid clashes and minimise downtime.

Decisions & time horizon:
Real-time to hourly for outages and incident response; daily–weekly for planned maintenance; monthly–quarterly for upgrades and optimisation.

Pain points:

- Alarms are noisy; hard to see the true root cause quickly.
- Maps show average coverage, not route-based QoS where safety services run.
- Rural areas have power/backhaul fragility and long travel times to sites.
- Information is scattered (operator NOC, RSU logs, works calendars).
- After “fixes”, it’s hard to prove restoration and track recurrences.

User stories:

- *As a telecom engineer, I need alerts about ground shifts near telecom assets, so as to prevent service outages.*
- *As a telecom engineer, I need forecasts of terrain instability, so as to prioritise reinforcement works.*
- *As a telecom engineer, I need to plan and track restoration works, so as to minimise service downtime.*
- *As a telecom engineer, I need to monitor connectivity QoS, so as to ensure critical safety services are uninterrupted.*
- *As a telecom engineer, I need to validate that restoration works are effective, so as to ensure service reliability.*
- *As a telecom engineer, I need compliance reports on connectivity, so as to demonstrate SLA adherence to regulators.*

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Accessibility & language needs:

High-contrast heatmaps; large numbers/labels; colour-blind safe palettes; simple terms; mobile-friendly for field use; bilingual or multilingual where needed.

Core data:

- **QoS metrics:** signal/coverage (e.g., RSRP/RSRQ/SINR), latency, jitter, throughput, packet loss, handover failures.
- **Route-based measurements** from probe runs/OBUs and RSUs (aggregated).
- RSU / smart roadside **equipment status** (online/offline, firmware, last contact).
- Backhaul & power **telemetry** (link up/down, utilisation, battery/UPS state).
- Network **alarms & tickets** (open/acknowledged/resolved) with timestamps.
- **ISAD readiness** summaries for corridors (cooperative services availability).
- **Environmental context**: terrain/obstructions, weather/visibility affecting RF.
- **Road works & events** calendars to deconflict interventions.
- **Digital twin** outputs: connectivity heatmaps, restoration tracker, persistent weak-spot lists.

Sensitivity: Operational network data; access controlled; no personal subscriber data; GDPR-compliant handling of any probe information (aggregated/pseudonymised).

Constraints:

SLA targets; site access and permits; safety requirements near live traffic; multi-vendor equipment; limited spares; long rural distances; power/utility dependencies.

Key UX needs/features:

- Route view of QoS with clear thresholds and red/amber/green.
- Alarm correlation panel (mast, RSU, backhaul, power) with likely root cause.
- Start/stop restoration button with timer and notes; auto history.
- Before/after charts pinned to the affected corridor.
- Weak-spot list ranked by impact and recurrence.
- Planner overlay for road works/events to avoid clashes.
- Mobile mode for field teams with offline tiles and quick photos/notes.
- Export a short restoration report for records and audits.

2.2.3 CONCLUSION OF THE STRATEGY PLANE

The Strategy Plane has clarified for whom EvoRoads is being built and why it matters, translating developer-side business value into end-user value across eight representative personas. These profiles surface concrete goals, decision horizons, pain points, and accessibility needs, giving us a human-centred anchor for the platform's design and evaluation. They also establish early success signals - latency bounds for operators, equity and evidence needs for planners and policy makers, inclusivity for citizens and VRUs, and robustness for telecom support - against which subsequent choices can be judged.

However, not every request or requirement identified here will be implemented wholesale. The next subsection, the Scope Plane, will prioritise and phase them, distinguishing the minimum viable set (MVP) from enhancements scheduled for later releases. This prioritisation will balance user impact, technical feasibility, data availability, privacy and security obligations, and interoperability constraints, ensuring that scarce effort is directed to the highest-value outcomes.

Finally, while the Strategy Plane frames who and why, verification of how it works in practice will be further addressed in *D4.1*, which outlines the pilot set-ups, use cases, and evaluation touchpoints. With these foundations in place, we now move from strategic intent to scoped, testable functional and content requirements.

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2.3. USER EXPERIENCE SCOPE PLANE

The **Scope Plane** translates the project's intent into a verifiable set of capabilities and information assets that the EvoRoads platform must provide. Grounded in the Strategy Plane and LL findings, it specifies functional requirements (*what users can do*) and content requirements (*what the system must know, store, and present*), and binds them to evidence: personas, use cases, pilot contexts, and acceptance criteria. Scope gives delivery teams a shared contract - clear enough to guide design and engineering yet structured to accommodate controlled evolution as pilots surface new insights.

Functionally, scope enumerates the core actions required across roles and views: real-time alert triage and operator actions (Live Ops), scenario analysis and investment planning (Planning), condition sensing and work-zone scheduling (Maintenance), conflict detection and micromobility operations (Micro-mobility), coverage and latency monitoring (Connectivity), policy benchmarking and reporting (Policy Snapshot), risk-aware public advisories and safer routing (Public Map), time-based reconstruction of events (Playback), and reproducible research services including dataset export and benchmarked KPI definitions (Research & Benchmarking). Each capability is traced back to one or more personas (road safety operator, municipal planner, maintenance lead, micromobility manager, citizen/VRU, policy maker/regulator, academic researcher, telecoms maintenance engineer).

On the content side, scope defines the information taxonomy and governance needed to make those capabilities credible: KPI dictionaries and metadata; geospatial layers and sensor streams; advisory texts and visual encodings; provenance, audit and versioning rules; accessibility assets (e.g., alternative text, plain-language summaries); and multilingual labels. Data freshness, accuracy thresholds, and update cadences are stated explicitly, as are privacy, security, and ethical boundaries for pseudonymised or sensitive data.

Not every request becomes a commitment. Competing ideas will be evaluated against programme objectives, safety impact, feasibility, and pilot readiness; lower-value or speculative items are deferred with clear decision logs. By establishing this scope baseline - complete, testable, and traceable - we provide a stable foundation for interface design, architecture, and integration, while leaving room for disciplined iteration as pilots progress and evidence accumulates.

2.3.1 FROM USER STORIES TO FUNCTIONAL CAPABILITY COMMITMENTS

The Strategy Plane defined the user context of the EvoRoads platform by identifying key personas, their responsibilities, and the goals they seek to achieve in their daily work. Building on this foundation, the Scope Plane defines the functional extent of the platform by establishing what categories of functionality are considered within scope, while remaining independent of specific technical implementations or pilot-specific configurations.

User stories, derived from LLs activities and subsequent analysis, constitute the primary input to this process. They articulate user intent, decision contexts, and expected value, providing a grounded understanding of how different actors interact with safety-relevant information. However, user stories are intentionally contextual and descriptive. As such, they are not directly used in this section to define detailed system behaviour. Instead, they are consolidated into higher-level functional commitments that express the intended scope of the platform in a stable and reusable manner.

To achieve this consolidation, EvoRoads adopts a **capability-based representation of scope**. Functional capability commitments define bounded areas of functionality that the platform supports in order to enable its identified personas to fulfil their roles. These commitments form the conceptual bridge between user intent and later technical specification, ensuring continuity without constraining implementation choices prematurely.

2.3.1.1 FUNCTIONAL CAPABILITY COMMITMENTS

A **functional capability commitment** denotes a coherent class of user-facing functionality that the EvoRoads platform supports across pilots and deployment contexts. Capabilities are expressed in terms of user-relevant outcomes rather than system internals, and they are defined independently of algorithms, data pipelines, or deployment architectures.

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Each capability commitment represents an intentional inclusion within the scope of the integrated platform. At the same time, it **does not prescribe feature completeness, performance targets, or uniform realisation across pilots**. Capabilities therefore define the functional envelope of the platform rather than an exhaustive list of functions.This abstraction allows the scope to remain stable even as detailed requirements evolve, technologies mature, or pilot-specific constraints are introduced.

2.3.1.2 CAPABILITY CLUSTERS SUPPORTING EVOROADS PERSONAS

Functional capability commitments are organised into a set of capability clusters that reflect recurring patterns of use observed across personas and operational contexts. These clusters aggregate related user intents and provide a structured representation of scope at platform level.

The principal functional capability clusters identified for the EvoRoads integrated platform are summarised below and include, among others:

- **Live Safety Operations and Situational Awareness:** Enabling real-time or near-real-time visibility into safety-relevant conditions, emerging risks, and network status in support of operational decision-making.
- **Infrastructure Condition Assessment and Maintenance Support:** Supporting the assessment, prioritisation, and planning of interventions related to road infrastructure, including assets such as pavement, markings, signage, and roadside equipment.
- **Connectivity and Communications Awareness:** Providing insight into the availability, quality, and degradation of communication channels that underpin connected and safety-critical services.
- **Planning, Policy Analysis, and Benchmarking:** Supporting medium- and long-term analysis of safety performance, trends, and intervention effectiveness across locations and time horizons.
- **Public-Facing Safety Information and Risk Communication:** Enabling controlled dissemination of safety-related information to citizens and vulnerable road users in a contextualised and comprehensible manner.
- **Research, Evaluation, and Knowledge Reuse:** Supporting structured access to data, indicators, and analytical outputs for evaluation, comparison, and research activities.

These capability clusters are intentionally broad and non-overlapping. Together, they define the functional domains within which the EvoRoads platform operates from a user perspective.

The inclusion of a capability cluster within the Scope Plane indicates that the EvoRoads platform supports that functional domain at platform level. It does not imply that all possible functions associated with that domain are implemented, nor that they are implemented uniformly across pilots. Capability commitments define a functional envelope within which specific functions may be selected, refined, or deferred. The selection of concrete functionality is influenced by pilot relevance, feasibility, expected impact, and integration constraints, and is addressed in later stages of the deliverable (see Subsection 4.1.7).

Table 1 summarises the functional capability clusters that define the scope of the EvoRoads integrated platform, indicating the primary personas they support, the functional envelope associated with each cluster, and the user-facing views through which these capabilities are conceptually exposed.

Table 1: Functional capability clusters of the EvoRoads Integrated Platform

CAPABILITY CLUSTER	PRIMARY SUPPORTED PERSONAS	FUNCTIONAL SCOPE (CAPABILITY ENVELOPE)	INDICATIVE USER-FACING VIEWS
Live Safety Operations & Situational Awareness	Road Safety Operator; Emergency Services Coordinator	Provision of timely, consolidated awareness of safety-relevant conditions across the road network, including emerging risks, abnormal patterns, and confidence	Live Operations View; Playback View

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CAPABILITY CLUSTER	PRIMARY SUPPORTED PERSONAS	FUNCTIONAL SCOPE (CAPABILITY ENVELOPE)	INDICATIVE USER-FACING VIEWS
		indicators. Supports prioritisation, triage, and monitoring activities under operational time constraints.	
Infrastructure Condition Assessment & Maintenance Support	Infrastructure Maintenance Engineer; Road Authority Asset Manager	Assessment and comparison of infrastructure condition over space and time, supporting identification of degradation patterns, prioritisation of maintenance needs, and planning of interventions. Focuses on decision support rather than operational control.	Maintenance View; Planning View
Connectivity & Communications Awareness	Telecommunications Network Maintenance Engineer; Road Safety Operator	Visibility into the availability, quality, and degradation of communication channels (cellular, roadside, V2X) that underpin safety-relevant services and connected systems. Supports diagnosis, planning, and assurance of communications readiness.	Connectivity View; Live Operations View
Planning, Investment & Scenario Analysis	Municipal Planner; Road Authority Decision Maker	Exploration and comparison of safety scenarios, intervention options, and investment strategies over medium- to long-term horizons. Supports evidence-informed planning, prioritisation, and trade-off analysis across locations and measures.	Planning View; Policy Snapshot View
Policy Monitoring, Benchmarking & Reporting	Policy Maker; Regulator; Public Authority Analyst	Aggregation and comparison of safety indicators across jurisdictions, time periods, and intervention types. Supports monitoring of policy objectives, benchmarking, and preparation of structured reports for governance and accountability purposes.	Policy Snapshot View; Research & Benchmarking View
Public-Facing Safety Information & Risk Communication	Citizen; Vulnerable Road User (VRU)	Controlled exposure of safety-relevant information to the public, including contextualised risk awareness and advisory content. Emphasises clarity, proportionality, accessibility, and avoidance of information overload or operational dependency.	Public Map View
Micromobility & VRU Safety Awareness	Micromobility Operator; Urban Mobility Manager; Citizen / VRU	Visibility into safety conditions and conflict patterns affecting vulnerable road users and micromobility services. Supports monitoring, planning, and awareness without replacing local operational platforms.	Micro-mobility View; Public Map View
Research, Evaluation & Knowledge Reuse	Academic Researcher; Safety Analyst	Structured access to safety indicators, datasets, and methodological artefacts for analysis, comparison, and evaluation. Supports reproducibility, longitudinal studies, and methodological transparency.	Research & Benchmarking View
Event Reconstruction & Temporal Analysis	Road Safety Operator; Analyst; Researcher	Time-based reconstruction and review of safety-relevant events and conditions, supporting post-event analysis, learning, and validation of interventions.	Playback View
Cross-Cutting Platform Oversight & Governance Support	Platform Administrator; Lead Authority Analyst	Oversight of platform usage, data provenance, scope boundaries, and governance-relevant metadata. Supports trust, accountability, and controlled evolution of platform capabilities.	Administrative / Governance Views (non-operational)

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2.3.2 CONTENT REQUIREMENTS FOR THE EVOROADS PLATFORM

The Scope Plane's content requirements define the categories of information that the EvoRoads platform manages and exposes in order to support the functional capability commitments identified in Section 2.3.1. These requirements specify *what information must be available*, how it is characterised, and how it can be interpreted across user roles and contexts, while remaining independent of specific technical implementations, processing pipelines, or deployment configurations.

The platform curates a coherent body of data and metadata originating from diverse sources and serving multiple purposes. Across all content categories, information is expected to be accurate, timely with respect to its intended use, privacy-preserving, interpretable, and traceable to its origin.

2.3.2.1 CONTENT SOURCES AND SEMANTIC ORGANISATION

The EvoRoads platform manages information originating from multiple classes of sources that contribute to safety awareness, assessment, and decision support. These include, among others:

- Roadside sensing and smart infrastructure equipment, providing information such as hazard detections, asset and signage status, and local observations;
- Vehicle- and micromobility-based crowdsensing, supplying pseudonymised observations related to surface condition proxies, markings, signage issues, and contextual anomalies;
- Strategic and wide-area sensing, including aerial imagery and ground-movement products derived from remote sensing techniques;
- Environmental and contextual information, such as weather conditions, visibility, and related external feeds;
- Operational context information, including planned works, lane closures, work zones, and event calendars;
- Communications-related information describing the state of connectivity and readiness of communication channels relevant to safety services.

Content originating from these sources is represented using consistent spatial and temporal references. Spatially, information is associated with common geospatial entities such as segments, junctions, corridors, or tiles. Temporally, content is characterised according to its relevance horizon, including instantaneous observations, short-term aggregates, and long-term time series. This semantic organisation enables consistent interpretation across views and user roles without prescribing how such representations are technically realised.

2.3.2.2 DERIVED INFORMATION AND INDICATORS

In addition to source-level information, the platform manages derived content that supports interpretation, comparison, and decision-making across capabilities. Such content includes, among others:

- Safety-relevant layers that combine observations with contextual attributes such as confidence, severity, and provenance;
- Risk-related indicators expressing relative levels, trends, or comparative assessments over space and time;
- Condition-related summaries for infrastructure assets, supporting assessment and prioritisation activities;
- Harmonised safety indicator catalogues, including definitions, units, update characteristics, uncertainty descriptors, and references to methodological context;
- Indicators related to vulnerable road users and micromobility activity, including conflict patterns and compliance summaries;
- Connectivity-related summaries describing coverage, quality, and status of communication services;
- Advisory and informational content intended for targeted dissemination, such as safety advisories and public-facing messages.

These derived information products are treated as content artefacts with defined semantics and metadata. Their presence within the platform indicates availability for interpretation and use, without implying specific analytical methods, accuracy guarantees, or uniform availability across pilots.

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2.3.2.3 PROVENANCE, QUALITY, AND VERSIONING

All content managed by the platform is accompanied by machine-readable metadata that supports transparency, trust, and auditability. This includes:

- Provenance information describing source, time of observation or generation, and relevant processing or derivation context;
- Quality descriptors indicating aspects such as completeness, confidence, latency class, or known limitations;
- Versioning information for indicators, definitions, and methodological artefacts, including change histories where applicable.

Historical states of content are preserved in order to support retrospective analysis, comparison over time, and traceability. Versioned definitions enable consistent interpretation of indicators even as methodologies evolve.

2.3.2.4 CONFIDENCE, CORROBORATION, AND INTERPRETABILITY

To support informed interpretation by different user roles, content items include attributes that express confidence and corroboration status. These attributes indicate, for example, whether information is based on single or multiple contributing sources, whether it reflects direct observation or derived assessment, and what contextual factors may affect its reliability.

Such attributes enable downstream users and services to assess the strength and limitations of the information presented, without embedding decision logic, validation rules, or escalation criteria within the content layer itself.

2.3.2.5 PRESENTATION AND NARRATIVE CONTENT

Beyond analytical and operational information, the platform manages narrative and presentation-oriented content that supports comprehension and communication across audiences. This includes:

- Plain-language advisory texts and explanatory descriptions;
- Multilingual labels and terminology;
- Iconography and visual encodings;
- Accessibility assets such as alternative text for imagery, high-contrast visual elements, and large-text representations.

For planners and policy-oriented users, content includes structured summaries such as maps, tables, and methodological cards that contextualise indicators, illustrate trends and uncertainty, and relate safety conditions to indicative cost or intervention categories. For citizens and vulnerable road users, public-facing content emphasises privacy-safe advisories, contextual awareness, and high-level progress indicators.

Connectivity-related content includes summaries and visualisations that support understanding of coverage conditions and service restoration status along routes or areas of interest.

2.3.2.6 TEMPORAL CHARACTERISTICS AND CURRENCY

Different categories of content are associated with different temporal dynamics. Safety observations, environmental conditions, and connectivity information are characterised by short relevance horizons, while operational context, infrastructure condition baselines, and strategic sensing products evolve over longer timescales.

Each dataset declares its expected update characteristics and temporal relevance, enabling users to recognise whether information reflects current conditions, recent aggregates, or longer-term baselines. Where appropriate, indicators signal when content may be outdated or superseded.

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2.3.2.7 ACCESS CONTROL, PRIVACY, AND PURPOSE LIMITATION

Content is partitioned and exposed according to user roles and usage contexts. Internal platform users may access granular information relevant to their responsibilities, while public and research-oriented content tiers expose aggregated, anonymised, or otherwise privacy-preserving datasets.

For all exposed content, metadata specifies access conditions, licensing, intended purpose, and retention considerations. Crowdsourced information includes moderation status and feedback references that allow contributors to understand outcomes without revealing personal identity.

2.3.2.8 RESEARCH SUPPORT AND REPRODUCIBILITY ASSETS

To support evaluation and research activities, content requirements include the availability of documented datasets and artefacts suitable for reproducible analysis. These include anonymised raw and processed datasets, dataset descriptors defining schema and units, and curated benchmark collections spanning pilots or time periods.

Methodological artefacts such as indicator definitions, model descriptions, and parameter documentation are identified with stable references to support citation, comparison, and reuse across studies.

2.3.3 CONCLUSION OF THE SCOPE PLANE

The Scope Plane has translated user intent into a traceable set of functional and content requirements that define what the EvoRoads platform shall do and what information it must curate. Requirements are linked back to personas and forward to views, acceptance criteria, and pilot validation, ensuring clarity of purpose and accountability for delivery. Functionally, we have enumerated capabilities spanning real-time operations, planning and maintenance workflows, micro-mobility management, connectivity monitoring, policy benchmarking, public advisories, playback, and research support. On the content side, we have specified KPI catalogues and metadata, geospatial layers and sensor products, advisory texts, provenance and audit trails, accessibility assets, multilingual labels, and explicit rules for freshness, accuracy, privacy, and security. This scoped baseline offers a stable frame for design and engineering, while remaining open to evidence-led refinement as pilots progress. The next step - addressed in the **Structure Plane** - organises these requirements into a coherent information and interaction architecture: navigation, states, flows, cross-view patterns, and error handling, alongside the mapping of data lifecycles and services. In moving from “what” to “how”, we ensure that the platform’s behaviour is systematic, learnable, and resilient in day-to-day use.

2.4. USER EXPERIENCE STRUCTURE PLANE

This chapter organises the scoped capabilities of EvoRoads into a coherent **structure** in the sense defined by Garrett: **interaction design** (how the system behaves in response to user actions) and **information architecture** (how content is organised and related), supported by the navigational framework and formal task/state flows. While the platform aggregates data from six European LLs, each authenticated user sees only the maps and datasets authorised for their country. All desktop access is through a single Dashboard (mobile applications are the exception for citizens and in-vehicle nudging). The sections that follow set platform-wide rules so that behaviour is consistent across views - Live Ops, Planning, Maintenance, Micro-mobility, Connectivity, Policy Snapshot, Public Map, Playback, and Research & Benchmarking - and predictable for our eight personas.

2.4.1 INTERACTION DESIGN PRINCIPLES AND USER INTENT FLOWS

The **interaction design** of the EvoRoads platform defines how users engage with safety-relevant information and translate observations into understanding and action. Across pilots and roles, the platform is used in situations ranging from real-time operational awareness to long-term planning and evaluation. The interaction model therefore establishes a common and predictable logic of engagement that applies across views, while remaining adaptable to the very different

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decision contexts encountered by operators, engineers, planners, policy makers, researchers, and, where applicable, citizens.

A central principle of interaction in EvoRoads is clarity of intent (indicative examples have been included in *Table 2*). In each interaction context, the platform foregrounds a limited number of meaningful actions that correspond to the user's immediate objective. For example, when a road safety operator is reviewing live hazard detections along a corridor, the primary interaction intent is to assess relevance and severity, not to explore historical trends or adjust analytical parameters. Conversely, when a planner is examining safety KPIs over multiple years, the dominant intent shifts toward comparison, aggregation, and scenario exploration. The interaction design supports these differing intents by structuring engagement around the user's purpose rather than around system features. User intent flows in EvoRoads typically follow recurring patterns. In operational contexts, interaction often proceeds from observing current conditions, to assessing confidence and impact, and then to acknowledging, contextualising, or handing over information for follow-up. In planning and policy contexts, interaction more commonly involves exploring spatial and temporal patterns, comparing indicators across areas or periods, and synthesising insights for reporting or investment decisions. These flows are intentionally simple and repeatable, allowing users to move between views - such as live operations, playback, or planning - without having to relearn how to interact with the system.

Table 2: Indicative user intent flows in the EvoRoads platform

INTENT FLOW	PRIMARY USER INTENT	TYPICAL CONTEXTS IN EVOROADS	REPRESENTATIVE INFORMATION ENGAGED
Observe → Assess → Acknowledge	Determine whether a safety-relevant condition requires attention or follow-up	Live safety operations; corridor monitoring during adverse conditions	Live hazard detections, confidence indicators, data freshness cues, contextual weather or traffic conditions
Explore → Compare → Contextualise	Understand patterns, differences, or trends across space or time	Planning and policy analysis; pilot comparison; benchmarking activities	Safety KPIs, historical series, spatial aggregations, uncertainty descriptors
Investigate → Reconstruct → Learn	Analyse past situations to understand causes, sequences, or outcomes	Playback and retrospective analysis; post-event review	Time-ordered hazard states, infrastructure condition snapshots, event timelines, contextual annotations
Inform → Advise → Communicate	Translate analytical insight into information suitable for wider dissemination	Public-facing safety communication; stakeholder reporting	Aggregated risk indicators, simplified advisory content, explanatory summaries, progress status information

Feedback and system state awareness are integral to interaction. EvoRoads presents safety indicators, hazard layers, and risk assessments together with contextual information that supports interpretation. For instance, when a short-term risk index is displayed for a road segment, it is accompanied by cues that indicate its confidence, temporal relevance, and methodological context. Similarly, when infrastructure condition summaries are reviewed, users can recognise whether these reflect recent observations, aggregated trends, or longer-term baselines. This ensures that users do not need to infer reliability or currency indirectly when making decisions.

Temporal awareness is particularly important given the mixture of real-time and strategic content within EvoRoads. Interaction design makes the temporal character of information explicit, allowing users to distinguish between live hazard detections, recent aggregates, and historical series. For example, when switching from a live safety operations view to a playback or benchmarking view, the interaction context shifts from immediate situational awareness to retrospective analysis. The platform supports this shift by clearly signalling changes in time horizon and analytical intent, reducing the risk of misinterpretation.

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Error prevention and control are addressed through interaction principles that favour early guidance and reversibility. Users configuring analytical perspectives, selecting spatial extents, or preparing advisory content are guided so that incompatible or inconsistent choices are identified before commitment. Actions with wider implications - such as issuing public-facing advisories or finalising analytical summaries - are framed in a way that makes their scope and audience clear. Wherever possible, interaction favours reversible steps and explicit confirmation of intent rather than abrupt or opaque transitions.

Consistency across information lifecycles is another defining characteristic of interaction in EvoRoads. Safety-relevant entities - such as hazards, advisories, or analytical findings - follow recognisable stages from identification through review, contextualisation, and closure. Users encounter these stages consistently across views, whether they are examining live detections in an operational setting or reviewing outcomes retrospectively in the Playback view. This consistency supports shared understanding across teams and facilitates audit and learning without imposing rigid workflows. Interaction design also reflects the **variability of operational conditions** across pilots. Differences in data availability, sensing coverage, or connectivity are treated as contextual factors that shape interpretation rather than as hidden system states. When such factors affect the reliability or completeness of information, this is surfaced through interaction cues, allowing users to adapt their judgement accordingly. This is particularly relevant in EvoRoads, where urban and rural pilots, as well as different sensing technologies, coexist within a single platform framework.

Finally, **role differentiation** in EvoRoads is expressed through availability of actions rather than through fundamentally different interaction models. Operators, planners, researchers, and policy users engage with the same underlying interaction logic, even though the actions available to them may differ according to role, scope, or context. Where actions are not available, interaction cues clarify the nature of the limitation without exposing internal governance mechanisms, supporting predictability and trust.

Through these principles, the interaction design of EvoRoads supports **a shared grammar of engagement** that remains intelligible across diverse safety contexts.

2.4.2 INFORMATION ARCHITECTURE: CONTENT ORGANISATION AND CATEGORISATION

The **information architecture of the EvoRoads platform** (outlined in ***Figure 4***) specifies the conceptual model of EvoRoads and the labelling and grouping rules that make content findable and comprehensible across contexts. The model pivots on a small set of well-defined entities and relationships. Network elements - segments as the atomic unit of the road graph, junctions, and corridors as ordered sets of segments - carry attributes such as functional class, speed limits, urban/rural status, and proximity to sensitive sites like schools and hospitals. Events and operational states - alerts, advisories, work zones, and operator-logged incidents—possess explicit lifecycles with timestamps and provenance. Measures and model outputs - KPIs, risk scores, condition indices, and connectivity metrics - are defined with units, update cadences, confidence bands, and links to methodological notes. Assets - roadside units, dynamic signs, beacons and sensors - expose status, firmware and last contact. Data bundles - datasets, exports, and reports - are treated as first-class objects with schemas, licences, and versioning. Actors - users, teams, organisations - are bound to roles and constrained by country scope.

The information architecture defines how safety-relevant information is conceptually organised, labelled, and related so that users can interpret and combine it consistently across views, roles, languages, and pilot contexts. It establishes a shared semantic and structural framework that allows heterogeneous data assets, analytical outputs, and advisory content to be understood as parts of a coherent system, independently of their technical origin or local deployment. This architecture is informed by the platform asset inventory, which identifies the classes of sensing, analytical, and decision-support assets integrated within EvoRoads, and by the demonstrations planning guidelines, which highlight the need for comparability and coherence across pilots with differing objectives and operational realities. The resulting information architecture balances stability at platform level with flexibility at pilot level.

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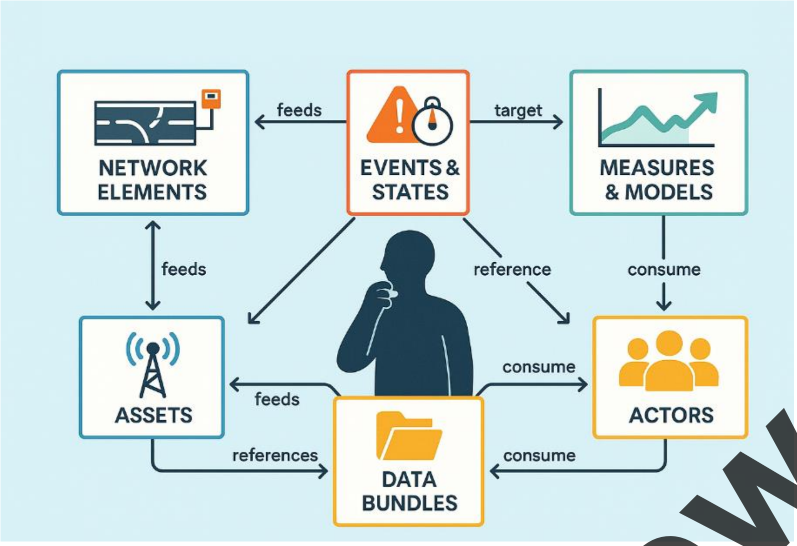

Figure 4: EvoRoads Platform Information Architecture: Content Organisation and Categorisation

2.4.2.1 CORE CONTENT DOMAINS AND CONTROLLED VOCABULARIES

At the highest level, EvoRoads information is organised into a small number of **recurring content domains** that reflect what the information concerns, rather than how it is produced. These include safety conditions and hazards, infrastructure and assets, indicators and assessments, contextual and environmental information, communications and connectivity status, and advisory or narrative content.

To ensure semantic coherence across languages and jurisdictions, these domains are underpinned by controlled vocabularies. Alert types, for example, distinguish clearly between behavioural signals (such as speed variance or harsh braking), infrastructure-related issues (including potholes or faded markings), environmental conditions (such as poor visibility or ice risk), conflict patterns affecting vulnerable road users, and communications-related incidents such as degradation of quality of service. Advisory types express intended action succinctly and consistently, covering cases such as recommended speed, lane merge, hazard ahead, school zone caution, work-zone warning, or micro-mobility hotspot caution.

By constraining labels and categories to shared vocabularies, the platform maintains semantic consistency across pilots and supports localisation without ambiguity. Geography tags further characterise content by denoting urban, suburban, or rural contexts, with overlays for sensitive areas and optional equity-related tags where relevant.

2.4.2.2 SPATIAL, TEMPORAL, AND CONTEXTUAL STRUCTURING

Spatial and temporal dimensions act as primary structuring axes within the information architecture. Content is associated with **spatial** entities such as points, segments, corridors, or broader network extents, enabling users to reason about safety conditions at appropriate scales. This supports demonstration scenarios ranging from localised urban interventions to long rural corridors.

Temporally, information is characterised according to its relevance horizon. Instantaneous observations, short-term aggregates, and long-term historical series are treated as distinct but related content forms. This allows users to distinguish between live operational awareness, recent trends, and strategic baselines when moving between views or analytical contexts.

Contextual attributes cut across all domains. These include *confidence, uncertainty, provenance*, and *applicability* to specific operational or policy contexts. Rather than creating separate content silos, these attributes accompany information wherever it appears, ensuring that interpretation cues remain consistent across the platform.

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2.4.2.3 DERIVED INFORMATION AND SEMANTIC RELATIONSHIPS

Beyond source-level content, the information architecture accommodates derived information such as indicators, summaries, and assessments. These are treated as first-class content artefacts with **defined semantics and metadata**, rather than as opaque outputs. Relationships between content domains are explicitly represented: hazards are linked to affected infrastructure assets and locations; indicators are linked to underlying observations and methodological definitions; advisories are linked to the assessments and conditions that motivate them.

Confidence levels are expressed using harmonised categories and numeric bands that are consistent within each signal family and described using uniform phrasing. This allows users to compare confidence across different types of content without recalibrating interpretation for each source.

2.4.2.4 CONTENT CHUNKING AND STRUCTURAL PATTERNS

Information is structured using a consistent overview–list–detail triad that applies across views and content types. At a conceptual level, each interaction context provides:

- an overview that surfaces key metrics, trends, or status summaries;
- a collection of items that can be filtered, sorted, or selected;
- and a detail context that binds to a selected item or spatial focus and exposes fields, relationships, and provenance.

Table 3 further explains this approach.

Table 3: Overview–List–Detail triad in EvoRoads Information Architecture

STRUCTURAL LAYER	CONCEPTUAL ROLE	WHAT IT CONTAINS	WHY IT MATTERS IN EVOROADS
Overview	Orientation and sense-making	High-level metrics, trend summaries, status indicators, and context cues relevant to the current view or intent	Allows users to rapidly understand what is going on (e.g. overall risk level on a corridor, current alert load, KPI trends) before engaging with detail
List	Selection and comparison	A collection of comparable items (e.g. hazards, advisories, work zones, indicators) that can be filtered, sorted, or selected	Supports scanning, prioritisation, and comparison across space or time without losing context
Detail	Inspection and justification	Attributes of a selected item or spatial focus, including relationships, confidence, freshness, and provenance	Enables informed judgement, auditability, and learning by explaining why something appears as it does

Within this structure, a shared "card grammar" applies to recurrent content types such as alerts, advisories, work zones, and datasets (further explained through *Table 4*). Each card is characterised by a clear title and type, a concise location reference, confidence and freshness indicators, key explanatory drivers, and access to extended descriptive and provenance information. Provenance is treated as an integral part of content rather than an afterthought, with explanatory context available at the point of need.

Table 4: Shared card grammar for recurrent content types

CARD ELEMENT	SEMANTIC MEANING	EXAMPLES IN EVOROADS
Title & Type	What the item is	"Hazard: Ice Risk", "Advisory: Reduced Speed"

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CARD ELEMENT	SEMANTIC MEANING	EXAMPLES IN EVOROADS
Location Reference	Where it applies	Corridor name, road segment, junction, or area
Confidence Indicator	How reliable the information is	Confidence band, category, or qualitative label
Freshness Indicator	How current the information is	Last update time, temporal relevance cue
Key Drivers	Why the item exists	Primary contributing signals or conditions
Provenance Access	How it was produced	Sources, timestamps, processing or methodology references

This grammar ensures that alerts, advisories, datasets, and indicators are recognisable at a glance, even when they originate from different assets or pilots.

2.4.2.5 SCOPING, QUALITY, AND INTERPRETABILITY

Country and jurisdictional scoping is reflected structurally in the information architecture. Content is associated with geographic and administrative scope attributes that determine where and how it is visible. Cross-border information is distinguishable from nationally scoped content, allowing users to recognise boundaries without encountering unexpected omissions.

Data quality and currency are made legible through content attributes rather than technical terminology. Items carry last-update information, and content categories are associated with expected temporal characteristics, ranging from near-real-time relevance for hazards, through periodic updates for environmental and operational layers, to acquisition-cycle updates for strategic sensing products. Quality indicators such as confidence measures or sample characteristics accompany content to guide responsible interpretation.

2.4.2.6 STABILITY AND EVOLUTION

The information architecture is designed to remain stable over the lifetime of the project while accommodating evolution. New assets, indicators, or advisory types can be incorporated by mapping them onto existing domains, vocabularies, and structural patterns. This stability is essential for maintaining comparability across pilots and over time, particularly as demonstrations progress and new use cases are introduced.

By defining information architecture in terms of domains, vocabularies, relationships, and structural patterns, the EvoRoads Structure Plane provides a shared mental model that anchors interaction and navigation design. It ensures that complex, heterogeneous safety-related information can be explored, compared, and communicated coherently across the platform, forming a robust foundation for subsequent navigation design and visual realisation.

2.4.3 NAVIGATION FRAMEWORK: GLOBAL, LOCAL, AND CONTEXTUAL PATHS

Navigation binds the information architecture to interaction, enabling users to move between concepts and tasks without losing their place. EvoRoads employs a layered framework that balances global wayfinding with local focus and contextual shortcuts.

At the **global level**, a fixed navigation bar presents the nine views. The **current view** is clearly indicated, and the set itself is pruned according to role and country scope so that, for example, citizens do not see internal operational modules. A single **global search** accepts common entities - segments, corridors, junctions, addresses, alert IDs, work zones, datasets - and returns results grouped by type, allowing users to jump directly to the relevant detail. The **profile area** displays the user's country scope and role; a brief overlay clarifies permissions and links to data-access terms, reinforcing expectations about what is visible and actionable.

Locally, each view adheres to a **stable list-map-detail composition**. The left panel lists objects relevant to the view and respects saved filters; the central map anchors spatial understanding; the right panel presents detail, charts and actions for the selected item. Tabs within the detail panel follow a consistent order - overview first, then provenance, history, and comments - so that learned habits transfer between modules. Users can save combinations of filters (time ranges, geographies, object types) as named views and recall them instantly, promoting repeatable workflows for shift change, weekly reviews or portfolio work.

Figure 5 below illustrates the concept, without the EvoRoads branding elements as of yet:

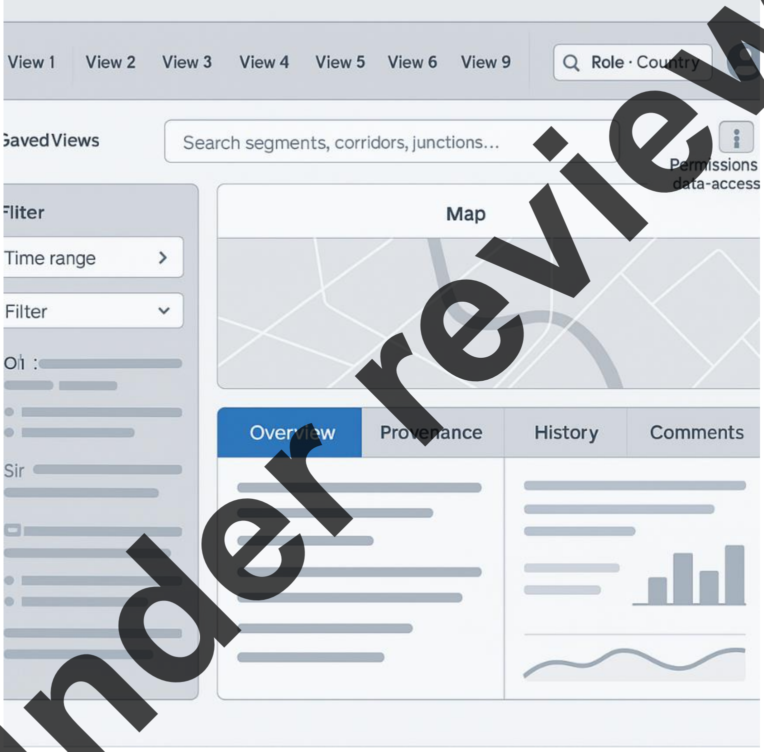

Figure 5: EvoRoads user interface layered framework wireframe

Contextual navigation reduces friction during multi-view tasks. **Map popovers** provide compact, in-situ summaries with deep links so that users can change vantage point without reconstructing their query. Breadcrumbs appear in content-heavy areas such as Planning and Research, making hierarchies explicit (for example, Region → Corridor → Measure) and offering landmarks such as "Top ten risky corridors" for quick return. **Keyboard shortcuts** are available and consistent across views - acknowledge, save, help and close - and a small help overlay lists them on demand. **Back navigation** is predictable: the back button returns to the last list state with filters intact; cross-view switches preserve the previous selection; a reset action restores defaults. Deep links to objects are stable and shareable within authorised teams; unauthorised recipients are routed to a friendly access-denied page that points to the appropriate channel for requesting access.

By combining clear global signposting, a disciplined local layout, and helpful contextual jumps, the navigation framework makes the platform legible from the first session and efficient thereafter, without sacrificing the constraints required by country scoping and role-based access.

Navigation continuity across views is treated as a first-class concern. Users frequently move between operational, analytical, and planning perspectives while investigating the same safety issue. To support this, EvoRoads preserves semantic anchors (such as the currently selected corridor, asset, or time window) when users transition between views. For example, switching from Live Operations to Playback or Planning retains the spatial focus and temporal context unless explicitly changed. This continuity allows users to change analytical lens without re-establishing context, supporting investigative and comparative workflows that span multiple views.

The navigation framework also recognises that EvoRoads demonstrations **are pilot-driven**. Each view makes the **active pilot context visible where relevant**, without fragmenting navigation into pilot-specific menus. Pilot awareness is expressed through contextual cues (such as pilot labels, applicable datasets, or coverage extents) rather than through separate navigation branches. This ensures that users can reason about pilot-specific content while remaining within a unified platform structure, and that cross-pilot comparison is enabled without switching navigation modes.

Navigation supports both **exploratory and repeatable use**. Exploratory navigation allows users to follow emerging questions through links, breadcrumbs, and contextual jumps, while repeatable navigation supports routine activities such as shift monitoring, periodic reporting, or portfolio review. Saved views, stable deep links, and predictable back behaviour ensure that users can return to known states quickly, while still allowing ad-hoc exploration when needed. This balance is particularly important in EvoRoads, where the same platform must support both continuous operational use and episodic analytical work. To avoid disorientation, the navigation framework makes scope boundaries explicit rather than implicit. When content is filtered by country, role, or pilot applicability, this constraint is visible and stable across navigation actions. Users do not encounter silent disappearance of content when switching views; instead, navigation preserves awareness of why certain objects or actions are not available in a given context. This approach reinforces trust and reduces the cognitive overhead associated with multi-jurisdictional operation.

Finally, navigation design deliberately avoids embedding process logic. Moving between views does not imply progression through a workflow or completion of a task. Users remain free to enter, exit, and revisit views according to their intent, whether they are monitoring live conditions, reconstructing past events, or preparing planning material. This non-prescriptive navigation model reflects the diversity of EvoRoads use cases and ensures that the platform supports human decision-making rather than enforcing rigid sequences.

2.4.4 TASK AND STATE MODELS ACROSS USER ROLES

The Structure Plane is completed by defining the tasks users perform in the EvoRoads platform and the states in which information is perceived from the user's perspective. Rather than prescribing workflows or operational procedures, this model establishes a shared conceptual language that aligns interaction, information architecture, and navigation across roles, views, and pilot contexts.

Tasks in EvoRoads are defined in terms of **user intent**, not job titles. Across the platform, a small set of recurring task types can be observed, regardless of whether the user is a road safety operator, infrastructure maintenance engineer, planner, policy analyst, researcher, or citizen. These task types include monitoring, investigation, planning, evaluation, and communication. Each task type manifests differently depending on role and view, but the underlying intent remains consistent. Examples are summarised in *Table 5*.

For example, **monitoring** occurs when a Road Safety Operator uses the Live Operations View to maintain situational awareness of hazards and short-term risk indicators along a corridor during adverse weather. The same task type appears when a Telecommunications Network Maintenance Engineer monitors connectivity and QoS conditions affecting roadside communications in the Connectivity View. In both cases, the user's intent is to remain aware of current conditions and detect situations that may require attention.

Investigation tasks arise when users seek to understand causes, patterns, or sequences of events. A Road Safety Operator or Analyst may switch to the Playback View to reconstruct how a hazard evolved before and after an incident,

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while an Academic Researcher may use the Research and Benchmarking View to explore historical trends or correlations across pilots. Although the temporal scope and depth differ, both cases involve moving from observation to explanation.

Planning and evaluation tasks are typical for Infrastructure Maintenance Engineers, Municipal Planners, and Policy Makers. These tasks are supported primarily through the Planning View and Policy Snapshot View, where users compare safety indicators, infrastructure condition summaries, and scenario outcomes across space and time. Here, the intent is not immediate action but prioritisation, comparison, and justification of interventions or investments.

Communication tasks involve translating analytical insight into information suitable for broader audiences. This includes the preparation of summaries for decision-makers, reporting against safety objectives, or issuing public-facing advisories. For instance, a planner may extract aggregated indicators and trend summaries for a policy briefing, while citizens encounter simplified, privacy-safe advisories through the Public Map View. Although the audience differs, the task intent is the same: to convey safety-relevant information clearly and responsibly.

Table 5: Indicative task and state examples across EvoRoads personas and views

TASK TYPE	PERSONA EXAMPLE	PRIMARY VIEW(S)	TYPICAL INFORMATION STATE
Monitoring	Road Safety Operator	Live Operations View	Current, confidence-qualified
Monitoring	Telecoms Maintenance Engineer	Connectivity View	Current or degraded
Investigation	Road Safety Analyst	Playback View	Historical, contextualised
Investigation	Academic Researcher	Research & Benchmarking View	View Historical, uncertain
Planning	Infrastructure Maintenance Engineer	Planning View	Projected, comparative
Evaluation	Policy Maker	Policy Snapshot View	Aggregated, benchmarked
Communication	Municipal Planner	Planning / Policy Snapshot Views	Summarised, explanatory
Communication	Citizen / VRU	Public Map View	Current, simplified

Alongside task types, the platform defines **information states as they are perceived by users**. Content may be experienced as current (e.g. live hazard detections), historical (e.g. past incident patterns), or projected (e.g. scenario-based risk assessments). Information may also be perceived as certain, uncertain, or incomplete, depending on confidence, coverage, and provenance. These states are communicated consistently across views so that users can interpret information appropriately without needing to infer limitations. Non-nominal states are explicitly recognised. For example, when data coverage is partial in a rural pilot, or when connectivity affects the freshness of observations, this condition is treated as a visible state rather than a hidden system issue. This allows users across roles to adapt judgement and avoid over-reliance on incomplete information.

Finally, tasks and states intersect through shared lifecycle concepts. Safety-related entities such as hazards, advisories, or analytical findings progress through recognisable stages - from identification and review to contextualisation and closure. These stages are visible across views, supporting handover between roles (for example, from operator to planner) and enabling audit and learning without enforcing rigid process flows. By grounding task and state models in EvoRoads personas and views, the Structure Plane ensures that users encounter a coherent and predictable interaction logic across the platform. This alignment supports collaboration, cross-view navigation, and consistent interpretation, while remaining flexible enough to accommodate the diverse operational and analytical contexts of the EvoRoads pilots.

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2.4.5 CONCLUSION OF THE STRUCTURE PLAIN

The Structure Plane has articulated how EvoRoads behaves and how its information is organised, in strict alignment with Garrett's definitions. The interaction rules - immediate feedback, explicit confidence and freshness, conservative profiles under degraded conditions, reversible actions, and consistent ownership workflows - make behaviour predictable for operators under time pressure and comprehensible for non-specialists. The information architecture (clear entities and relationships, controlled vocabularies, disciplined chunking, visible provenance, and enforced country scoping) ensures that content can be found, trusted and reused across contexts. The navigational framework (stable global signposting, a consistent list–map–detail composition, and helpful contextual links) supports both first-time orientation and expert efficiency. Finally, the formal task and state flows capture the happy paths and the exceptions that reality will inevitably introduce.

The next chapter, the Skeleton Plane, will render these structural decisions into concrete screen layouts and control placements. It will specify the grid and panel hierarchy for each view, the alignment and grouping of controls, the placement of status and provenance cues, the focus order and keyboard shortcuts, and the patterns used for empty, loading and error states. In moving from structure to skeleton, we turn platform-wide rules into tangible, testable interfaces that design and engineering can implement with confidence.

2.5 ON WHAT COMES NEXT: SKELETON, SURFACE, AND DEMONSTRATOR MATERIALS

With Strategy, Scope, and Structure now established, the next stage is to give the platform decisive form on screen and a coherent visual voice. These activities - codified by Jesse James Garrett as the Skeleton and Surface planes - will be elaborated during the second iteration of this deliverable (*D1.4*), as outcomes of Task 1.5. Concretely, **Skeleton** will translate structural decisions into wireframes and interaction layouts that specify where components live, how users traverse content, how focus and keyboard navigation behave, and how empty, loading, error and confirmation states manifest consistently. The **Surface** plane will then apply the visual language and brand: typographic scale, colour and contrast tokens, spacing and density rules, iconography, motion and micro-animations, and component states (default, hover, active, disabled). Surface is not decoration; it is the final layer of communication that sustains legibility, accessibility (e.g., WCAG contrast and focus indications), and trust, while reflecting the project's identity across countries and roles. Importantly, Surface expresses Skeleton; it does not rearrange it. This separation preserves traceability from user needs to interaction patterns and onward to visual choices.

To support understanding, training, and reuse by stakeholders, the demonstrator will be accompanied by short task-focused videos and concise documentation. These materials will be shared with LL participants to facilitate feedback loops and to prepare operators, planners, and other users for pilot activities. Tutorials will emphasise the list–map–detail composition, how to read confidence and provenance, and how to act safely (e.g., publishing advisories, scheduling works) with clear fall-backs under degraded communications. The documentation will also cover localisation, privacy controls, and the rationale behind specific interaction standards, so that future teams can extend the platform without diluting its usability.

2.5.1 CONCEPTUAL DEFINITIONS OF THE NINE VIEWS

Taken together, Skeleton and Surface will turn our structural principles into tangible screens, and the demonstrator materials will make them adoptable in practice. What follows, as a prelude to *D1.4*, is a concise definition of the platform's nine views at a conceptual level (what each view exists to do and the kind of content it must present) so that design and engineering can proceed with a shared mental model.

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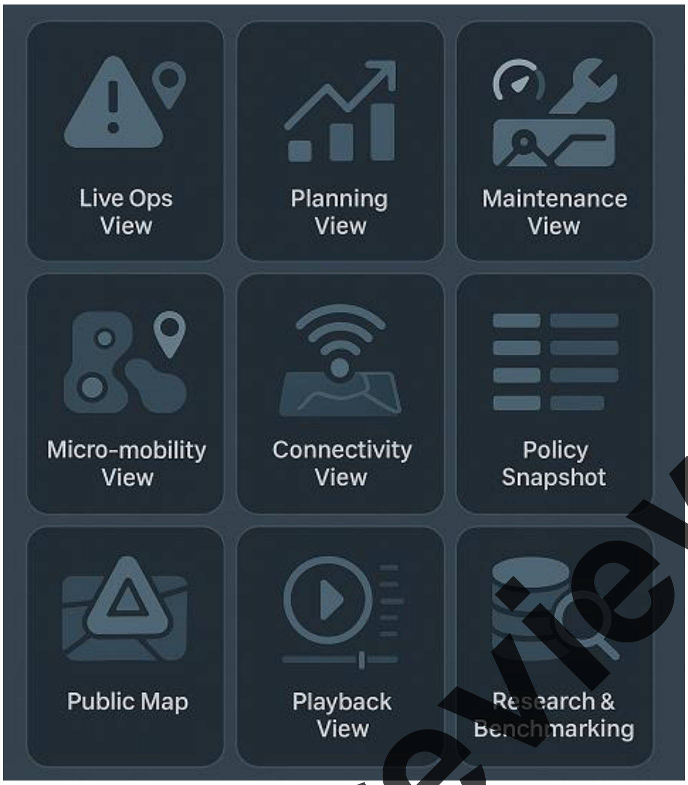

Figure 6: Summary of the nine EvoRoads integrated dashboard views

- The **Live Ops View** is the operational front line for safety-critical decision-making. Its purpose is to surface real-time alerts in a clear priority order, bind them to place on a map, and support proportionate action. Content centres on current conditions (risk indices with confidence, top drivers, freshness) and short, reversible commands, including advisory publishing and rule adjustments, with full lifecycle audit.
- The **Planning View** provides an analytical vantage point over weeks, months, and years. It assembles longitudinal KPIs, scenario tools, and impact-per-euro comparisons to help authorities choose corridors and programmes. Its content is explanatory and comparative: trend lines with uncertainty, equity and rural/urban cuts, and exportable briefing packs that capture rationale and assumptions for governance.
- The **Maintenance View** focuses on assets, condition, and safe work execution. It blends condition summaries from sensing, deterioration forecasts, and traffic/context constraints to produce a risk-ranked backlog and a scheduling workspace. Verification is integral: post-works evidence and before/after indicators are captured so the asset register and forecasts improve with each intervention.
- The **Micro-mobility View** addresses shared scooters and cycles where human–infrastructure conflicts often concentrate. It reveals conflict hotspots and time-of-day patterns, enforces geofences and parking rules, and tracks compliance and impact. Its tone is collaborative: privacy-safe summaries suitable for city dialogue and pragmatic tools for quick, reversible operational adjustments.
- The **Connectivity View** renders the health of communications that safety services depend upon. It maps QoS along corridors, correlates alarms across mast/RSU/backhaul/power, and times restoration against service targets. Its outputs include route-based weak-spot lists and planned optimisations, with clear badges when degraded communications force conservative profiles elsewhere in the platform.
- The **Policy Snapshot** aggregates harmonised KPIs across regions to support target-setting, funding decisions, and accountability. It privileges comparability and clarity: methodology cards attached to each indicator, progress-

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to-target bars with confidence, equity views (including VRUs and rural networks), and “impact per euro” summaries that link decisions back to evidence.

- The **Public Map** offers citizens and vulnerable users a simple, privacy-preserving window into safety information. It provides clear, context-aware advisories and safer routes, and a one-minute reporting flow for hazards with transparent status. In driving mode, it uses hands-free cues for hazards ahead, always complying with legal and non-distraction constraints.
- The **Playback View** is the time machine of the platform. It reconstructs sequences (before, during, and after incidents or interventions) so teams can audit actions, understand causality, and refine thresholds and rules. Its content is narrative and evidential: synchronised charts and map states, bookmarked moments, and comparable periods.
- The **Research & Benchmarking View** is the evidence workbench. It exposes documented, anonymised datasets with versioned KPI definitions, simple previews, export/API options, and model cards for benchmark comparisons. Its design assumes reproducibility: stable identifiers, change logs, and example notebooks that make it straightforward to replicate results or test alternatives.

These nine views, summarised in ***Figure 6***, are distinct but interdependent. Live Ops depends on Communications for reliable delivery and feeds Playback for audit; Maintenance consumes Planning’s priorities and returns verified outcomes; Policy Snapshot reads from the same KPI catalogue that Research documents and tests. Each view is constrained by role and country scope, ensuring users see only what they are entitled to act upon. In *D1.4* the Skeleton plane will translate these conceptual purposes into concrete layouts - grids, panels, control placement, and state patterns - while the Surface plane will apply the final visual system to make those layouts legible, accessible, and coherent at scale.

With the experiential envelope defined, the report now turns to the quantitative backbone that enables it to function credibly. The next chapter will delve into the development and application of dynamic methodologies for quantifying and updating traffic safety criteria and related KPIs. The work builds on the foundations set in Chapter 2, focusing on how real-time, data-driven safety measures inform the user through the platform's user interfaces, whose UX was previously outlined. These dynamic safety KPIs offer an enhanced, adaptable traffic system, providing business value by improving the decision-making process for users and stakeholders in real-time.

2.5.2 SKELETON AND SURFACE DESIGN CONSTRAINTS AND GUARANTEES

While wireframes and visual mock-ups are deferred to *D1.4*, the Skeleton and Surface planes are already constrained by a set of explicit design guarantees derived from the Strategy, Scope, and Structure defined in this chapter. These guarantees ensure continuity and traceability from user needs to final visual outcomes, independent of specific layout realisations.

At the **Skeleton level**, layouts will adhere to the structural patterns established in Section 2.4: the overview–list–detail composition, stable spatial anchoring via maps, and predictable placement of actions relative to content. Interaction layouts will privilege clarity of focus, keyboard accessibility, and consistent handling of primary versus secondary actions across all views. Skeleton designs will also encode non-nominal states - loading, empty, degraded, error, and confirmation - as first-class patterns rather than ad hoc exceptions.

At the **Surface level**, visual design will be constrained by accessibility and legibility requirements rather than stylistic preference. Colour, typography, contrast, and motion will be used to communicate hierarchy, confidence, freshness, and state, not decoration. Visual emphasis will align with interaction intent (e.g. prioritisation in Live Ops, comparison in Planning, explanation in Policy Snapshot), while remaining consistent across roles and countries. Surface design will not alter structural relationships defined in the Skeleton; it will express them more clearly.

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These constraints guarantee that future wireframes and visual designs will remain faithful to the UX logic defined here. They also ensure that visual decisions remain auditable against user needs, task models, and content semantics, rather than evolving independently.

2.5.3 VALIDATION, ACCESSIBILITY, AND DESIGN CONSISTENCY CRITERIA

In the absence of early wireframes, EvoRoads establishes validation criteria that will govern the development and assessment of Skeleton, Surface, and demonstrator materials in *D1.4*. These criteria provide objective checkpoints for usability, accessibility, and consistency across views and pilots.

Validation will focus on task completion and interpretability, not visual preference. Designs will be assessed on whether representative personas can complete core tasks - such as acknowledging hazards, comparing KPIs, or preparing planning summaries - without prior training, and whether confidence, provenance, and freshness are correctly interpreted in context. Cross-view continuity will be tested to ensure that users can change perspective without losing spatial or temporal focus.

Accessibility is treated as a baseline requirement. Skeleton and Surface designs will conform to recognised accessibility standards (e.g. WCAG contrast ratios, focus order, keyboard navigation) and will explicitly support non-visual cues for critical states. This is essential given the operational contexts in which EvoRoads is used and the diversity of user roles involved.

Consistency criteria ensure that the platform behaves as a single system rather than a collection of bespoke dashboards. Recurrent content types (alerts, advisories, work zones, indicators) must follow the shared card grammar; navigation patterns must behave identically across views; and terminology must conform to the controlled vocabularies defined earlier. These criteria allow new views, pilots, or assets to be added without fragmenting the UX.

By defining these criteria upfront, EvoRoads ensures that Skeleton, Surface, and demonstrator materials can be evaluated rigorously and iterated collaboratively with Living Labs, even before full visual realisation.

Table 6: Design consistency criteria for Skeleton, Surface and Demonstrator Materials

CONSISTENCY DIMENSION	CRITERION	WHAT MUST BE CONSISTENT ACROSS THE PLATFORM
Interaction Patterns	Intent-preserving behaviour	Core interaction patterns (acknowledge, explore, compare, act) behave the same across views, regardless of role or pilot
Information Structure	Overview–list–detail triad	All views organise content using the same conceptual structure, enabling rapid orientation and predictable drill-down
Content Representation	Shared card grammar	Alerts, advisories, work zones, indicators, and datasets expose title, scope, confidence, freshness, and provenance in a uniform way
Terminology and Labels	Academic Researcher	Research & Benchmarking View
Planning	Controlled vocabularies	Alert types, advisory actions, confidence levels, and geographic tags use harmonised terms across languages and jurisdictions
Navigation Behaviour	Predictable transitions	Switching views preserves spatial and temporal context unless explicitly reset by the user
State Communication	Explicit non-nominal states	Loading, degraded data, uncertainty, and restricted access states are visible and explained consistently
Accessibility	Inclusive interaction	Keyboard navigation, focus order, contrast, and non-visual cues follow the same standards in all views

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CONSISTENCY DIMENSION	CRITERION	WHAT MUST BE CONSISTENT ACROSS THE PLATFORM
Role and Scope Enforcement	Transparent constraints	Country and role scoping is applied uniformly and explained when content or actions are unavailable
Visual Semantics	Meaningful emphasis	Colour, hierarchy, and motion communicate priority, confidence, and status consistently, not decoratively
Documentation and Training	Alignment with UI logic	Tutorials and videos reflect the same structures, terms, and interaction logic present in the platform

2.5.4 USABILITY AND USER EXPERIENCE EVALUATION APPROACH

To ensure that the Skeleton, Surface, and demonstrator materials deliver on the UX foundations defined in this chapter, EvoRoads adopts a structured approach to usability and UX evaluation. This approach is intended to validate design assumptions, identify usability risks early, and support iterative refinement in collaboration with pilot partners and LL participants.

Usability evaluation activities will focus on **representative tasks** derived from the personas and intent flows defined in Sections 2.2 and 2.4. Rather than assessing aesthetic preference, evaluations will examine whether users can effectively complete core activities - such as interpreting hazards, comparing safety indicators, or preparing planning material - while correctly understanding confidence, freshness, and provenance. Particular attention will be paid to safety-critical interactions, where misinterpretation or hesitation could have operational consequences.

Testing will involve **role-appropriate participants**, including road safety operators, infrastructure and telecommunications engineers, planners, policy analysts, researchers, and, where relevant, citizen users. Scenarios will be grounded in pilot realities, reflecting differences between urban and rural contexts, data availability, and connectivity conditions. This ensures that findings are relevant across the heterogeneous environments in which EvoRoads is deployed.

Evaluation methods will combine **task-based walkthroughs, scenario-driven usability sessions**, and lightweight heuristic reviews aligned with the design consistency criteria defined in Section 2.5.3. These activities will assess clarity of navigation, consistency of interaction patterns, legibility of information states, and accessibility aspects such as keyboard navigation and focus management. Where applicable, feedback will also consider learnability and cognitive load, particularly for users who engage with the platform intermittently.

Findings from usability and UX evaluations will be documented in a structured manner, distinguishing between critical issues affecting safety or task completion and incremental improvements related to efficiency or comfort. This distinction supports prioritisation and avoids overfitting the design to isolated preferences. Results will feed directly into iterative updates of Skeleton and Surface artefacts in *D1.4* and into demonstrator refinements ahead of pilot activities.

By embedding usability and UX evaluation within the design lifecycle, EvoRoads ensures that the platform evolves in response to real user interaction rather than assumption. This approach reinforces trust, supports adoption across roles and countries, and helps maintain alignment between user needs, design decisions, and the platform's operational and analytical objectives.

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2.6 CONCLUSION: USER EXPERIENCE FOUNDATIONS FOR THE EVOROADS PLATFORM

This chapter has established the UX foundations of the EvoRoads platform by systematically progressing through the Strategy, Scope, and Structure planes. Beginning with a clear articulation of user personas and their goals, it defined the strategic intent that anchors all subsequent design decisions. The Scope Plane translated this intent into functional capability commitments and content requirements, deliberately avoiding premature implementation detail while ensuring traceability from user needs to platform responsibilities. The Structure Plane then articulated how users interact with, navigate through, and make sense of information within the platform. By defining interaction principles, information architecture, navigation logic, and task and state models, the chapter provided a coherent framework that supports diverse roles, heterogeneous pilot contexts, and both operational and analytical use. Concrete examples drawn from EvoRoads technologies and views demonstrated how these abstractions apply in practice, ensuring that the framework remains grounded and actionable.

Importantly, this chapter has treated UX not as a visual afterthought, but as a system of decisions that shape trust, interpretability, and effectiveness. The explicit separation of planes preserves design discipline and ensures that future work on layout, visual language, and demonstrators remains aligned with user intent and content semantics. By defining constraints, consistency criteria, and validation principles in advance of wireframes, EvoRoads establishes a robust basis for iterative design without relying on placeholder artefacts.

With these experiential foundations in place, the project is positioned to move from conceptual coherence to tangible realisation. Subsequent work will translate the structures defined here into concrete layouts, visual systems, and demonstrator materials, while the following chapters turn to the quantitative and methodological backbone - dynamic safety criteria and KPIs - that underpin the platform’s analytical credibility. Together, these strands ensure that EvoRoads delivers not only advanced technology, but a usable, trustworthy, and extensible platform for improving road safety across Europe.

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3 DYNAMIC SAFETY KPIS FOR EVOROADS PLATFORM

This chapter will delve into the development and application of dynamic methodologies for quantifying and updating traffic safety criteria and related KPIs. The work builds on the foundations set in Chapter 2 and D1.1, focusing on how real-time, data-driven safety measures can inform the user through the platform's user interfaces, whose UX was previously outlined. These dynamic safety KPIs offer an enhanced, adaptable traffic system, providing business value by improving the decision-making process for users and stakeholders in real-time.

3.1 THE TERM “KPI” IN ROAD SAFETY

Road safety KPIs (in this chapter simply referred to as KPIs) are metrics for evaluating the safety performance in terms of loss of life and health on a given road network. For KPIs to be useful there must exist a relation between the metrics captured by the KPIs and fatality and/or injury outcomes. First when this relation has been established should the KPI be used to evaluate traffic safety policies and interventions. The most straightforward examples of KPIs are those that aim to measure the outcome directly, that is, to measure the number of persons killed or injured and the severity of the injuries. In this report we refer to these KPIs as *Outcome KPIs*. This terminology is, for example, used by the Swedish Transport Administration [9]. Data for outcome KPIs are usually sourced from police or hospital reports and are followed up on a monthly or yearly basis.

Outcome KPIs are foundational to traffic safety because they aim to measure the end goal. However, these KPIs alone might not provide the necessary details to understand the factors leading to crashes and injury outcomes on a system level. Furthermore, they are inherently reactive as they measure the outcome after the fact. Thus, there exists a wide range of KPIs to measure aspects of the road network, traffic flow and user behaviour that correlate with outcome KPIs. For example, the Baseline project [10] focuses on some well-established KPIs such as metrics concerning speed, safety belt and helmet usage, alcohol, vehicle safety and infrastructure. Deliverable 1.1 provides a comprehensive catalogue of KPIs as input to the EvoRoads pilots and the work at hand.

3.2 THE TERM “DYNAMIC” IN ROAD SAFETY DATA

According to Oxford Language the term “dynamic” (of a process or system) is characterized by constant change, activity, or progress. In road safety data, the degree of dynamism refers to the temporal resolution at which the data can be collected and analysed. This temporal resolution can range from real-time updates to hourly, daily, weekly, monthly, and yearly intervals.

An example of non-dynamic is data on the road infrastructure such as road type, number of lanes or the presence of central barriers) that only very seldom changes. This can be interpreted as static data. On the other end of the spectrum are real-time data, for example, traffic flow and speed measurements from roadside sensors or vehicle data that can be continuously collected and updated frequently.

In EvoRoads we divide the data into three categories of temporal resolution:

High - real-time or near real-time (hourly). High temporal resolution is needed for data that is used to identify changes that occur rapidly, or when events/states/incidents are detected in real-time.

Intermediate – ranges from daily to monthly. Intermediate temporal resolution data relates to slower changes than real-time but still within the span of daily–monthly.

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Low – static data that changes its nature very slowly. The temporal resolution with which the data is collected ranges from yearly to near static.

The purpose of the broad categories above is to provide general guidance on the data requirements and common implementation of the KPIs studied. This means that the temporal resolution in the context of the state of the art refers to how the data is used to calculate KPIs. For example, if the sampling frequency of data is high but the KPI aggregates the data yearly the temporal resolution for the KPI will be low. However, in this case there is a potential to design a new, better KPI based on the higher temporal resolution.

3.3 DYNAMIC REPRESENTATION OF STATE-OF-THE-ART KPIS

To understand the association between traffic safety and the KPIs identified in Task 1.1 and Task 1.3, a literature review was performed. Based on the literature, KPIs were then grouped into broad categories and assigned a temporal resolution based on the degree of possible dynamic representation given commonly used data sources. Table 7 provides the KPI categories and temporal resolutions, together with common examples, a summarising description and references. The table is not exhaustive, only categories most relevant for EvoRoads at this stage in the project are included.

Table 7: Identified relevant KPI categories with examples, descriptions and temporal resolution

KPI CATEGORY	COMMON EXAMPLES	DESCRIPTION	TEMPORAL RESOLUTION (SOTA)
Outcome	Number of fatalities (total / per capita / per traffic volume) Number of seriously injured (total / per capita / per traffic volume)	Fatality definition is commonly a person who dies within 30 days as a result of a road traffic crash. Confirmed suicides and other acute diseases are excluded when possible. The definition of seriously injured varies and is still most widely reported by Police where it tends to include persons who have sustained fractures, crushes, tears, serious cuts, concussion, internal injuries or other injuries that is expected to require hospitalisation. Hospital data is more accurate where injuries can be coded according to AIS (Abbreviated Injury Scale). MAIS3+ (maximum AIS at 3 or above) is common but other measures such as MAIS2+, ISS (Injury Severity Score), and PMI (Permanent Medical Impairment) are also used. ***Ref:*** [11] [12] [13] [14]	Low
Traffic	Speed (space or time mean speed km/h / speed distribution) Flow (number of vehicles passing per time unit) Density (number of vehicles per length of road at a given time) Occupancy (proportion of time detector is occupied)	Very strong evidence for the positive traffic safety effect of reduced mean speeds and speeding. The power- and exponential models can be used to estimate the effects on outcome KPIs based on mean speed reductions. The association between outcomes and other traffic KPIs is more unclear. Early work suggested links between crashes and speed variance (which depends on flow, occupancy and density), but this has been revised to some extent. Several studies point to that speed variance may affect the frequency of some types of crashes (e.g., property-damage-only crashes) while speed effects all crashes. Police and speed camera enforcement has been very successful in lowering speeds and thereby increasing traffic safety. There is also a large potential for increased speed compliance in vehicle speed management systems such as Intelligent speed assistance, Adaptive cruise control, and Geofencing. ***Ref:*** [15] [16] [17] [18] [19]	Intermediate. High potential

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KPI CATEGORY	COMMON EXAMPLES	DESCRIPTION	TEMPORAL RESOLUTION (SOTA)
Road surface maintenance	IRI (international roughness index measured longitudinally, m/km) Rutting (rutting depth, mm) PSI (present serviceability index, number typically 0 to 5) PCI (pavement condition index, number 0 to 100) Friction coefficient (relationship between friction force and normal force) Macrotexture (mean profile depth / mean texture depth, mm)	Traffic flows and weather conditions cause deterioration of the road surface pavement thereby increasing IRI, rutting and other road condition measures. Several studies have found that both a higher IRI and higher rutting is associated with higher crash risk. Severe rutting can also lead to increased driver distraction. However, the link between surface conditions and crash frequency is nuanced where some studies report reverse associations and other factors such as speed limits, weather, and road type may affect the results. The association with crash severity is even more ambiguous where some studies suggests that both poor pavement conditions and very good pavement conditions were associated with proportionally more severe crashes. This is likely due to that poor conditions may cause crashes due to more difficult vehicle manoeuvring, risk of skidding and distracted drivers, while very good condition may invite speeding which increases both crash frequency and severity. Both PSI and PCI exhibit similar ambiguous results. Furthermore, though many studies report statistically significant results, the magnitude of the effects are often rather small. High road surface friction is important to ensure high traffic safety, though it can be difficult to measure consistently. Friction is not a system feature as it is the result of two surfaces in contact moving relative to each other. Thus, it depends on both road user road contact (e.g., tires or shoes), speed and angles, and it is also dependent on weather conditions. Nonetheless, studies show that reductions in crashes can be achieved by enhancing textures and friction, in particular for wet weather crashes. Proper maintenance to maintain surfaces is therefore important and removal of loose gravel and other debris is important, in particular to reduce VRU-crashes. For example, studies have shown that loose gravel and sand is a common factor in bicycle and motorcycle crashes. ***Ref:*** [20] [21] [22] [23] [24]	Low. Intermediate potential
Weather	Precipitation (maximum rainfall / number of rainy days in month) Temperature (road surface temperature / air temperature / number of zero crossings) Fog (average visibility m per time unit / minimum visibility m per time unit / number of days with fog) Wind (average m/s wind per time unit / maximum m/s wind gust per time unit)	Studies have shown that slippery road conditions caused by adverse weather such as rain, snow, or ice increase crash frequencies This is due to reduced friction between the vehicle tires and the road surface. In particular, precipitation is associated with increased crash frequency because even if drivers compensate for slippery roads, decreased visibility of rain or snowfall increases crash risk. The effect of precipitation on injury outcomes is not as clear. Thus, associations with crash risk may not translate directly to associations with fatality- och serious injury outcome indicators. The effects of other factors such as temperature, fog and wind are inconclusive. Some studies have found an increased crash frequency from increased maximum wind gust though more research is needed to verify this. Climate changed is expected to bring more zero crossings (days where air temperature passes below and above zero degrees Celsius) which may in particular increase VRU single crashes. Studies from Sweden show that skidding from snow or ice is the most common type of single bicycle crash. ***Ref:*** [25] [17] [26] [27] [28]	Intermediate to High. High potential.

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3.4 POTENTIAL IMPROVED OR NEW SAFETY KPIS

This section presents potential improved or new safety KPI's that can be collected within EvoRoads based on the tools that will be developed. At this stage in the project, data collection, co-creation processes, and tools and systems development are still ongoing. This means that the presented KPIs are first versions, based on task descriptions, initial data descriptions and task meeting information, to be refined as the project progresses.

EvoRoads tools will be developed to, for example, measure infrastructure in larger detail compared to what is currently done in many countries. These tools will generate improved and new types of data, enabling the calculation of safety KPI's, related to the indicators in *Table 7* with a higher temporal resolution compared to traditional methods. However, before introducing new safety KPIs, it is essential to establish a proven relationship between the KPI and safety. This ensures that the KPI will be a useful tool for practitioners to monitor and improve traffic safety.

Section 3.4.1 provides an overview of a suggested methodology with concrete steps to establish such a relationship and subsequent sections provides description of the suggested KPIs. Thereafter, Section **3.4.2-3.4.4** suggest Potential safety KPIs of relevance for EvoRoads, considering the tools developed within the project.

3.4.1 OVERVIEW OF THE METHODOLOGY

Figure 7 provides an overview of the steps required to define useful safety KPIs aimed at improving traffic safety. The core objective, in accordance with Vision Zero, is to eliminate fatalities and serious injuries in traffic. Therefore, outcome indicators are the most crucial metrics for tracking progress towards this goal. **Steps 1 and 2** emphasize the importance of establishing a clear relationship between other indicators and the outcome indicators to ensure the objectives of Vision Zero are met. Only then can the indicators be considered useful for improving traffic safety, with the goal of using them as benchmarks to define and follow up on countermeasures. **Step 3** involves defining specific safety KPIs, while **Step 4.1** identifies the data sources needed to calculate these KPIs and **Step 4.2** focuses on defining the temporal resolution (dynamic representation) of the data sources. Finally, **Step 5** outlines the method for calculating the safety KPIs.

Step 6, marked in a lighter colour in ***Figure 7***, is not the core of the EvoRoads project but is perhaps the most crucial for improving traffic safety. This step involves applying countermeasures, which is when a change in traffic safety is expected. The type of countermeasure depends on the temporal resolution of the KPI. High temporal resolution allows for immediate actions, intermediate resolution supports periodic adjustments, and low resolution is suited for long-term infrastructure projects. Depending on the data sources, the safety KPIs can have different temporal resolutions (high, intermediate, or low). KPIs with high temporal resolution allow for real-time or near-real-time countermeasures, such as in-vehicle warnings to drivers or traffic control measures such as warnings on variable message signs. Intermediate temporal resolution KPIs enable adjustments on a daily to monthly basis, such as changes in temporal designs (road works) or infrastructure measures based on weather conditions (preventive measures to reduce risks of slippery roads). These KPIs are mainly useful for infrastructure owners or actors who can adjust temporal designs (e.g., roadwork contractors). Low temporal resolution KPIs are suitable for measures requiring significant contributions, such as rebuilding infrastructure or road maintenance, typically managed by local or national infrastructure owners.

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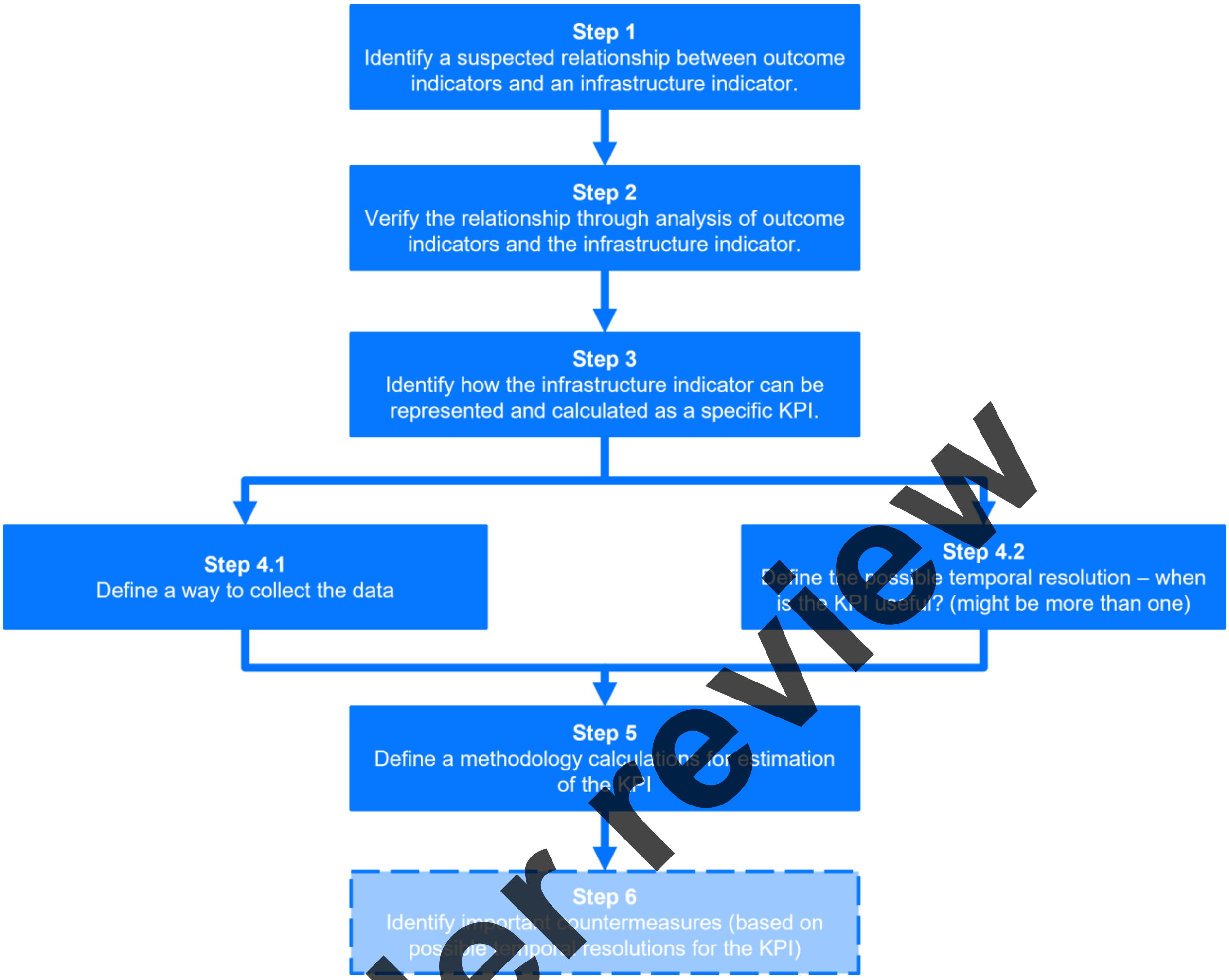

Figure 7: Description of the required steps for defining safety KPI's

As D1.3 is the first version of a later deliverable, the goal is to outline the methodology rather than include specific methodologies for specific safety KPIs. In D1.4, 1-3 promising safety KPIs (within the core of EvoRoads project) will be further evaluated and a methodology for performing the steps in ***Figure 7*** will be detailed.

3.4.2 POTENTIAL SAFETY KPI #1: SLIPPERY ROADS

Step 1 Assertion: *Slippery roads, caused by fluctuating temperatures around zero (frequent zero crossings) and humidity, result in more accidents.*

The changing climate is expected to lead to more frequent occurrences of zero crossings (in temperature) in many countries [29]. There are concerns that these zero crossings, particularly when combined with high humidity, will create hazardous road conditions, resulting in slippery surfaces [30]. This could potentially lead to an increase in accident rates under such conditions. Hence, safety KPIs that quantify slippery roads can indeed be of interest.

Step 2 Verification of Step 1: Identify if a correlation exists between outcome indicators (number of killed / injured / crashes) and infrastructure indicators (road temperature around zero and humidity).

Previous studies have showed that slippery road conditions, such as those caused by rain, snow, or ice, significantly increase the likelihood of traffic accidents (see, e.g., [31] [26] [27]). This is due to reduced friction between the vehicle tires and the road surface, which can lead to loss of control and longer stopping distances. [31] showed that the risk of an accident was higher during snowstorms. [26] found that the relative accident risk was highest for icy rain and slippery and very slippery road conditions. Further the temperatures below zero did result in higher relative accident risks. According to [27] analysis of data on weather conditions and vehicle crashes, injuries and fatalities gathered for 13 U.S. cities showed that there was an increase of 19 and 13%, for traffic crashes and injuries, respectively, due to winter precipitation compared to dry conditions.

Additional to the state-of-the-art, a method for analysing the correlation between crashes and different parameters are suggested in Section 3.5. Based on the data within the EvoRoads project it might be possible to analyse the relationship between slippery roads and accidents, provided that data exists with good enough quality.

Step 3 and 5 Define the safety KPI related to "slippery road" and propose a methodology for calculating it: The definition will be based on a *state-of-the-art review* and *investigation of data sources* from example data or data from Task 2.4 in the EvoRoads project. This step will be further elaborated in the next version of the deliverable and a methodology for calculating the KPI will be proposed (*D1.4*).

Step 4 Available data and Temporal resolution: Task 2.4 (On-the-edge and connected road safety systems) will detect environmental conditions on the road, including fog, rain and asphalt temperature. Table 8 provides an overview of the data sources with a temporal resolution in accordance with the EvoRoads DMP.

Table 8: Overview of data sources for proposed KPI#1

MEASUREMENT	DATA SOURCE	TEMPORAL RESOLUTION
Road and environmental temperature	Optical temperature sensor using infrared technology	High
Fog	Sensor to detect fog	High
Rain	Sensor to detect rain	High

Step 6 Propose countermeasures*: Predictions based on historical data of temperature and fog/rain, which may be used to warn drivers about upcoming traffic safety risks related to slippery road conditions.*

This step is only to be part of the next version of the Deliverable (D3.3) if it is feasible given the availability of data and the resources within the project.

In case applicable, the foundation for the proposed prediction will be based on current state-of-the-art and the availability of data. These models can help to warn road users about increased risks of accidents due to slippery road conditions.

3.4.3 POTENTIAL SAFETY KPI #2: DISTRESS AND DETERIORATION OF INFRASTRUCTURE

Step 1 Assertion: *IRI increase the risk of accidents*

Infrastructure does require updates due to that it wears out based on vehicle usage and weather conditions. Task 2.2 (AI-based tools for cyber-physical road infrastructure monitoring) and Task 2.3 (Predictive maintenance and post-impact repair analysis solutions) will develop tools for measuring and predicting needs for maintenance of the infrastructure. Distress and deterioration measures such as IRI, pothole detection etc. will be used to predict the needs of maintenance. However, the need for maintenance might be even higher if there is also a relationship between traffic safety and the distress or deterioration, hence KPI's related to IRI and risk of crashes might be of relevance.

Step 2 Verification of Step 1: Identify if a correlation exists between outcome indicators (number of killed/injured/crashes) and infrastructure indicators (IRI).

[23] has found that there is a relationship between friction and International Roughness Index (IRI) and crash risk. Several studies indicate that higher IRI values correlate with increased crash rates [32] [33]. For instance, [32] found that rigid pavements with IRI values greater than 2.25 m/km are associated with higher crash rates, while an IRI around 1.50 m/km suggests safer roadways. Similarly, in Alberta, Canada, an increase in IRI values is linked to a higher number of collisions [33]. In Nigeria, crash rates increase with IRI values up to critical thresholds of 4.4 and 6.15 for specific road segments, beyond which the crash rate drops [34]. However, according to [35] and [36] higher IRI values lead to reduced free-flow and peak-hour speeds which might in turn be related to lower risk of severe crashes [24]. For example, a 2 m/km increase in IRI can reduce free-flow speed by 3.2 km/h on 2-lane sections and 1.6 km/h on 3-lane sections 8 9. Various models have already been developed to predict the relationship between IRI and traffic crashes. For example, negative binomial regression models show that higher IRI values are significant predictors of both single-vehicle and multiple-vehicle accidents [37] [24].

Additional to the state-of-the-art, a method for analysing the correlation between accidents and different parameters are suggested in Section 3.5. Based on the data within the EvoRoads project it might be possible to analyse the relationship between distress and deterioration of infrastructure and accidents, provided that data exists with good enough quality.

Step 3 and 5 Define the safety KPI related to "Distress and deterioration of infrastructure" in relation to traffic safety and propose a methodology for calculating it: The definition will be based on a *state-of-the-art review* and and *investigation of data sources* from example data or data from Task 2.2 in the EvoRoads project. This step will be further elaborated in the next version of the deliverable and a methodology for calculating the KPI will be proposed (D1.4).

Step 4 Available data and Temporal resolution: Task 2.2 (AI-based tools for cyber-physical road infrastructure monitoring) will provide distress and deterioration measures such as IRI and pothole detection. *Table 9* provides an overview of the data sources with a temporal resolution in accordance with the EvoRoads DMP.

Table 9: Currently identified data sources for potential KPI #2

MEASUREMENT	DATA SOURCE	TEMPORAL RESOLUTION
Surface variations - to be determined	Vehicle mounted sensors	Intermediate

Step 6 Propose countermeasures: *Predictions of safety risks based on historical data of IRI, which may be used to indicate the need for maintenance based on traffic safety issues.*

This step is only to be part of the next version of the present Deliverable (D1.4) if it is feasible given the availability of data and the resources within the project.

In case applicable, the foundation for the proposed prediction will be based on current state-of-the-art and the availability of data. These models can help transportation agencies in decision-making for road maintenance and safety improvements.

3.4.4 POTENTIAL SAFETY KPI #3: SPEED COMPLIANCE IN RELATION TO PERFORMANCE OF COMMUNICATING SPEED LIMITS (CAV'S READINESS)

Infrastructure is commonly classified according to its safety level, as seen in frameworks such as [38] and the Swedish classification framework [39]. Speed has long been recognized as having a clear relationship with traffic safety [15] [16], which is why speed limits are included as an important factor in these classification frameworks.

With the introduction of new types of vehicles, such as connected and automated vehicles (CAVs), CAV functionalities are becoming important. One of the early systems already introduced today, which must be part of future CAV functionalities, are systems that can read and interpret speed limit signs through vehicle-mounted systems (e.g., video) to

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adapt the speed accordingly. In the future, it is even expected that physical signs will be complemented by digital representations, allowing speed limits to be communicated directly to vehicles without requiring human or system vision or GNSS. Therefore, the current safety KPIs should preferably be adapted to assess risks and benefits with CAV functionalities, such as lack of speed compliance due to erogenous reading or communication of speed limits and the possibility for higher compliance due to system helping the drivers to keep the speed limit. Additionally, these KPIs can probably be monitored with higher temporal resolution, as it might be possible to acquire and communicate speeds from individual vehicles with finer granularity compared to today's roadside sensor measurements.

Step 1 Assertion: *The quality of the speed limit information communicated to vehicles through digital maps or read by vehicle mounted video systems might have an impact on traffic safety for those vehicles.*

Intelligent speed adaptation, ISA, [40] [41] was early proven to be an effective countermeasure to reduce speeding. Recently, informative ISA has become a mandatory feature in new vehicles sold within EU (though the user can still choose to turn the system off each time the vehicle is started). Mandatory ISA and geofencing [42] that provide resistance in the gas pedal are now also emerging as a promising countermeasure by making it more difficult or impossible to override the speed limit.

Both intelligent speed adaptation and geofencing require accurate reading of speed limit signs through vehicle-mounted systems or communication of speed limit zones via digital maps. Geofencing relies on GNSS or RFID technology to define virtual boundaries, meaning the accuracy of these systems can be compromised by receiver quality, weather, urban canyons, tall buildings, and other signal interference, leading to potential inaccuracies in speed enforcement [43].

Therefore, KPIs measuring speed compliance of vehicles with CAV functionalities are crucial, as are KPIs that can measure the accuracy of the speed limits communicated to drivers or read by vehicle-mounted video systems.

Step 2 Verification of Step 1: Identify if a correlation exists between outcome indicators (number of killed/injured/crashes) and infrastructure indicators (speed compliance, inaccuracies in read or communicated speeds to vehicles compared to speed limit).

Road traffic speed management is central for achieving a safe system. Reducing the traffic speed improves safety in two main ways. Firstly, it decreases the reaction time so that there is a greater chance to avoid a crash. Secondly, it lowers the impact force which, in turn, lessens the severity of injuries. Extensive research has been performed on the effects of lowering the speed of traffic and there are well-established models to calculate the expected reduction of the number of killed, seriously injured and crashes based on the mean speed decrease achieved by interventions [44] [16] [15]. These models show that that even relatively modest decreases in mean speeds can give significant reductions. As an example, model estimates suggest that a 10 % decrease in mean speed provides a 40 % decrease in fatal crashes and a 20 % reduction in serious injury crashes [45] [15].

Lack of speed compliance is a major concern in most countries and enforcement strategies that increase compliance have been very successful in reducing fatalities and injuries (e.g., [19]). In EU-project Baseline, the speed compliance was studied in 17 countries [46]. The results showed that speed compliance for cars on rural roads varied between 30 and 90 % depending on country. In Sweden, estimations have suggested a 20–25 % reduction in fatalities if all drivers complied with the speed limits [47].

Step 3 and 5 Define the safety KPI: "speed compliance using individual vehicle data" and "discrepancies in speed limits communicated to or read by vehicles compared to speed limit" and propose a methodology for calculating it: The definition will be based on a *state-of-the-art review* and *investigation of data sources* from example data or data from Task 2.2 and 3.4 and data presented in the EvoRoads DMP. This step will be further elaborated in the next version of the deliverable and a methodology for calculating the KPI will be proposed (D3.3).

Step 4 Available data and Temporal resolution: Task 2.2 (AI-based tools for cyber-physical road infrastructure monitoring) and Task 2.3 (Predictive maintenance and post-impact repair analysis solutions) will design vision AI-based tools to detect and classify the status of traffic signs, where speed limit signs could be one such sign. Further, individual

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speeds from vehicles with CAV functionalities may be available from connected vehicle data or on-board sensors. Table 10 provides an overview of the data sources with a temporal resolution in accordance with the DMP (REF).

Table 10: Currently identified data sources for potential KPI #2

MEASUREMENT	DATA SOURCE	TEMPORAL RESOLUTION
Quality of speed limit sign	Video-based (Task 2.2)	High
Individual speeds	On-board sensors (accelerometer data)	High
Individual speeds	Connected vehicle data	High

Step 6 Propose countermeasures

Step 6 will not be part of EvoRoads project since countermeasures for speed compliance are known. However, the need for improved digital maps might be highlighted based on the safety KPI related to “discrepancies in speed limits communicated to or read by vehicles compared to speed limit” although this is more of a need for improvement of a digital twin rather than implementation of a countermeasure.

3.5 PROPOSED METHODOLOGY FOR ANALYSIS OF CORRELATION BETWEEN CRASHES AND ROAD INFRASTRUCTURE PARAMETERS

The methodology for analysis is being developed in tandem with the development of the EvoRoads platform and the pilot cases. At this stage, a method for analysing the correlation between crashes and road parameters by applying regression models to a demonstration case has been developed. The demonstration case is based on already available data from Stockholm, Sweden, in preparation for the data being gathered in the EvoRoads platform. The demonstration and data gathering are described in more detail in Section 3.6. Furthermore, the state-of-art and feasibility of using more novel methods has been analysed.

3.5.1 NOVEL METHODS TO EVALUATE KPI’S RELATION TO SAFETY

EvoRoads, as outlined in D1.1, is structured around 10 road safety metrics categories, which directly impact road safety outcomes (fatalities, injuries of various severities, total number of accidents). The selection of papers was guided by the identification of correlations between specific road safety metrics and road safety outcomes, with a particular focus on:

- established models that remain highly relevant.
- innovative or less tested models that exploit new data sources and whose data can be gathered with greater frequency or even in real time.

The following analysis of road safety models has been structured around three key categories, considering also future project developments in the pilot’s sites, which will strongly focus on infrastructure characteristics and optimal maintenance:

- **Infrastructure**: e.g., road design, pavement status, and environmental conditions. The Highway Safety Manual – HSM [48] serves as a fundamental reference for infrastructure-related road safety analysis. Originally developed to provide quantitative evaluation methods for road safety improvements, the HSM incorporates well-established statistical models, particularly Poisson and Negative Binomial Regression, for predicting accident frequency based on roadway characteristics. In recent years instead, the European Commission [49] released

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the Network-Wide Road Safety Assessment (NWRSA), which is a systematic approach to evaluating road safety across an entire road network, addressing both a reactive (crash based) and a purely proactive (feature based) safety assessment. It relies on a combination of data sources, including traffic volumes, road geometry, speed limits, roadside conditions, intersection layouts, and historical crash data. Unlike the Highway Safety Manual (HSM), the NWRSA incorporates proactive risk assessment techniques, leveraging road infrastructure and operational characteristics to identify potential hazards before crashes occur. The NWRSA goes in the direction of harmonizing approaches for assessing infrastructure safety across Europe, at least on motorways and primary roads. Besides these comprehensive frameworks, several other studies have been conducted also in recent years to assess the impact of infrastructure characteristics on accidents occurrence and severity. The research by [50] focuses on factors associated with injury severity for both single and multi-vehicle crashes using data from over 550,000 crashes in Japan from 2019 to 2021. In particular, it explores different types of variables such as those related to road infrastructure, traffic control, environment, vehicle and driver, and accident type. The results show that traffic control variables had no significant effect on the injury of single-vehicle crashes. Guardrails were associated with higher severity in both single-vehicle and multi-vehicle crashes at intersections. The impact of the centreline varied between intersections and non-intersections for multi-vehicle crashes.

- **Traffic**: e.g., congestion levels, speed variations, and flow patterns. The work of [45] [44] [16] has played a pivotal role in shaping our understanding of the relationship between speed variables and accident rates. Recent studies by [51] and [52] have explored the role of congestion in accident occurrence, proposing a U-shaped relationship where both extremely high and low congestion levels influence crash risk. However, further research is required to refine these analyses at finer spatial and temporal scales, as most existing studies focus on large-scale urban correlations over extended periods (e.g., annual trends). More granular, real-time assessments could improve the knowledge on this topic, predictive accuracy and policy interventions. Another study by [53] from Australia proposed a different method to evaluate the correlation between traffic congestion on total crashes, fatal serious injury (FSI) crashes, and fatal-only crashes in peak periods. Bayesian mixed-effect negative binomial model investigates the relationship between a congestion index and the frequency of total and FSI crashes. In addition, Bayesian mixed-effect binary logistic model explores the association between the congestion index and the likelihood of having fatal crashes in Statistical Area Level 2 (SA2) zones. Results indicate that traffic congestion tends to increase total crashes in both the AM and PM peak periods and FSI crashes in the AM peak period. In contrast, it tends to decrease the likelihood of having fatal crashes at both the AM and PM peaks. Moreover, the article by [54] leverages big data and a Poisson model with fixed effects to understand the causality of traffic congestion on road accidents in ten cities in Latin America. Analysing over 10 billion observations in 2019, results show a positive non-linear causality of congestion on the number of accidents. Overall, the results suggest that a 10% reduction in traffic delay would reduce accidents by 3.4%.
- **Vulnerable Road Users (VRUs)**: e.g., incidents involving pedestrians, cyclists, and infrastructure devoted to them. Analysing VRU-related accidents presents significant challenges due to systematic underreporting in conventional crash databases. Traditional datasets may not capture pedestrian and cyclist risk factors effectively, requiring alternative data sources such as video analytics, smartphone-based monitoring, and crowdsourced incident reporting. Recent studies focus on different aspects of VRU-related road safety and crash risk. A spatial analysis of VRU fatalities in Delhi highlights that fatalities are associated with demographic factors, traffic characteristics, and built environment features [55]. Another study across 24 cities in five European countries finds that cities with higher walking and cycling modal shares tend to be safer for vulnerable road users, while low-speed road networks mainly reduce injuries for car occupants. This emphasizes the importance of policies promoting active mobility to enhance safety for VRUs [56]. In addition, a study comparing different ML models found that random forest is the most suitable method to predict crash severity starting from several critical risk factors, including driver behaviour, road geometry, time, speed, and weather conditions [57].

The key statistical models adopted in the selected literature review include:

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- **Poisson Regression Model** [58] [48] and **Fixed Effects Poisson Regression** [54]**:** the Poisson Regression model assumes that the number of crashes follows a Poisson distribution where the variance equals the mean. It is commonly used in basic models to predict crashes as a function of variables like traffic volume and infrastructure. However, it struggles with overdispersion (when variance exceeds the mean). The Fixed Effects Poisson Regression extends this by incorporating fixed effects (e.g., site-specific or time-period-specific factors), allowing control for unobserved heterogeneity across analysis units (e.g., specific roads or regions). This approach is useful for longitudinal studies with panel data, capturing spatial and temporal variations more effectively.
- **Negative Binomial (NB) Regression Model** [48]: unlike Poisson Regression, the NB model introduces an additional dispersion parameter, making it more effective for over dispersed crash data, where variance exceeds the mean. This model is widely used in safety studies because crash data typically exhibit overdispersion due to unobserved influencing factors.

Both Poisson and Negative Binomial models can also be used in their “zero-Inflated” versions to better account for the spatial and temporal dispersion of crash data.

- **Bayesian Mixed-Effects Negative Binomial Regression** [59]: this model builds upon the standard Negative Binomial approach by incorporating Bayesian inference and hierarchical structures, allowing for flexible updates with new data. It is particularly useful when incorporating prior knowledge or domain expertise and enables a probabilistic interpretation of crash risks. Bayesian approaches also account for uncertainty more explicitly and improve robustness when dealing with small datasets.
- **Bayesian Mixed-Effects Binary Logistic Regression** [59]: it is a statistical approach used to predict a binary outcome while accounting for both fixed effects (predictors with consistent influence across groups) and random effects (group-specific variations). The Bayesian framework allows incorporating prior knowledge and quantifying uncertainty in parameter estimates through probability distributions. This method is particularly useful when data are hierarchical or clustered. It outputs posterior distributions for model parameters, offering more flexible inference than traditional frequentist approaches.
- **Bayesian Hierarchical Modeling Approach with a Poisson-lognormal Regression Model** [55]: This model is used to analyse count data (e.g., number of accidents) with varying levels of grouping, such as areas or regions. The model assumes counts follow a Poisson distribution, while allowing for overdispersion by modelling the rate with a lognormal distribution. Hierarchical structure captures both local (within-group) and global (between-group) effects. This approach is particularly suited for spatial or nested data with random variability.
- **Bias-reduced Logistic Regression and Ordered Logit** [50]**:** Bias-reduced logistic regression is a variation of standard logistic regression designed to address small-sample bias or separation issues. It applies a penalized likelihood approach to produce more reliable parameter estimates, especially when traditional maximum likelihood estimation fails or yields infinite estimates. Ordered logit is used when the dependent variable is ordinal, that is, it has a natural order (e.g., satisfaction level: low, medium, high). It estimates the probability of an observation falling into each category, assuming the relationship between each pair of outcome categories is the same.
- **Power Model/Exponential Model** [16]**:** often used to estimate speed-accident relationships. The main difference between the two is that with the Power model the effect of change in speed is independent of initial speed, while with the Exponential model the effect depends on the difference in speed before and after a change. Both models, however, have been demonstrated to fit data well.
- **Machine Learning-Based Approaches:** these approaches leverage advanced computational techniques to integrate real-time traffic monitoring data and improve predictive accuracy. Some of the commonly used models include:

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- **Random Forest (RF)** [57]: A decision tree is a flowchart-like structure in which each internal node represents a test on an attribute, each branch represents the outcome of the test, and each leaf node represents a class label. The paths from root to leaf represent classification rules. A Random Forest is an ensemble learning method based on Decision Trees. Unlike a single decision tree, a random forest builds multiple decision trees (estimators) during training and combines their outputs (via averaging for regression or majority voting for classification). This approach helps improve the model's accuracy, reduce overfitting, and enhance generalization. The described models capture nonlinear relationships and interactions between different risk factors.
- **Multiple Linear Regression (MLR)** [56]: This is a method used to model the relationship between one dependent variable and two or more independent variables. It aims to fit a linear equation to the observed data by minimizing the sum of squared differences between actual and predicted values. It represents a traditional approach used as a baseline comparison for more complex machine learning models.
- **Deep Learning and Neural Networks** [60]: emerging methods that leverage large-scale sensor and video data to predict crashes with high accuracy. Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) have been explored for their ability to process spatial and temporal traffic patterns, respectively.

The different road safety models use various safety metrics (covariates) as input variables, ranging from traffic conditions to infrastructure characteristics. One key aspect is understanding which of these data are highly relevant, despite their collection methodology and needed update frequency. On the other hand, it is also important to notice which of these data can be collected and modelled with high temporal resolution (eventually in real-time) enhancing the accuracy and applicability of predictive models, exploiting modern technologies and innovative data sources.

Among the most critical and widely used data sources, those requiring high accuracy and sufficient spatial resolution include:

- Traffic data
- Speed limits and operating speeds
- Congestion levels
- Population density

Accurate traffic volumes (AADT), disaggregated by vehicle type (heavy vs. light vehicles), are essential. Traditional estimation methods, such as simulation models, may introduce biases and errors, whereas real-time sensor-based monitoring stations and commercial traffic data providers (e.g., Here, TomTom) offer more reliable insights that could be integrated systematically into models' calibration procedures.

Additionally, infrastructure characteristics play a significant role in road safety assessment. Key elements include:

- Intersection classification (e.g., simple four-leg intersections vs. complex multi-intersection nodes, roundabouts).
- Road geometry (curve radius, lane width, number of lanes, lane slope, pavement conditions, centreline, visibility - presence of black spots).
- Safety barriers and lane boundaries.

While some of these variables remain static over time, they are still challenging to obtain (e.g., accurately measuring curvature radius). Other variables instead have the potential to be gathered with high temporal resolution, such as pavement conditions and visibility.

Finally, crash data remains a fundamental input since they are the key output variable of the considered models, ideally including detailed geolocation and severity classification (fatalities, injuries). These datasets, typically updated annually, are essential for model calibration and validation. However, it should be noted that these data could become obsolete

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whenever referred to previous infrastructure conditions, then updated through corrective measures or even more significant changes.

3.5.2 LOGISTIC REGRESSION APPLIED TO DEMONSTRATION CASE

When the outcome variable is binary (e.g., crash/no crash), logistic regression is a relevant starting point for exploring associations between outcomes and road network conditions. This section provides an overview of how this methodology was applied to the demonstration case presented in Section 3.6 below. The method was used to determine if the probability of a crash increases or decreases when the values of chosen numeric predictor variables increase. This serves as an early example of how proposed methodologies could be applied to the data that is being gathered to the EvoRoads platform.

The applied logistic regression model finds the best fit coefficients β_0, β_1, …, β_n to the logistic regression equation

$$log\left(\frac{p(x)}{1-p(x)}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n,$$

where p(x) is the probability that a crash occurs and X_1, X_2, …, X_n are the predictor variables. The model was fitted using Matlab (function 'fitglm' with binomial distribution) which uses the maximum likelihood method for model estimation.

The methodology applied can be summarised in the following steps:

1. Identify relevant crash data for the dependant variable.
2. Identify relevant predictor data that could be associated with the outcome crash.
3. Check for multicollinearity (remove predictor variables that are highly correlated with other predictor variables).
4. Run the regression with all predictors (not including interaction effects for this example).
5. Use backwards elimination, removing one non-significant (p-value > 0.05) predictor variable with the highest p-value at a time.
6. Calculate the odds ratios for the significant predictor variables.

The odds ratios (ORs) describe how much the odds of a crash increases (OR > 1) or decreases (OR < 1) when the predictor variable increases by one unit. For example, a OR of 1.1 means that the odds of a crash increases by 10 % indicating a positive association with crash risk for that variable.

3.6 DEMONSTRATION CASE – VISUALIZATION AND ANALYSIS

To demonstrate how geographical information systems (GIS) and statistical methods can be used for visualisation and analysis of KPIs, a demonstrator case was developed in Task 1.3. The purpose was to provide inspiration and begin development of analysis methods early in the project before the EvoRoads platform design and data gathering had begun. The chosen case was rural roads in Stockholm County, Sweden, a site that shared many similarities with the pilot sites and for which data was already available. It is also the area in Sweden with the highest penetration of traffic measurements due to the traffic intensity. The idea was to develop a conceptual GIS framework to show what such a tool could look like and how it could be applied. The tool includes available data sources covering a wide range of information, and the data has been evaluated for availability and relevance to the purpose. Examples of relevant data are infrastructure information (speed limit, number of lanes, road standard, etc.), traffic information (vehicle flows, ongoing work zones, etc.), historical crash data (position, severity, etc.), weather data, etc. The developed demonstrator GIS-model can be interpreted as a digital twin (similar to what is developed within Task 3.1). However, this GIS-model is only for demonstration of how the tool can be used and is not implemented as an interactive tool within the EvoRoads project.

The following subsections describe the data sources used, the visualisation framework and the results from the data analysis using logistic regression.

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3.6.1 HIGH TEMPORAL RESOLUTION DATA

To limit the number of data sources and keep the focus on road safety characteristics, priority was given to data related to traffic, road surface, and weather. Several data sources can provide similar data (e.g. traffic conditions can be estimated from floating car data, Global Positioning System (GPS) service providers, etc.), but the data sources listed below were those that provided high quality data and offered a high degree of freedom in terms of area coverage and penetration.

3.6.1.1 GOOGLE DATA

Through Google APIs such as the Distance Matrix API or the Directions API [61], travel times in traffic can be estimated based on real-time measurements. The response from the platform includes the journey time and length for a specific route with user-defined start and end points. This source gives the user a high degree of freedom as the data covers large areas and allows the user to determine the length of individual segments. Potential disadvantages include that information on the number of contributing vehicles (penetration rate) or vehicle types are not included in the data. Journey times are also given as integers in seconds, which can be limiting when defining short distances (which may not capture variations in time).

Data is available in both real time and generalised for typical conditions at the current time of day. A limited amount of data is available free of charge, but larger amounts of calls to the API are subject to a fee.

3.6.1.2 DATA EXCHANGE PORTAL

The Data Exchange Portal is a service provided by the Swedish Transport Administration [39] that makes it easier to find, understand and use their data. It makes available a variety of information related to the transport system, such as

- Real-time data for traffic information, weather, traffic conditions, etc.
- Information on the road and rail network, including road numbers, road pavements and speed limits, etc.
- Environmental data on traffic impacts, such as noise and air pollution
- Information on planned and ongoing maintenance work
- Images from cameras observing traffic conditions or road surface

The data is open and accessible to the public via the portal website [62]. Login is required to create a personal token and retrieve data, but creating an account is free. For this specific project, real-time data is used in the form of traffic measurements, journey times, road conditions, traffic information, weather data and cameras in the road environment. Note that only real-time data is available from the platform, historical data requires other technical solutions to order and retrieve data.

3.6.2 INTERMEDIATE TEMPORAL RESOLUTION

This type of data describes characteristics that change over time but are less dynamic in terms of significant changes from a short-term perspective, implying less need for real-time representation.

3.6.2.1 METEOSTAT

Meteostat is a platform providing open weather and climate data from weather stations around the world. The platform uses an open data policy and offers detailed historical weather observations and climate statistics based on thousands of weather stations. Data is available for each weather station, and it is possible to download data directly from the official website or by using API. Data includes the following information:

- Temperature
- Perception
- Wind speed
- Wind direction

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- Air pressure

Data is free and accessible to locations all over the world [63].

3.6.2.2 STOCKHOLM CITY

The City of Stockholm uses traffic measurements to monitor patterns in the transport system and to develop and ensure that the city offers relevant services in the form of safe and reliable transport solutions for citizens. The measurements are open traffic data available through the website Miljöbarometern and the City of Stockholm's data portal [64].Through these services it is possible to retrieve information on:

- Traffic flows divided into the number of light vehicles, heavy vehicles, motorcycles, and bicycles. These flows are primarily based on sample measurements but have then been distributed over links.
- Actual traffic measurements (sample points). Data is compiled down to 15-minute intervals and includes both traffic flow and average as well as the 85th percentile for speed.
- Flows of electric scooters (only at fixed measurement points).
- Locations for electric scooters and city bikes.

There is also aggregated data from the congestion charging scheme and speed observations for individual measuring points with a long historical perspective (back to 1991).

3.6.3 LOW TEMPORAL RESOLUTION

This type of data usually includes characteristics such as infrastructural elements, legislation, population, documented correlated effects, etc. Data often contain long time series and are mainly updated as needed, either regularly or when conditions change.

3.6.3.1 NATIONAL ROAD DATABASE (NVDB)

The Swedish National Road Database (NVDB) [65] includes detailed information on Sweden's road network and its characteristics. It is managed by the Swedish Transport Administration and is used to support various traffic and transport-related services and analyses. The database includes information that can be categorized into the following classes:

- Road equipment (e.g., speed cameras, rumble strips, speed bumps, noise barriers, wildlife fences, etc.)
- Traffic regulations (speed limits, load-bearing classes, road maintenance authority, restricted axle load, etc.)
- Road design (road width, number of lanes, intersections, bridges/tunnels, pavement layers, etc.)
- Other administrative data (network type, road number, traffic safety classification, road type, environmental zones, traffic volume, etc.)

The database includes traffic safety classification of roads and intersection divided into perspective of cars and pedestrians/walking, with grade 1 to 4 (1 = very good, 4 = low). The classification is based on the design of road (median barrier, separated bicycle path etc.) and historical information about occurred incidents. The classification does not cover the complete road network (only a part of the national road network).

The database covers the full road network in Sweden independent of road operator (governmental, municipal or private road) and type of road (car, bike, pedestrian). Data is considered historical and covers the available road infrastructure elements, data also includes time dimension enabling analysis of historical infrastructural designs and developments over time. The data is open access and provided without a fee.

3.6.3.2 PAVEMENT MANAGEMENT SYSTEM (PMSV4)

Pavement Management System version 4 (PMSv4) [66] is a tool used by the Swedish Transport Administration to manage and analyse data on the condition of the state roads in Sweden. Data is mainly collected through road surface measurements carried out by measuring vehicles equipped with different instruments to read road surface characteristics

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(e.g. laser, optical sensors, ultrasonic sensors, GPS, etc.) Road surface measurements are carried out annually or every two years depending on the road category. The available data can be broadly classified as:

- Road geometry (curvature, gradient and crossfall)
- Road surface characteristics (IRI (International Roughness Index), rut depth, edge depth, surface damage, rut width, etc.)
- Pavement information (laying date, binder, thickness, warranty periods, etc.)

Data covers the national road network and the resolution is as detailed as 20 or 100 meters. Data is considered offline or historical and covers the actual road standard, data also contains time dimension allowing analysis of historical road surface measurements [67].

3.6.3.3 OPEN STREET MAP (OSM)

OpenStreetMap is a collaborative platform (OpenStreetMap, 2024) which aims to create and distribute free and editable maps. It contains data under an open license and allows anyone to contribute, edit, and use the map data.

The map includes similar information to the National Road Database (NVDB) but is a worldwide service containing not only road related information but also objects related to other transport modes and services (like buildings, lakes etc.) [68].

3.6.3.4 STATISTICS SWEDEN (SCB)

Statistics Sweden (SCB) is the national statistical agency in Sweden and operates under the ministry of finance. The agency is responsible for producing official statistics regarding population, economy, education, labour market etc.

Statistics Sweden offers a wide range of open access data that is available through external website or API. Within the GIS-tool, data is included covering population, urban and county boundaries. Population is provided in grid format with resolution of 1 000 meters, data is considered as offline and includes time dimensions enabling visualization of historical developments [69].

3.6.3.5 SWEDISH TRAFFIC ACCIDENT DATA ACQUISITION (STRADA)

The Swedish Traffic Accident Data Acquisition (Strada) [70] is an information system that collects and manages data on traffic accidents and injuries within the road transport system in Sweden. Data is collected through reports of crashes from the police, reports from emergency hospital visits, and the coast guard. The Swedish Transport Agency is responsible for developing and managing the system.

The resolution of the data is divided into each crash occurrence, the data is considered as offline and includes historical perspective. Available data from Strada consists of a range of attributes related to each individual crash, for example the following information:

- Location
- Accident type
- Severity and combined severity
- Road conditions
- Road surface
- Weather conditions
- Coordinates

The data is not public available, VTI as an authority has access to data extracts.

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3.6.4 VISUALIZATION

The listed geographical information in previous chapters is included within the developed GIS-tool designed to visualize different characteristics affecting traffic safety for road users. ***Figure 8*** gives an example of how the GIS-tool can be used to display and analyse data to visualize traffic related KPIs and identify hot spots with increased risk for traffic incident. Furthermore, ***Figure 9*** provides a screenshot of the actual GIS development environment that has been used.

Figure 8: Illustration of the GIS-tool including different layers with traffic safety related information. From the bottom layer with infrastructural data (road etc.), layer with population, layer with historical traffic measurements, layer with road standard observation, layer with live data about surface temperature, layer with live updates from traffic cameras, layer with heatmap of historical information about incidents.

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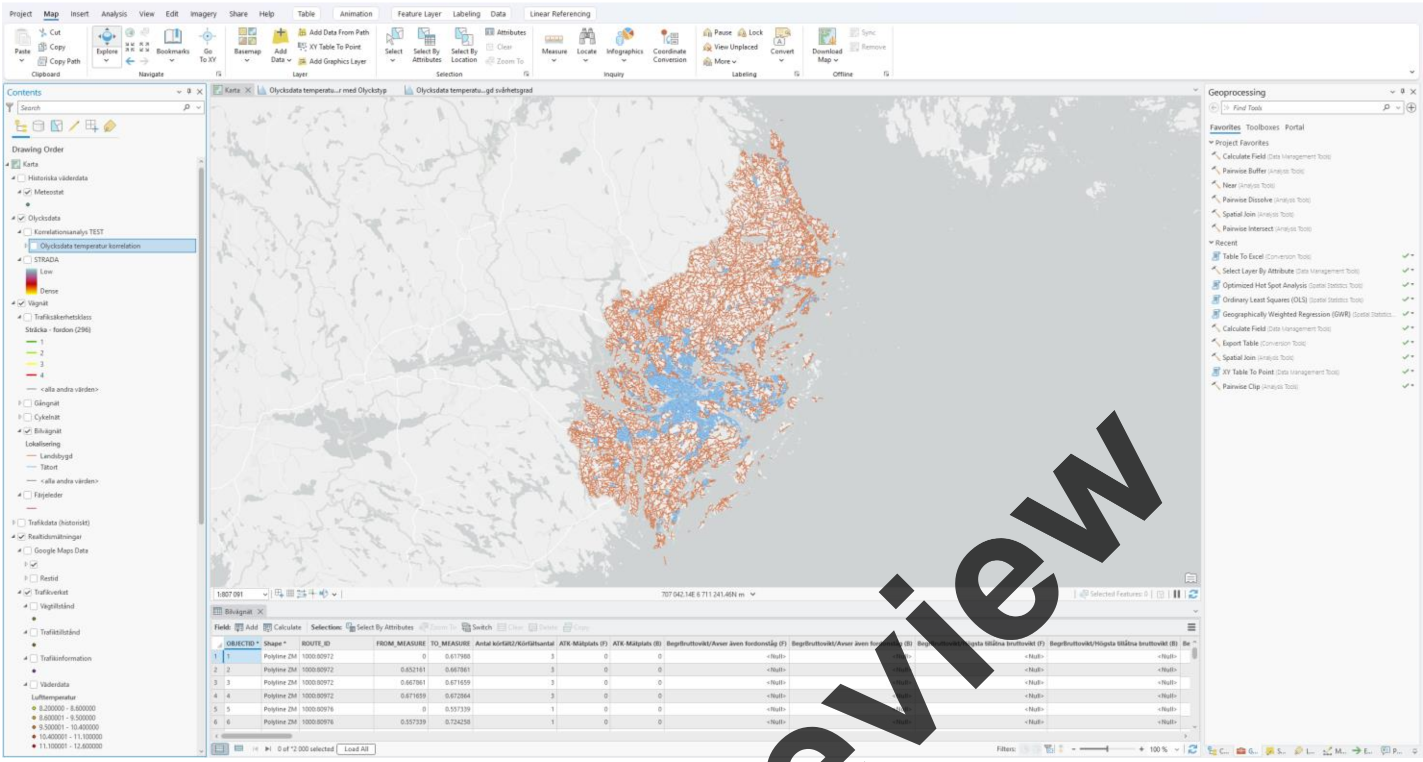

Figure 9: The demonstrator case development environment implemented in ArcGIS Pro.

3.6.5 ANALYSIS AND RESULTS

The year 2023 was chosen for demonstration. Applying the method outlined in 3.5.2, police reported crash data were retrieved from Strada and matched to rural roads on the national road network within Stockholm County by GNSS coordinates. In total, close to 900 kilometres of road were included in the analysis. The roads were divided into 100 metre segments and aggregated values for each segment were retrieved from the sources listed above to obtain the following predictor variables (KPI categories are given in parenthesis):

- ADT – Average daily traffic (Traffic)
- Speed limit (Traffic – surrogate for actual speed)
- Curvature (Road surface maintenance)
- Longitudinal slope (Road surface maintenance)
- IRI (Road surface maintenance)
- Rut depth (Road surface maintenance)
- Surface temperature (Weather)

Initially, road width was also included, but analysis of multicollinearity showed a high correlation between road width and speed limit (since wider roads are designed for a higher speed limits). Therefore, road width was excluded from the analysis. The variable with the highest temporal resolution was surface temperature, where daily measurements from weather stations where obtained. Thus, the model features one observation per day and per 100 metre road segment for the year 2023. Note that average daily traffic (ADT) was estimated from yearly averages (AADT) using indices that scale the values based on vehicle type, month, and day of the week.

Two models were considered: the first with dependant variable Killed or Seriously Injured (KSI) crash (one if a killed or serious injury crash occurred on the road segment on that day, zero otherwise) and the second with dependant variable Slight crash (one if a slight injury crash occurred on the road segment on that day, zero otherwise).

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The results for the final KSI crash model showed statistically significant ($p < 0.05$) associations between KSI crash occurrence and IRI, as well as between KSI crash occurrence and ADT. The regression results are provided in *Table 11*.

Table 11: Final KSI crash model results. Ch^2-statistic vs. constant model p-value = 0.000.

PREDICTOR	ESTIMATE	SE	T-STAT	P-VALUE	ODDS RATIO
(Intercept)	−11.839	0.189	−62.723	0	0.000
IRI	−0.107	0.052	−2.033	0.042	0.897
ADT	0.000	0.000	5.098	0.000	1.000

Note that although ADT is technically significant, the estimate is very close to zero and therefore the odds ratio is very close to one. This means that ADT has no practical effect on the odds of a KSI crash occurring. For IRI, however, there appears to be a negative association, where the odds of a KSI crash occurring is reduced by about 10 % for every unit that IRI increases. Though deeper study is required to draw any definitive conclusions, this result contradicts some previous studies on IRI (see Section 3.3.9), while it is in line with other studies that suggest that lower road surface quality may lead to better traffic safety, possibly because it causes the driver to lower the speed of the vehicle.

The results for the final Slight crash model showed statistically significant ($p < 0.05$) associations between Slight crash occurrence Rut Depth, Edge depth, ADT as well as Speed limit (see results in *Table 12*). However, all results are minor in terms of actual effects on the odds of a slight crash, ranging between −1.5% to 2.5%. Nonetheless, the results from these two models do align with the previous literature concerning that different KPIs may be relevant depending on the type of crash considered.

Table 12: Final Slight crash model results. Ch^2-statistic vs. constant model p-value = 0.000.

PREDICTOR	ESTIMATE	SE	T-STAT	P-VALUE	ODDS RATIO
(Intercept)	−9.500	0.219	-43.367	0	0.000
Rut depth	0.015	0.005	2.809	0.005	1.015
Edge depth	−0.026	0.003	−7.547	0.000	0.975
ADT	0.000	0.000	25.556	0.000	1.000
Speed limit	−0.014	0.003	−5.36	0.000	0.986

3.7 CONCLUSIONS AND NEXT STEPS

Table 13 summarises the findings from the work conducted so far in Task 1.3. Three potential safety KPIs have been identified as having a strong connection to EvoRoads' tools and pilots. These KPIs will be further explored in the next phase of the project.

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Table 13: Description of potential safety KPIs that may be related to traffic safety impacts and relations to task and pilots that will be further investigated within EvoRoads.

POTENTIAL SAFETY KPI	RELATIONS TO TASKS/PILOTS AND PROPOSED NEXT STEPS	MEASUREMENTS	DATA SOURCE	TEMPORAL RESOLUTION
Slippery roads	In **Task 2.4**, tools will be developed to collect the proposed measurements for assessing slippery road conditions on a high temporal resolution. The HAIM-tool is one of the tools developed in Task 2.4 will be able to collect road surface temperature, ambient temperature, detects road obstructions, and counts vehicles passing through the area where it is installed. Once the relationship between safety (outcome indicators such as fatalities and serious injuries) and slippery roads, or the specific measurements collected during the pilot, has been verified (as a **next step of Task 1.3**), it will be possible to propose refined safety KPIs based on the temporal resolution of the data. Countermeasures, such as smart lightning and app warnings, used to warn driver about upcoming slippery road conditions are expected to be developed within **Task 3.2 and 3.3**. An app to warn road users about hazards such as slippery roads are expected to be developed as part of the work in **Task 3.1, 3.4 and 4.2**	Road and environmental temperature	Optical temperature sensor using infrared technology	High (collection frequency high)
		Fog	Sensor to detect fog	High (collection frequency high)
		Rain	Sensor to detect rain	High (collection frequency high)
Distress and deterioration of infrastructure	In **Task 2.2**, AI-based tools for physical road infrastructure monitoring will be developed to allow for measurements of surface variations on a high temporal resolution. However, the surface variations itself are expected to change with an intermediate temporal resolution. In the **Santa Oliva pilot (Task 3.4, 4.2)** surface data from CAV's and the HAIM tool developed in **Task 2.2** will be used to assess asphalt surface data. Once the relationship between safety (outcome indicators such as fatalities and serious injuries) and distress and deterioration measured as surface variation measurements collected during the pilot has been verified (as a **next step Task 1.3**), it will be possible to propose refined safety KPIs based on the temporal resolution of the data. Countermeasures enabling predictive maintenance and post-impact repair analysis solutions are being developed within **Task 2.3**. Predictive maintenance	Surface variations - to be determined	Vehicle mounted sensors	Intermediate (collection frequency high)

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POTENTIAL SAFETY KPI	RELATIONS TO TASKS/PILOTS AND PROPOSED NEXT STEPS	MEASUREMENTS	DATA SOURCE	TEMPORAL RESOLUTION
	and post-impact solutions are forecasted based on clustering algorithms that consider surface condition (e.g., IRI or texture roughness), historical deterioration trends, as well as environmental and traffic-related data allowing us to predict which road sections are likely to deteriorate soon and require maintenance. If correlations are confirmed between surface variation measurements and outcome indicators, such as fatalities and severe injuries, the proposed solutions may incorporate safety criteria, derived from the developed safety KPIs, as an additional parameter. This would allow for decision-making based on traffic safety aspects as well when prioritising and conducting maintenance activities and post-impact repair analyses. However, the potential correlation must be evaluated as part of future work of Task 1.3.			
Speed compliance in relation to performance of communicating speed limits (CAVs readiness)	In Task 2.2 and Task 2.3, vision-based AI-algorithm for traffic signs. The tool may be used to detect and measure the quality and readability of speed limit signs. Based on the quality measurements of road signs, it is possible to design safety KPI's as part of **next steps of Task 1.3**. One example is percentage of speed limit signs successfully read per road segment, which can serve as an indicator of how effectively vehicles equipped with speed-limiting systems are able to operate on specific road sections. The relation between speeding and injury level is well-proven. However, it is uncertain if erogenous reading of speed limits, and thereby erogenous adapting towards the legal speed limit, will affect the overall performance of the vehicles with active speed limiting systems. This might be evaluated to some extent as part of next steps of Task 1.3, if such studies already exist. Countermeasures include maintenance of signs to increase readability, which allow correct reading of speed limits signs and thereby an increased level of speed compliance towards legal speed limits for vehicles with passive and active speed limiting systems.	Quality of speed limit sign	Video-based (Task 2.2)	High (collection frequency high)
		Individual speeds	On-board sensors (accelerometer data)	High (collection frequency high)
		Individual speeds	Connected vehicle data	High (collection frequency high)

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4 EVOROADS INTEGRATED PLATFORM ARCHITECTURE

This chapter will describe the architecture of the EvoRoads platform using the **4+1 architectural view model**, which organises the platform into five complementary perspectives: **logical, development, process, physical, and scenarios**. It will give a detailed account of core services, data stores, pipelines, and interfaces, and the ways they collaborate to realise the functional capabilities and satisfy the requirements identified earlier. From the developer's vantage point, the chapter will make explicit the contracts between components, the dependency boundaries, and the cross-cutting concerns (performance, availability, resilience, privacy, auditability, interoperability, and observability) that shape implementation choices. It will also set out how users and systems access the platform (single Dashboard with role-based control and country scoping, companion mobile applications, and public/research APIs), how third parties can exercise interfaces in a sandbox, and how assurance is obtained through conformance testing, security testing, and independent verification activities.

Within the **logical view**, we will decompose the domain into services for data ingestion, fusion and analytics, digital-twin computation, alerting and advisory orchestration, and presentation. The **development view** will map these elements to source repositories, modules, and libraries, including coding standards. The **process view** will capture concurrency, event flows, and runtime interactions across services and edge nodes, with attention to scalability and graceful degradation. The **physical view** will describe deployment topologies across cloud, on-premise, and edge/roadside environments, detailing environments (development, test, staging, production), telemetry, backup, and disaster recovery. The **scenarios view** will anchor the architecture in representative use cases - drawn from the nine platform views described in the previous chapter - to validate key paths and trade-offs.

4.1 LOGICAL VIEW: CORE COMPONENTS AND INTERACTIONS

The **Logical View** of the EvoRoads Integrated Platform Architecture focuses on the static organisation of the system's software modules. It provides a detailed breakdown of the system's building blocks, describing how the platform is structured at the code and module level. This view emphasises the separation of concerns and the modularity of the platform, ensuring each component can be developed, maintained, and tested independently.

4.1.1 SCOPE AND ROLE OF THE LOGICAL VIEW WITHIN EVOROADS

The Logical View plays a central role in the description of the EvoRoads Integrated Platform Architecture by providing a structured, technology-agnostic representation of the platform's functional composition. In a project characterised by heterogeneous technologies, multiple pilot contexts and a strong emphasis on user-centred design, the Logical View establishes a common architectural language that connects user needs to system integration. Its primary purpose is to describe *what the integrated platform does* and *how its main functional responsibilities are organised*, independently of implementation choices or deployment constraints.

4.1.1.1 WHY THE LOGICAL VIEW IS NEEDED IN EVOROADS

EvoRoads integrates capabilities developed across several WPs, ranging from data acquisition and analytics to digital twins and user-facing services. Without an explicit logical decomposition, these capabilities risk being interpreted as independent solutions rather than as parts of a coherent platform. The Logical View addresses this by identifying the principal functional areas of the integrated platform and clarifying their roles and interactions at an abstract level. This abstraction is particularly important in EvoRoads, where components are developed by different partners and may evolve

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asynchronously. By focusing on logical responsibilities rather than technical implementations, the Logical View provides a stable reference that supports consistency throughout the project lifecycle.

4.1.1.2 RELATIONSHIP TO LIVING LABS, PERSONAS AND USER NEEDS (TASK 1.2)

The Logical View is directly grounded in the outcomes of Task 1.2, which focused on Living Lab activities, persona identification and the elicitation of user needs. These activities revealed distinct user groups - such as road authorities, infrastructure managers, analysts and decision-makers - with differing expectations regarding data access, analysis, visualisation and decision support. The Logical View translates these findings into functional responsibilities, ensuring that the integrated platform is structured around *what users need to do*, rather than around individual technologies or algorithms.

Rather than prescribing user interfaces or interaction details - which are extensively discussed in Chapter 2 - the Logical View provides the functional backbone that enables those UXs. For example, requirements related to situational awareness, safety assessment or infrastructure prioritisation are reflected in logical components responsible for data aggregation, analytics orchestration and information exposure. In this way, the Logical View ensures continuity between user-centred analysis and architectural design, without duplicating the detailed UX and UI considerations already covered elsewhere in the present document.

4.1.1.3 ROLE IN SYSTEM INTEGRATION (TASK 1.5)

As a core output of Task 1.5, the Logical View underpins the integration of the EvoRoads platform. Integration in EvoRoads is not limited to technical interoperability but involves the coordinated operation of functionally distinct components developed across WPs. The Logical View defines clear functional boundaries and interaction points, enabling components to be integrated incrementally while preserving overall coherence. This is particularly important given that some components may be deployed differently across pilots or adapted to local constraints. The Logical View thus serves as the primary integration blueprint, guiding how platform capabilities are composed and exposed to users.

4.1.1.4 CLARIFYING PLATFORM BOUNDARIES AND EXTERNAL INTERFACES

A key aspect of architectural discipline is the explicit definition of system boundaries. In EvoRoads, the integrated platform comprises the logical components responsible for data ingestion coordination, analytics and digital twin services, safety indicator computation, and user interaction and visualisation. These components collectively deliver the functionality perceived by end users through dashboards and tools described in Chapter 2.

At the same time, the Logical View clearly distinguishes external systems that are interfaced but not part of the platform. These include data sources operated by third parties, pilot-specific sensing infrastructures, and external data spaces with which EvoRoads exchanges information (kindly consult Section 5.1.1). By treating these elements as external actors with defined interfaces, rather than as internal components, the Logical View avoids scope creep and clarifies responsibility boundaries.

4.1.1.5 ARCHITECTURAL DISCIPLINE AND SCOPE CONTROL

By grounding the platform architecture in user needs (Task 1.2), clearly defining functional responsibilities, and distinguishing between internal platform components and external systems, the Logical View demonstrates architectural discipline and scope control. This approach ensures that EvoRoads remains focused on delivering an integrated platform that addresses validated user needs, while remaining interoperable with external ecosystems. The Logical View thus provides a solid foundation for the subsequent architectural views, which will elaborate on behaviour, development and deployment aspects without revisiting fundamental questions of purpose and scope.

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4.1.2 INTEGRATED PLATFORM HIGH-LEVEL FUNCTIONAL DECOMPOSITION

The EvoRoads stack is organised in seven cooperating layers that separate concerns cleanly while preserving end-to-end provenance, privacy, and auditability. The objective is to move from diverse signals to trustworthy decisions, with each layer adding structure, confidence, and control before handing off to the next. ***Figure 10*** illustrates the layered concept, and ***Figure 11*** maps responsibilities to the WP structure to clarify ownership and conceptual touchpoints.

Figure 10: The Seven Conceptual Layers of the EvoRoads Platform Architecture

At the base, the **Sensor and Acquisition Layer** gathers field data as close to origin as possible. This layer spans on-edge and in-situ sources: embedded sensors and roadside units (RSUs), on-board units (OBUs) reporting signage condition and driver–vehicle interactions, vehicle-borne kits on micro-mobility fleets, and strategic sources such as drone imagery and satellite products. Data ingestion capabilities at the perimeter provides authenticated ingest, buffering, and time–space normalisation, ensuring that raw inputs are geo-referenced, time-stamped, and signed. Typical examples include OBUs used for signage condition (indicatively Tasks 4.2 and 4.3) and behaviour monitoring, and the hazard-aware infrastructure monitoring tool (Task 2.4) used by operators to capture near-field risks.

Above this foundation, the **Edge Processing and Filtering Layer** executes algorithms near the data source to compress, denoise, and pre-classify observations. Compute on micro-vehicles, RSUs, or gateway devices runs lightweight inference to detect salient patterns - e.g., an embedded road-defect detector on a scooter or service vehicle (Tasks 2.2 and 3.5). Crucially, the edge emits compact **detection events** (rather than full raw streams) that travel upstream with latency bounds and resilience to bandwidth variability. Back-pressure and retry policies are explicit, and degraded-communications profiles can be applied without losing the integrity of the event trail.

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The **Integration and Harmonisation Layer** absorbs detection events and bulk feeds, aligning them to shared schemas and regulatory expectations. Data engineering tools such as the **Chimera** harmonisation platform (Task 1.4) and the **Data Acquisition and Processing Platform** (Task 2.1) resolve identifiers, unify coordinate systems, enrich records with metadata, and conform to semantic and regulatory models (e.g., Data Catalogue Application Profile (DCAT-AP) derivatives for cataloguing [3], ETSI C-ITS message alignment where applicable). The result is a privacy-preserving, provenance-rich corpus that is consistent across jurisdictions and ready for modelling.

On this harmonised base, the **Digital Twin and Simulation Layer** maintains living representations of the network and its users. Models of infrastructure condition and road-user behaviour, aerial pavement defect detection and classification, and corridor-level connectivity twins are fused to estimate state, forecast evolution, and explore scenarios (indicatively Tasks 2.2, 2.3, 2.4, 3.1, 3.3). Knowledge frameworks - KPI catalogues, ontologies, rule libraries - are applied to ensure interpretability and to maintain methodological traceability (model versions, assumptions, and calibration sets are recorded alongside outputs).

The **Analytics and Decision Layer** synthesises twin outputs with harmonised streams to produce actionable recommendations and decision support. Representative services include road-risk identification (Task 2.2) and intervention support (highlighting black-spot probabilities and recommending targeted mitigations), infrastructure prognostics (treatment timing and expected risk reduction), and post-repair effectiveness analysis (before/after comparisons with learned weights) (Task 2.3). Where relevant, outputs include classification against **ISAD** readiness levels to inform connectivity-dependent services (indicatively Tasks 3.4, 4.2). Every recommendation carries confidence, uncertainty bounds, and a concise “why” narrative derived from the top contributing indicators, so that operators and planners can act with accountability.

For controlled extroversion, the **Data Space and Interoperability Layer** exposes selected datasets and services via governed connectors. The **Safe Mobility Data Space (SMDS)** enforces data-sharing policies, licences, and consent while enabling publication, discovery, and federation across trusted parties (Task 1.4). This layer separates internal operational detail from external views, ensuring that citizen-facing and research-oriented access remains aggregated, anonymised, and compliant, and that cross-border collaborations can be executed without undermining national scopes.

Finally, the **Interface and Application Layer** delivers the experience to people and systems. The integrated **Dashboard** (Task 1.5) provides role-based access to the nine views defined earlier (e.g., Live Ops, Planning, Maintenance, Micro-mobility, Connectivity, Policy Snapshot, Public Map, Playback, Research & Benchmarking), enforcing country scoping and least-privilege controls. Companion applications operate at the edge and in public spaces: the smartphone nudging application for in-vehicle advisories (Task 3.3); urban safety feedback displays (Tasks 3.3 and 4.2); and plastronics smart beacons (Task 3.2) that broadcast localised warnings. Across all interfaces, accessibility, localisation, and consistent microcopy ensure that content is understandable and action is safe under time pressure.

End-to-end, the design is **event-driven** and **evidence-preserving**. Raw signals are stabilised at ingest; salient observations are elevated as detection events at the edge; harmonisation yields compliant datasets; twins transform data into state and scenario; analytics convert state into recommendations; the data space governs sharing; and interfaces deliver the right level of insight at the right moment. This layered approach supports independent evolution of components, predictable integration, and rigorous verification, while keeping provenance, privacy, and security as first-class properties throughout.

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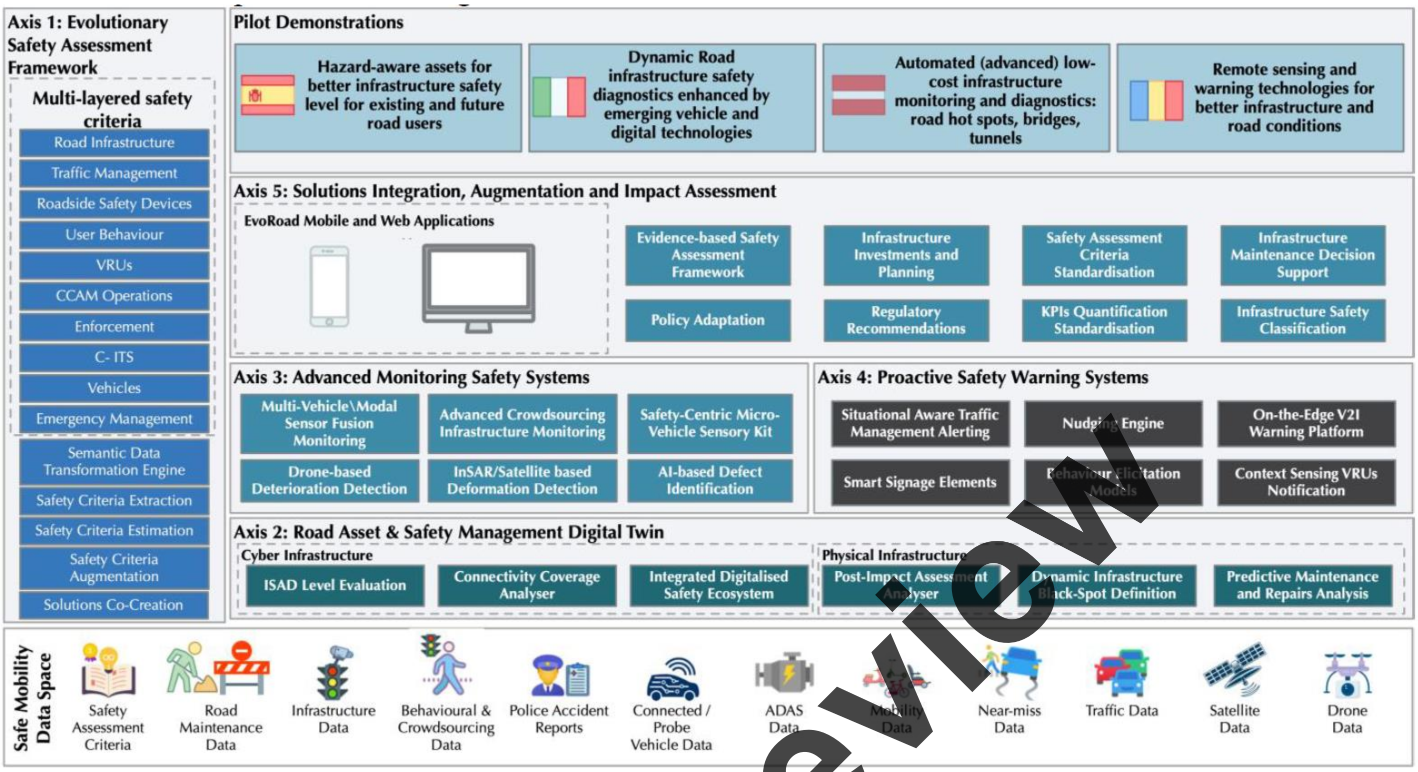

Figure 11: Concept of the EvoRoads Platform Classifying Modules by Value Axis

4.1.3 CORE COMPONENTS

To make this view concrete, the following tables catalogue **all technologies developed** under the auspices of EvoRoads as stand-alone components prior to their integration. For clarity, components are grouped by nature and runtime context: mobile applications, AI-enabled algorithms, non-AI software and services, the Safe Mobility Data Space (SMDS) ecosystem, physical/hardware assets (e.g., roadside units, sensing payloads), and knowledge frameworks (methodologies, KPI catalogues, ontologies). Each row represents one technology with a stable identifier and a succinct purpose statement. Because these technologies ultimately compose the integrated demonstrator, a dedicated column links every item to the EvoRoads demonstrator deliverables in which it is presented in detail as a stand-alone artefact (e.g., component specifications, test results, API descriptions). A second column maps each technology to the Expected Innovations enumerated in the project's Description-of-Action, ensuring traceability from contractual commitments to concrete software and hardware outcomes. Taken together, these tables function as the logical inventory of EvoRoads: a navigable index that underpins module independence during development while preparing a clean handover to integration, testing, and the subsequent architectural views.

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4.1.3.1 CROWD-FACING APPLICATIONS

Table 14: Crowd-facing Web and Mobile Applications of the EvoRoads Platform (apart from the Integrated Platform)

LEAD	IDENTIFIER	DESCRIPTION	TASK(S)	LL(S)	ABBREVIATION	REPORTED	PART OF DOA EXP INN
BEIA	Citizen road defect helpdesk smartphone app	This module enables citizens to report road infrastructure defects directly from their smartphones. It captures GPS coordinates and optional photos at the tap of a button and submits this information through an integrated helpdesk interface, automatically syncing with the municipality's portal via API to generate geo-referenced defect reports.	T2.1, T4.5	Romania	BEIA_21_01	N/A	EI2.1
CEFRIEL	Coney surveying toolkit	An interactive platform that enables the creation and management of digital questionnaires, participatory surveys, and feedback campaigns. Within EvoRoads, it supports behaviour analysis and nudging tasks by collecting structured user input and stakeholder feedback.	T3.3, T4.3	Italy	CEF_33_01	D3.2, D3.3	EI3.4
FRONT	Smartphone nudging application	A mobile app that delivers real-time feedback and safety prompts directly to road users. By linking behavioural data to personalised messages, it encourages safer mobility choices and raises awareness of risks during everyday travel.	T3.3, T4.2	Santa Oliva	FRO_33_01	D3.2, D3.3 (D1.3, D1.4)	EI3.4
UCY	Crowdsourced road defect reporting app [FixCyprus, FixRiga]	A mobile application that enables citizens to submit geolocated images and descriptions of road infrastructure issues such as pavement damage or unsafe crossings. Reports are processed through an integrated web portal where management authorities can review, classify, and assign tasks to maintenance teams, while feedback is sent back to citizens. The system incorporates machine learning to filter duplicates and improve issue categorisation.	T4.4 (?)	Latvia, Romania (?)	UCY_44_01	N/A	EI2.1

4.1.3.2 AI-ENABLED ALGORITHMS

Table 15: Software Components of the EvoRoads Platform (AI-enabled)

LEAD	IDENTIFIER	DESCRIPTION	TASK(S)	LL(S)	ABBREVIATION	REPORTED	PART OF DOA EXP INN
BEIA	Drone-based infrastructure defect detection and annotation module	This module processes high-resolution images captured by drones to detect and annotate road infrastructure defects such as potholes. It employs edge-detection algorithms accelerated with POSIX thread-based parallel processing to extract defect contours efficiently, generating geo-referenced defect labels for subsequent mapping and inspection.	T2.3, T4.5	Romania	BEIA_23_01	D2.1, D2.3 (D1.3, D1.4)	EI2.2
CEA	Automatic infrastructure annotation and refinement module	This asset is an automated annotation engine that generates and refines pseudo-labels for infrastructure elements in images and videos by combining an OpenVOC-based detector with DIOD self-distillation techniques, enriching the Safe Mobility Data Space with high-quality labelled datasets for downstream AI applications.	T1.4	TBD	CEA_14_01	D1.3, D1.4	EI2.2
CEA	Network digital twin for V2X connectivity analysis	Tool that dynamically virtualises selected segments of the V2X network infrastructure and predict future network states to support specific what-if-analysis functionalities, under cyber threats or operational degradations. These specific functionalities encompass anomaly detection and network congestion risks.	T3.1, T4.2, T4.5	Galicia (?)	CEA_31_01	D3.1, D3.3 (D1.3, D1.4)	EI3.5
CEA	Vision-based AI for traffic sign defect monitoring	This asset is a vision-based AI algorithm that analyses road-user camera images to detect, classify, and monitor traffic signs with occlusions or defects, providing timely, actionable insights for predictive maintenance and post-impact repair planning.	T2.2, T2.3	Italy	CEA_22_01	D2.1, D2.3 (D1.3, D1.4)	EI2.2, EI2.3
DOTS	Embedded road defect detection algorithm for micro-vehicles	The onboard defect detection algorithm for micro-vehicles processes live camera and sensor data directly on the scooter to identify road defects such as potholes and automatically generate geo-tagged risk events for real-time reporting and infrastructure monitoring.	T2.2, T3.5, T4.4	Latvia	DOTS_22_01	D3.2, D3.3 (D1.3, D1.4)	EI2.2, EI3.6
DTU	Asset management plan module	The Asset Management Optimisation Module uses multi-objective optimisation techniques to generate cost-effective predictive maintenance schedules, forecast future asset performance and costs, and deliver insights on condition trends, maintenance history, and upcoming needs.	T2.3	Italy	DTU_23_03	D2.2, D2.3 (D1.3, D1.4)	EI2.3

DTU	Infrastructure prognostics analysis module	The Prognostic Analysis Module uses machine learning and real-time condition data to continuously assess and forecast the health of road structures, producing reliable predictions that inform maintenance scheduling, asset segmentation, and repair evaluations.	T2.3	Italy	DTU_23_02	D2.2, D2.3 (D1.3, D1.4)	EI2.3
DTU	Post-repair effectiveness analysis tool	The Post-Repair Effectiveness Analysis Tool evaluates the severity and location of infrastructure damage, predicts the materials, labour, and equipment needed for specific repairs, and generates prioritized, cost-efficient repair strategies that help minimize cost overruns, optimize resource allocation, and improve safety.	T2.3	Italy	DTU_23_04	D2.2, D2.3 (D1.3, D1.4)	EI2.3
DTU	Predictive maintenance solution	This solution continuously monitors the condition of road assets in many types of road structures using various sensors, data sources, and environmental inputs. The system leverages advanced analytics to predict potential failures or degradation before they occur, allowing for timely interventions.	T2.3	Italy	DTU_23_01	D2.2, D2.3 (D1.3, D1.4)	EI2.3
DTU	Road condition assessment system	This solution is a dynamic safety assessment system that generates real-time infrastructure safety KPIs by analysing up-to-date data from road sensors, connected vehicles, and the digital twin, calculates ISAD levels to evaluate the readiness of roads for CCAM services, and supports traffic management decisions and situational risk monitoring for safer and more efficient road operations.	T3.4, T4.3	Italy	DTU_34_01	D3.2, D3.3 (D1.3, D1.4)	EI2.2, EI3.5
EUT	Artificial intelligence algorithms for road hazard detection	A set of AI algorithms for detecting road surface and roadside hazards, including cracks, potholes, degraded signs, and obstacles. Using computer vision and data fusion, it classifies defects and generates alerts in near real time for integration into connected vehicle and infrastructure systems.	T2.4, T4.2	Santa Oliva	EUT_24_01	D2.2, D2.3 (D1.3, D1.4)	EI2.5
INDRA	Probe-Vehicle pavement assessment system	AI models fuse vertical accelerometer + GPS data from connected vehicles to detect cracks, potholes and other surface defects, then map them. Signal quality is ensured with Kalman and high/low-pass filtering to isolate pavement-induced vibration.	T2.2, T4.2	Madrid	INDR_42_02	D2.2, D2.3, D4.1, D4.2 (D1.3, D1.4)	EI2.2

INLE	Road risk identification and intervention support tool	This is an AI-enabled tool that assesses and classifies road segments based on accident risk and its evolution over time, supporting evidence-based decision-making for road safety interventions.	T2.2, T2.3	Italy	INLE_22_01	D2.1, D2.2, D3.2, D3.3 (D1.3, D1.4)	EI2.2, EI3.2
LINKS	Pedestrian crossing behaviour recognition algorithm	Algorithm that takes sensor input from roadside cameras and LiDAR, processes the data in real time, and detects specific crossing-related events such as pedestrian presence, vehicle approach speed, and violations of traffic rules. The outputs are structured signals that trigger corresponding messages on the nudging displays, ensuring that the visual feedback is directly tied to observed behaviours.	T3.3, T4.3	Italy	LIN_43_03	D4.1, D4.2 (D1.2, D1.3, D1.4)	EI3.4
LINKS	Road user behaviour analysis algorithms	AI-driven models that process video and sensor data from vehicle OBUs and roadside cameras to classify atypical behaviours, such as speeding, unsafe lane usage, near-misses, and interactions with vulnerable road users. These algorithms complement crossing-specific recognition by providing broader detection of risk-relevant behaviours, feeding structured events into the Digital Twin and informing both enforcement and nudging strategies.	T4.3	Italy	LIN_43_04	D4.1, D4.2 (D1.2, D1.3, D1.4)	EI3.4
UCY	Aerial pavement defect detection and classification models	Computer vision and machine learning models trained on drone, satellite, and Street View imagery to identify cracks, surface distress, and other infrastructure defects. These algorithms process overhead visual data to enable large-scale monitoring and comparative assessment of pavement conditions.	T2.2, T.2.3, T4.5	Romania	UCY_22_01	D2.1, D2.2, D3.2, D3.3 (D1.3, D1.4)	EI2.2

4.1.3.3 NON-AI SOFTWARE MODULES

Table 16: Software Components of the EvoRoads Platform (Non-AI enabled)

LEAD	IDENTIFIER	DESCRIPTION	TASK(S)	LL(S)	ABBREVIATION	REPORTED	PART OF DOA EXP INN
CTAG	CCAM connectivity performance heatmap generator	A georeferenced mapping tool that measures and visualises connectivity performance on rural and secondary road networks. It aggregates parameters such as latency, bandwidth, and packet loss into a detailed heat map, showing where network quality is sufficient for connected and automated mobility services. The results feed into ISAD level classification, helping determine road readiness for CCAM and C-ITS features.	T4.2	Galicia	CTAG_42_01	D4.1, D4.2 (D1.2, D1.3, D1.4)	EI3.5
CTAG	CCAM service viability assessment module	A evaluation tool that measures connectivity quality and service readiness in rural and secondary roads. Using onboard data collection units, validation tools (e.g. ping, iPerf), and connectivity indicators, it generates georeferenced heatmaps to show where CCAM services can be reliably offered. The assessment classifies road sections by ISA/ISAD levels, identifies blind spots and low-quality zones, and highlights areas requiring improvements for connected mobility deployment.	T4.2	Galicia	CTAG_42_02	D4.1, D4.2 (D1.2, D1.3, D1.4)	EI3.5
CTAG	Infrastructure-to-vehicle risk advertisement system	An alert management module that generates and distributes Infrastructure-to-Vehicle Information (IVI) messages based on detected risks and system logs. The system follows a hybrid communication model: alerts are transmitted via short-range RSUs connected to the ITS Centre and via long-range channels, ensuring that vehicles receive timely warnings even in areas with limited or no network coverage.	T4.2	Galicia	CTAG_42_03	D4.1, D4.2 (D1.2, D1.3, D1.4)	EI3.4
FRONT	InSAR Infrastructure Deformation Detection module	A satellite-based monitoring module that uses Synthetic Aperture Radar interferometry (InSAR) from sources such as Sentinel-1 to detect vertical displacements in road infrastructure. It provides millimetre-level accuracy on surface deformation, highlighting areas potentially affected by rutting, ponding, or subsidence, which can then be prioritised for detailed drone or ground surveys.	T2.2	Romania	FRO_22_01	D2.1, D2.3 (D1.3, D1.4)	EI2.2

IDIADA	On-the-edge processing and real-time C-ITS alerting module	A roadside processing module that receives raw sensor data, detects dangerous situations, and generates standardised Cooperative ITS (C-ITS) messages. These real-time alerts are transmitted to connected vehicles and road users before they reach conflict areas, increasing driver awareness and supporting automated vehicles with machine-readable safety information.	T4.2	Santa Oliva	IDIA_42_01	D2.1, D2.2, D3.2, D3.3 (D1.3, D1.4)	EI3.4, EI4.1
INDRA	GIS-backed road segment classification twin	A GIS-backed digital twin service that classifies road segments by condition and assigns alert codes. It flags sections needing maintenance while preserving full context via segment identifiers and metadata for any downstream component.	T2.2, T4.2	Madrid	INDR_42_01	D2.2, D2.3, D4.1, D4.2 (D1.3, D1.4)	EI3.5
LINKS	Smart mobility digital twin	The Digital Twin serves as a unified access point that integrates real-time and historical road data from multiple pilots, harmonizing diverse sources into a common schema for analysis and safety diagnostics.	T3.1, T4.2, T4.3, T4.4, T4.5	All	LIN_31_01	D3.1, D3.3 (D1.3, D1.4)	EI3.1, EI3.2

4.1.3.4 DATA SPACE ECOSYSTEM

Table 17: Data Space Ecosystem Components of the EvoRoads Platform

LEAD	IDENTIFIER	DESCRIPTION	TASK(S)	LL(S)	ABBREVIATION	REPORTED	PART OF DOA EXP INN
CEFRIEL	Chimera data harmonisation platform	A containerised software environment that preprocesses, cleanses, and harmonises heterogeneous road safety datasets into a common reference model. It supports semantic mappings across diverse formats, ensures interoperability with data spaces, and enables consistent, high-quality data streams for analysis and downstream services.	T1.4, T4.3	Italy	CEF_14_01	D1.3, D1.4 (D2.3)	EI1.4, EI2.1
CEFRIEL	EvoRoads DMP (via Argos)	A structured project-wide DMP created and maintained in the Argos platform. It documents datasets, distributions, responsibilities, and compliance measures, ensuring FAIR-aligned and consistent management of research data across all partners.	T6.4	All	CEF_64_01	D6.2	N/A
CEFRIEL	EvoRoads DCAT-AP Metadata Profile	An adaptation of the European DCAT-AP standard, customised to describe EvoRoads datasets and services. It defines metadata fields and semantics for cataloguing, enabling discoverability and alignment with EU-wide open data practices.	T6.4	All	CEF_64_02	D6.2	N/A
FRONT	EvoRoads CKAN-based Dataset Repository	An open-source repository where project partners upload and describe their datasets using structured metadata. It serves as the central hub for dataset discovery and sharing, with entries subsequently transferred to Argos to populate and update the project's DMP.	T1.4, T6.4	All	FRO_64_01	D1.3, D1.4	EI1.4, EI1.5
FRONT	EvoRoads integrated platform	A nified environment that consolidates inputs from the Safe Mobility Data Space, the Digital Twins, and the full suite of monitoring tools and algorithms. It integrates defect detection outputs, behavioural indicators, connectivity assessments, and safety criteria into harmonised views, which are visualised through interactive dashboards. By combining real-time and historical insights into a single access point, the platform enables stakeholders to explore, compare, and act upon safety-relevant information across diverse contexts.	T1.5	All	FRO_15_01	D1.3, D1.4	EI1.5, EI2.4, EI2.5

FRONT	Safe Mobility Data Space	A federated environment that aggregates and harmonises heterogeneous safety-related datasets from vehicles, infrastructure, sensors, and external sources. It uses standardised connectors and semantic models to ensure interoperability, enabling secure data exchange, integration of static and real-time streams, and provision of structured inputs to EvoRoads applications and services.	T1.4	All	FRO_14_01	D1.3, D1.4	EI1.4, EI1.5
UCY	Data Acquisition and Processing Platform	A backend environment that collects heterogeneous multi-source data streams from vehicles, roadside sensors, drones, satellites, and maintenance records. It performs profiling, cleansing, noise filtering, transformation, and reduction to deliver high-quality, standardised datasets that feed into the Safe Mobility Data Space and downstream AI models.	T2.1	All	UCY_21_01	D1.3, D1.4	EI2.1

4.1.3.5 PHYSICAL AND HARDWARE COMPONENTS

Table 18: Physical and Hardware Components of the EvoRoads Platform

LEAD	IDENTIFIER	DESCRIPTION	TASK(S)	PILOT(S)	ABBREVIATION	REPORTED	PART OF DOA EXP INN
CTAG	OBU-equipped demonstration vehicle	A dedicated vehicle equipped with three on-board units (OBUs), each with its own antenna and Human-Machine Interface (HMI), as well as logging systems for data collection. This equipment supports laboratory dry runs, controlled track validation at CTAG facilities, and full-scale real-road testing on the N-550, enabling demonstration of connected mobility services under diverse conditions.	T4.2	Galicia	CTAG_42_04	D4.1, D4.2 (D1.2, D1.3, D1.4)	EI4.1
DOTS	Mountable sensory kit for micro-vehicles	A compact, rugged device mounted on e-scooters, combining a multi-mode 3D camera, an onboard computer (Raspberry Pi), GPS, and an accelerometer to capture detailed road condition and ride dynamics data in real time.	T3.5, T4.4	Latvia	DOTS_35_01	D3.2, D3.3 (D1.3, D1.4)	EI3.6
EUT	Hazard-aware infrastructure monitoring tool	A monitoring solution that integrates roadside sensing and vehicle-based data to identify hazards such as debris, ice, puddles, and other unexpected conditions. It applies anomaly detection to multi-sensor inputs, enabling continuous tracking of road environments and the isolation of areas affected by safety-relevant events.	T2.4, T4.2	Santa Oliva	EUT_24_02	D2.2, D2.3 (D1.3, D1.4)	EI2.2
EUT	Plastronics smart beacon system	The Plastronics smart beacon system developed by Eurecat is a low-cost, durable road safety solution that embeds electronics into retroreflectors using overmolding techniques to achieve long service life in harsh outdoor conditions. Installed along secondary and rural roads, these beacons display dynamic light patterns and colours linked to real-time infrastructure and hazard data, providing intuitive warnings that nudge drivers and vulnerable users towards safer behaviour.	T3.2, T3.3	Santa Oliva	EUT_32_01	D3.1, D3.3 (D1.3, D1.4)	EI3.3
LINKS	LiDAR and camera-enhanced Road Side Units for	This module combines LiDAR and high-resolution cameras to detect illegal parking, improper pedestrian crossings, vulnerable road user behaviours, and mobility obstructions for emergency vehicles, all in real time. It processes events locally and supports nudging strategies by feeding violation	T4.3	Italy	LIN_43_01	D4.1, D4.2 (D1.2, D1.3, D1.4)	EI4.1

	behaviour surveillance	data to information displays, enhancing situational awareness and compliance.					
LINKS	On-Board Units for signage condition and behaviour monitoring	These modules are installed on vehicles to capture real-time data on road signage conditions, surface maintenance needs, and atypical driving behaviours. They leverage embedded cameras and positioning systems to detect anomalies while in motion, transmitting processed insights to back-end platforms and the Digital Twin to support timely maintenance, safety interventions, and compliance monitoring.	T4.3	Italy	LIN_43_02	D4.1, D4.2 (D1.2, D1.3, D1.4)	EI4.1
LINKS	Urban safety feedback display	An interactive roadside unit, fed by data from roadside units, that provides real-time visual feedback to drivers and pedestrians based on detected behaviours at crossings.	T3.3, T4.3	Italy	LIN_33_01	D4.1, D4.2 (D1.2, D1.3, D1.4, D3.2, D3.3)	EI3.4
VTI	Micromobility safety markings	Specially designed road surface patterns that guide cyclists and e-scooter riders toward safer speeds and trajectories. By subtly altering lane perception and rider behaviour, they serve as a low-cost intervention to reduce risky manoeuvres and improve crossing safety.	T3.3, T4.4	Latvia (?)	VTI_33_01	D3.2, D3.3 (D1.3, D1.4)	EI3.4

4.1.3.6 KNOWLEDGE FRAMEWORKS

Table 19: Knowledge Frameworks of the EvoRoads Platform

LEAD	IDENTIFIER	DESCRIPTION	TASK(S)	LL(S)	ABBREVIATION	REPORTED	PART OF DOA EXP INN
LINKS	Multi-layered safety assessment criteria catalogue	An integrated reference model that consolidates state-of-the-art safety practices into a multi-layered catalogue of criteria and indicators. It defines primary and composite safety dimensions, associated metadata, and interoperability requirements, enabling consistent evaluation and benchmarking of infrastructure, user behaviour, vehicles, and connected systems within the safe system approach.	T1.1	All	LIN_11_01	D1.1, D1.2	EI1.1, EI1.2
VTI	User behaviour monitoring protocols	Standardised methodologies that combine roadside sensors, vehicle OBUs, micro-vehicle kits, on-site observers, and surveys to systematically capture how road users behave in different contexts. The resulting datasets translate observed interactions into structured indicators, allowing consistent measurement and comparison of behavioural patterns across mobility environments.	T3.3	All	VTI_33_02	D3.2, D3.3 (D1.3, D1.4)	EI3.4
VTI	User behaviour taxonomy	A structured classification that categorises mobility behaviours of different road users across contexts, providing a reference framework for analysing and comparing behavioural patterns in EvoRoads.	T3.3	All	VTI_33_03	D3.2, D3.3 (D1.3, D1.4)	EI3.4
VTI	Dynamic safety criteria and KPI framework	A methodological suite that quantifies safety criteria and KPIs using statistical and AI-based models, enabling both real-time updates and post-processed evaluations. It integrates traditional crash and road attribute data with new behavioural and sensor-based inputs, ensuring that safety performance can be measured, compared, and adapted across diverse mobility contexts.	T1.3	All	VTI_13_01	D1.3, D1.4	EI1.3

4.1.4 MAPPING PLATFORM COMPONENTS TO THE LOGICAL ARCHITECTURE

The catalogue of platform components listed in this section is intentionally interpreted through the logical structure introduced in Subsection 4.1.2. Rather than constituting an independent inventory, each component contributes to one or more of the logical layers previously defined, thereby operationalising the abstract architecture. For example, components classified as AI algorithms - such as defect detection, behaviour analysis or risk estimation modules - primarily populate the **Analytics and Decision Layer**, where harmonised data and digital twin outputs are transformed into indicators, recommendations and decision-support artefacts. These components are not isolated analytics tools, but are designed to consume standardised inputs and to produce outputs that can be traced, explained and reused downstream.

Hardware and sensing assets, including on-board units, roadside equipment, drones and smart beacons, contribute mainly to the **Sensor and Acquisition Layer** and, where applicable, to the **Edge Processing and Filtering Layer**. Their architectural role is not limited to data capture, but extends to early-stage processing, privacy protection and event extraction, ensuring that only meaningful and compliant observations propagate further into the platform. Similarly, components related to digital twins, simulation and modelling anchor the **Digital Twin and Simulation Layer**, providing structured representations of infrastructure, road users and connectivity contexts that are required for consistent analytics.

Finally, components associated with cataloguing, data governance and interoperability operationalise the **Data Space and Interoperability Layer**, enabling controlled exposure and federation without interfering with internal processing. By mapping concrete components to these logical responsibilities, the platform demonstrates that the layered architecture is not conceptual but actively instantiated through the selected assets.

4.1.5 INTERACTION PATTERNS BETWEEN LOGICAL COMPONENTS

The EvoRoads Integrated Platform is characterised by a set of well-defined interaction patterns that govern how logical components collaborate to support safety-oriented decision-making. These patterns are designed to accommodate heterogeneity across data sources, analytical processes and user roles, while preserving traceability and architectural coherence. Rather than relying on tight coupling between components, the platform adopts interaction mechanisms that favour loose coupling, explicit contracts and clear separation of responsibilities.

A predominant pattern is **event-driven interaction**, particularly between the sensing, ingestion and analytics-related components. Observations generated at the perimeter of the system are propagated as structured events, allowing downstream components to react asynchronously. This pattern supports scalability and resilience, as components can process events independently and at different rates, and it aligns with the need to handle both high-frequency sensor data and sporadic reports from human-in-the-loop applications. Event-driven interactions are complemented **by pipeline-based processing**, where sequences of transformations are applied in a controlled manner, ensuring that data quality, privacy and provenance constraints are enforced before analytics are executed.

Between analytical components, digital twin services and decision-support functions, interaction follows a **service-oriented pattern**. Logical services expose well-defined interfaces through which data products, indicators and contextual information can be requested and consumed. This enables analytical components to remain agnostic of the internal structure of the digital twin, while still benefiting from its contextualisation capabilities. Importantly, these interactions are mediated through abstract data models rather than direct data access, preserving modularity.

Interactions with user-facing components follow a **request–response pattern**, where dashboards and applications query the platform for curated information rather than raw data. This ensures that users interact with validated and interpretable outputs, while shielding them from internal complexity. Finally, interactions with external systems adopt a **federated exchange pattern**, in which data are shared selectively and under explicit conditions, without disrupting internal workflows. Collectively, these interaction patterns enable the EvoRoads platform to operate as a coherent yet flexible system, supporting integration across components while remaining adaptable to evolving requirements and contexts.

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4.1.6 LOGICAL ALIGNMENT OF PLATFORM COMPONENTS ALONG THE SAFETY DECISION VALUE CHAIN

While the preceding subsections describe the structural decomposition of the EvoRoads Integrated Platform, it is also important to clarify how the platform's concrete technological assets jointly support safety-oriented decision-making. EvoRoads is not conceived as a collection of standalone tools, but as an integrated system in which heterogeneous components contribute evidence at different stages of an infrastructure safety decision cycle. To make this relationship explicit, the platform assets listed in the present section 4.1.3 are aligned in *Table 20* below along a simplified safety decision value chain, spanning Detection, Diagnosis, Prioritisation, Intervention Planning, and Impact Assessment. This alignment clarifies how individual technologies contribute to distinct decision stages, and how apparent overlaps reflect complementary evidence generation rather than functional redundancy.

Table 20: Alignment of EvoRoads platform assets along the safety decision value chain

Safety decision stage	EvoRoads platform assets
Detection	Citizen road defect helpdesk smartphone app; Crowdsourced road defect reporting app [FixCyprus, FixRiga]; Drone-based infrastructure defect detection and annotation module; Aerial pavement defect detection and classification models; Embedded road defect detection algorithm for micro-vehicles; Mountable sensory kit for micro-vehicles; OBU-equipped demonstration vehicle; On-Board Units for signage condition and behaviour monitoring; LiDAR and camera-enhanced Road Side Units for behaviour surveillance; Pedestrian crossing behaviour recognition algorithm
Diagnosis	Vision-based AI for traffic sign defect monitoring; Road user behaviour analysis algorithms; Probe-Vehicle pavement assessment system; Automatic infrastructure annotation and refinement module; Smart mobility digital twin; Network digital twin for V2X connectivity analysis; CCAM connectivity performance heatmap generator; User behaviour taxonomy; User behaviour monitoring protocols
Prioritisation	Road risk identification and intervention support tool; Multi-layered safety assessment criteria catalogue; Dynamic safety criteria and KPI framework; CCAM service viability assessment module
Intervention Planning	Asset management plan module; Infrastructure-to-vehicle risk advertisement system; Micromobility safety markings; Coney surveying toolkit
Impact Assessment	Urban safety feedback display; Smart mobility digital twin; Dynamic safety criteria and KPI framework; Road risk identification and intervention support tool
Cross-cutting / Enabling (all stages)	Chimera data harmonisation platform; Data Acquisition and Processing Platform; EvoRoads DCAT-AP Metadata Profile; EvoRoads DMP (via Argos)

4.1.7 FUNCTIONAL CAPABILITIES AND PLATFORM REQUIREMENTS

This subsection consolidates the functional capabilities that the EvoRoads Integrated Platform is required to provide in order to support infrastructure-driven road safety management across diverse operational contexts. The requirements listed in *Table 21* below are expressed in a technology-agnostic manner and capture *what the platform must do*, independently of *how* individual components realise these capabilities. They synthesise user needs analysed earlier in the present deliverable and provide a common reference point against which pilot deployments and validation activities can be interpreted.

Table 21: Functional requirements of the EvoRoads Integrated Platform

ID	Functional Requirement	Category	Priority
FR-01	The platform **MUST** ingest safety-relevant data from heterogeneous sources, including vehicle-based, roadside, aerial and citizen-provided inputs.	Ingestion	MUST

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FR-02	The platform **MUST** support both streaming and batch data ingestion with consistent handling of time and spatial references.	Ingestion	MUST
FR-03	The platform **MUST** harmonise heterogeneous datasets into a common reference model suitable for cross-pilot analysis.	Ingestion	MUST
FR-04	The platform **SHOULD** support data quality checks and basic validation at ingestion time to detect incomplete or inconsistent records.	Ingestion	SHOULD
FR-05	The platform **MUST** transform raw observations into structured safety events suitable for downstream analysis.	Analysis	MUST
FR-06	The platform **MUST** support analytical processing to derive safety indicators, risk scores and readiness levels from ingested data.	Analysis	MUST
FR-07	The platform **SHOULD** support aggregation and clustering of events to identify recurring safety issues at segment or corridor level.	Analysis	SHOULD
FR-08	The platform **COULD** support scenario or “what-if” analysis based on historical or simulated data.	Analysis	COULD
FR-09	The platform **MUST** support prioritisation of safety issues based on severity, exposure and contextual criteria.	Decision support	MUST
FR-10	The platform **MUST** present prioritised safety information through role-appropriate dashboard views.	Decision support	MUST
FR-11	The platform **SHOULD** support export of prioritised outputs to external planning or maintenance systems.	Decision support	SHOULD
FR-12	The platform **MUST** support tracking of safety indicators over time to enable before/after comparison of interventions.	Decision support	MUST
FR-13	The platform **MUST** support real-time or near-real-time alert generation for safety-critical events where applicable.	Decision support	MUST
FR-14	The platform **SHOULD** support contextual user feedback and nudging mechanisms linked to detected safety events.	Decision support	SHOULD
FR-15	The platform MUST provide controlled access to datasets and derived products for different user roles and stakeholders.	Exposure	MUST
FR-16	The platform MUST support dataset discovery through metadata-driven cataloguing.	Exposure	MUST
FR-17	The platform **SHOULD** support versioning of datasets and definitions to enable reproducibility and auditability.	Exposure	SHOULD
FR-18		Exposure	MUST

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	The platform **MUST** support privacy-preserving publication of aggregated or anonymised outputs for public access.		
FR-19	The platform **COULD** support federation with external data spaces or research infrastructures under defined governance conditions.	Exposure	COULD
FR-20	The platform **MUST** support role-based visualisation views aligned with operational, planning, policy and research personas.	Decision support	MUST

4.1.8 VALIDATION COVERAGE ACROSS PILOTS AND OPERATIONAL CONTEXTS

The component table also evidences that EvoRoads Integrated Platform is validated across a **diverse and balanced set of pilot sites**, rather than being concentrated in a single context. Components are distributed across pilots with different geographic, organisational and infrastructural characteristics, ensuring that multiple aspects of the architecture are exercised in practice. Some pilots emphasise dense urban environments with high data volumes and complex interactions, while others focus on peri-urban or rural road networks where sensing is sparser and operational constraints differ.

This distribution is deliberate. Crowd-facing applications and user interfaces are validated in contexts where citizen engagement and operational feedback are critical, while infrastructure monitoring and analytics components are tested in pilots that reflect long stretches of secondary or rural roads. As a result, the platform is assessed against a broad spectrum of real-world conditions, reducing the risk of architectural bias towards a specific environment or use case.

Importantly, the pilot distribution ensures that validation is **systemic rather than anecdotal**. Different pilots exercise different combinations of components and logical layers, collectively covering the full platform scope. This approach allows EvoRoads to demonstrate that the integrated platform is adaptable and context-aware, while still preserving a common architectural backbone.

Table 22 summarises how the functional requirements defined in the preceding subsection are exercised across the pilot sites, illustrating the extent to which core platform capabilities are validated through diverse operational contexts rather than through isolated demonstrations.

Table 22: Traceability of functional requirements to pilot validation

Requirement ID	Capability Exercised	Pilots exercising it
FR-01–FR-03	Multi-source data ingestion and harmonisation	All pilots
FR-05–FR-07	Event detection and analytical processing	Madrid, Riga, Santa Oliva, Turin
FR-06, FR-09	Risk scoring and prioritisation	Madrid, Alba Iulia, Turin
FR-08	Scenario and readiness analysis	Galicia, Turin
FR-10, FR-12	Decision support and impact assessment	All pilots
FR-13	Real-time alerting	Santa Oliva, Turin
FR-14	Behavioural nudging and feedback	Riga, Santa Oliva, Turin
FR-15–FR-18	Controlled access, cataloguing and exposure	All pilots
FR-19	Interoperability and federation readiness	Galicia, Turin

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FR-20	Role-based visualisation views	All pilots

4.1.9 INTEGRATION RESPONSIBILITY, OWNERSHIP AND COMPOSABILITY

A further aspect of coherence emerges from the way components are integrated across tasks and partners. The "leading developer" attribute of each component reflects clear ownership and expertise, while Task 1.5 provides the architectural and integration framework that allows these components to operate together. Importantly, integration does not imply subsuming or centralising ownership. Each component remains under the responsibility of its developing partner and task, with well-defined interfaces governing how it interacts with the rest of the platform.

This approach reinforces architectural discipline by ensuring that responsibilities remain explicit and manageable. Task 1.5 focuses on alignment, interaction patterns and consistency, rather than on re-implementing or duplicating functionality. The component table therefore becomes evidence of coordinated integration rather than of fragmentation.

At the same time, it is important to clarify what the component list does *not* imply. Not all components are expected to be active in all deployments or pilots. The integrated platform is **composable**, allowing subsets of components to be deployed according to local needs and constraints. Components are designed to evolve independently, provided that their interfaces and contracts are respected. This avoids unnecessary coupling and ensures that the platform can adapt over time without architectural rework.

4.1.10 CONCLUSION OF THE LOGICAL VIEW AND TRANSITION TO SUBSEQUENT ARCHITECTURAL PERSPECTIVES

This concludes the Logical View of the EvoRoads Integrated Platform Architecture. The Logical View establishes a coherent, technology-agnostic understanding of the platform by identifying its core functional components, their responsibilities and the principal interaction patterns that bind them into an integrated system. It demonstrates how heterogeneous technologies and services contribute collectively to safety-oriented decision-making, while maintaining clear boundaries between internal platform functions and external systems. At the same time, the Logical View deliberately abstracts away implementation details, runtime behaviour and deployment constraints, in order to preserve architectural clarity and avoid premature design commitments.

The subsequent architectural views build upon this foundation. The Process View will describe how logical components collaborate at runtime, including control flows, event handling and synchronisation aspects. The Development View will focus on the organisation of software artefacts, codebases and development responsibilities across partners. Finally, the Physical (Deployment) View will address how the platform is instantiated across infrastructure, cloud and edge environments, translating logical design into concrete operational configurations. Together, these views provide a complete and consistent architectural description of the EvoRoads platform.

4.2 OPERATIONAL PERSPECTIVE: SAFETY-DRIVEN USE OF THE EVOROADS PLATFORM

While the 4+1 architectural view model provides a rigorous framework for describing system structure, behaviour and deployment, it does not explicitly capture how an integrated platform is *used operationally* to achieve domain-level objectives. For EvoRoads, this dimension is essential, as the platform is ultimately justified by its ability to support safety-driven decisions and infrastructure interventions rather than by the deployment of individual technologies. Section 4.2 therefore introduces an **operational perspective** that complements the formal 4+1 views by making explicit the relationship between platform capabilities, stakeholder actions and safety outcomes. This perspective is not presented as an additional architectural view in the strict sense, but as a bridging narrative that connects the Logical View with the runtime behaviour described in the Process View. It frames the EvoRoads platform as a decision-support system organised along a safety value chain - spanning **Detection, Diagnosis, Prioritisation, Intervention Planning and Impact Assessment** - and highlights how different components contribute evidence at each stage. By articulating this end-to-end operational logic, the section addresses the need to demonstrate coherence, purpose and value realisation, ensuring that the architecture is understood not only as a technical construct, but as an enabler of systematic and accountable improvements in road infrastructure safety.

4.2.1 PILOT SAFETY OBJECTIVES AND INTERVENTION INTENT

The EvoRoads pilot sites are operational road authorities and infrastructure managers that participate in the project with **explicit safety objectives grounded in infrastructure management practice**. Each pilot aligns with a specific subset of safety criteria defined in the EvoRoads baseline and augmented safety criteria catalogue (Deliverables D1.1 and D1.2), reflecting differences in network structure, scale, governance and available intervention levers. Rather than testing technologies in isolation, the pilots apply the EvoRoads platform to support **detection, diagnosis, prioritisation, intervention planning and impact assessment** for concrete safety-related infrastructure decisions.

The **Madrid pilot** addresses safety through a **network-scale focus on pavement degradation and road surface condition** across a large metropolitan road network. Its primary safety concerns fall within the *Road Infrastructure* category of the EvoRoads safety criteria, with particular emphasis on pavement condition, surface degradation patterns and consistency of infrastructure quality across the network. The pilot's intent is to improve the identification and prioritisation of maintenance interventions, supporting resurfacing planning and evidence-based allocation of maintenance budgets. Decision-making is shaped by the size and heterogeneity of the network, as well as by governance and procurement constraints that require robust, comparable indicators to justify interventions at scale.

The **Galicia pilot** operates in a predominantly rural and inter-urban context, where safety is closely linked to **network connectivity, continuity and serviceability**. Its focus extends beyond isolated infrastructure defects to encompass how degradation, environmental exposure and limited redundancy affect the safe functioning of an extensive secondary road network. Relevant safety criteria span *Road Infrastructure* and *Road Network Connectivity*, including continuity of service, availability of safe routes and the identification of connectivity-critical segments. The pilot's intervention intent centres on prioritising maintenance and upgrades that preserve network connectivity and reduce safety risks associated with disconnection or progressive degradation under constraints of wide geographic coverage and limited resources.

The **Riga pilot** focuses on **micro-mobility and cycling infrastructure**, with safety objectives aligned primarily with the *Vulnerable Road Users*, *Road Infrastructure* and *Roadside Safety Devices* categories of the EvoRoads safety criteria. The pilot is concerned with surface condition, obstacle presence, infrastructure legibility and the interaction between emerging mobility modes and existing road assets. Intervention levers include targeted maintenance, adjustment of markings and signage, and prioritisation of upgrades on corridors with higher exposure of micro-mobility users. Seasonal conditions and budgetary limitations influence decision-making, increasing the importance of early detection and prioritisation.

The **Alba Iulia pilot** represents a municipal-scale context where **resource constraints and selective intervention** dominate safety management. Its safety objectives are aligned with *Road Infrastructure* and *Roadside Safety Devices*, with particular attention to pavement defects, signage adequacy and localised hazards that affect overall network safety. The pilot's intent is to support prioritised maintenance and low-cost interventions through consolidated and defensible safety evidence. Constraints related to limited budgets and staffing reinforce the need for clear prioritisation criteria and measurable impact assessment, as articulated in D1.2.

The **Santa Oliva pilot** addresses safety on secondary and peri-urban roads, focusing on **roadside safety devices, infrastructure readiness and environmental risk factors**. Its safety criteria of interest fall within the *Road Infrastructure* and *Roadside Safety Devices* categories, including visibility, warning effectiveness and infrastructure condition under adverse conditions. Intervention intent includes targeted maintenance, selective deployment of safety-related roadside

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equipment and prioritisation of improvements on risk-prone segments. The pilot operates under constraints typical of low-density networks, favouring interventions that maximise safety impact without extensive physical redesign.

The **Turin pilot** concentrates on **dynamic safety diagnosis linked to road-user behaviour and infrastructure readiness**, particularly in relation to connected and automated mobility contexts. Its objectives align with the *User Behaviour*, *Traffic Management* and *C-ITS / CCAM Operations* categories of the EvoRoads safety criteria. The pilot seeks to understand behavioural risk patterns and the alignment between infrastructure condition, digital readiness and service provision. Intervention intent focuses on informed infrastructure adaptation and prioritisation, within a complex urban governance environment where safety measures must align with broader mobility strategies.

Across all six pilots, a consistent operational pattern emerges: **EvoRoads is used to support infrastructure safety decisions grounded in recognised safety criteria**, adapted to local contexts and constraints. The pilots differ in scale, focus and intervention levers, but collectively validate the platform as a decision-support system that links infrastructure condition, network properties and safety outcomes. This shared intent underpins the operational perspective developed in the remainder of Section 4.2 and provides a clear foundation for mapping platform components to safety-driven workflows.

4.2.2 A COMMON SAFETY DECISION WORKFLOW ACROSS HETEROGENEOUS PILOT CONTEXTS

This subsection articulates a shared operational logic that underpins the use of the EvoRoads platform across all pilot sites, while explicitly acknowledging contextual diversity. Although pilots differ substantially in scale, environment, governance arrangements and intervention capabilities, they are unified by a **common safety decision workflow** that structures how infrastructure-related safety problems are identified, analysed, acted upon and evaluated. Making this workflow explicit is essential to demonstrate that EvoRoads is not a collection of site-specific solutions, but a coherent decision-support platform that can be adapted to multiple operational contexts.

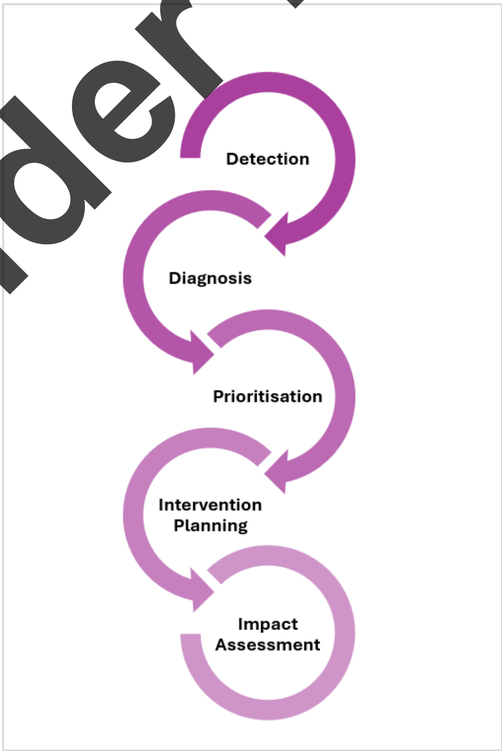

Figure 12: The five stages of the common safety decision workflow across EvoRoads pilot sites

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The workflow, illustrated in ***Figure 12*** below, is expressed as a five-stage decision chain: **Detection → Diagnosis → Prioritisation → Intervention Planning → Impact Assessment**. Each stage represents a logical step in infrastructure safety management, and all pilots engage with this chain, albeit with different emphases, data sources and intervention levers.

The **Detection** stage concerns the identification of safety-relevant signals related to infrastructure condition, network performance or emerging risk patterns. Across all pilots, detection serves as the entry point to the decision process, although the nature of detected signals varies considerably. Some pilots rely primarily on systematic sensing and automated observation, while others emphasise periodic surveys or aggregated reports. What unifies these approaches is not the technology employed, but the intent: to surface indications that infrastructure safety may be compromised or deteriorating. In network-scale contexts, detection focuses on identifying patterns of degradation, loss of serviceability or discontinuities across large road networks. In more localised contexts, detection may concentrate on specific assets or locations. In all cases, detection provides structured inputs for subsequent analysis rather than directly triggering intervention.

Following detection, the **Diagnosis** stage interprets observed signals in relation to safety criteria and contextual information. Diagnosis transforms raw or pre-processed observations into an understanding of why a safety issue exists and how it relates to the wider system. This stage is critical for avoiding reactive or anecdotal decision-making. Across pilots, diagnosis involves combining detected signals with contextual data such as road typology, environmental conditions, historical trends or network role. While some pilots emphasise condition-based diagnosis, focusing on the severity and progression of degradation, others incorporate additional operational dimensions depending on their scope. Importantly, diagnosis establishes traceability between observations and the safety criteria defined in the EvoRoads framework, ensuring that subsequent decisions are grounded in recognised and comparable dimensions of safety.

The **Prioritisation** stage reflects a common constraint faced by all pilots: limited resources require that safety issues be addressed selectively rather than exhaustively. Prioritisation translates diagnosis into an ordered set of actionable needs, enabling decision-makers to allocate effort and funding effectively. Across pilots, prioritisation logic varies according to network scale, governance arrangements and intervention cost, but the underlying principle is shared. Issues are ranked based on their relevance to safety objectives, severity, spatial extent and, where applicable, network criticality. For pilots managing extensive networks, prioritisation tends to emphasise aggregation and comparability, supporting budget allocation across competing needs. For pilots with smaller scopes, prioritisation may be more selective, focusing on identifying a limited number of high-impact interventions. Despite these differences, all pilots employ prioritisation as a formal step separating analysis from action.

The **Intervention Planning** stage concerns the translation of prioritised safety needs into concrete actions that can be implemented within the pilot's operational remit. Interventions may range from maintenance activities and infrastructure upgrades to the deployment of roadside equipment or adjustments to network configuration. What distinguishes this stage from earlier ones is its explicit linkage to real-world constraints, including budget cycles, procurement processes, regulatory frameworks and physical feasibility. While the types of interventions available differ across pilots, the decision logic remains consistent: interventions are planned based on prioritised needs, with an emphasis on proportionality and expected safety benefit. This stage represents the point at which the EvoRoads platform interfaces most directly with existing asset management and planning processes, reinforcing its role as a decision-support system rather than an operational controller.

The final stage, **Impact Assessment**, closes the decision loop by evaluating the effects of implemented interventions on safety-relevant indicators. This stage is essential for accountability, learning and continuous improvement. Across pilots, impact assessment is recognised as necessary but often challenging, due to data availability, time horizons or institutional practices. EvoRoads provides a structured context in which post-intervention conditions can be compared against pre-intervention baselines using consistent criteria. Some pilots place strong emphasis on this stage, particularly where governance frameworks require evidence of effectiveness, while others approach it more selectively. Nevertheless, all

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pilots acknowledge the importance of assessing whether interventions achieve their intended safety outcomes, reinforcing the cyclical nature of the decision workflow.

While all pilots adhere to this shared decision chain, they diverge in emphasis and operational depth at different stages. Network-scale pilots devote substantial attention to detection and prioritisation, reflecting the need to manage large volumes of infrastructure data and to allocate resources efficiently across extensive networks. In these contexts, impact assessment may be more aggregate and longer-term. By contrast, pilots with more localised scopes may place greater emphasis on diagnosis and impact assessment, enabling fine-grained evaluation of specific interventions. Urban pilots operating in complex governance environments may also invest more heavily in diagnosis to justify interventions within multi-actor decision processes.

Data sources and analytical depth also vary across pilots, influencing how each stage is operationalised. Some pilots rely predominantly on infrastructure-focused data, while others integrate additional contextual information. These differences do not undermine coherence; rather, they demonstrate the adaptability of the shared workflow. The EvoRoads platform is designed to support this variability by allowing different components and data sources to be combined according to local needs, while preserving the logical sequence of decision-making stages.

Taken together, the safety decision workflows observed across the EvoRoads pilot sites reveal a consistent operational structure underlying diverse local practices. Although pilots differ in context, scale and available intervention mechanisms, they all engage with a comparable sequence of activities that moves from the identification of safety-relevant signals to the evaluation of intervention outcomes. Variations arise primarily in the relative emphasis placed on individual stages of the workflow, reflecting differences in network extent, governance arrangements and data availability, rather than fundamentally different approaches to safety management. This common structure provides a stable foundation for the integrated platform, enabling it to support heterogeneous pilot needs while remaining architecturally coherent.

4.2.3 PILOT-SPECIFIC COMPOSITION OF PLATFORM COMPONENTS ALONG THE SAFETY WORKFLOW

The purpose of this subsection is to make explicit how the EvoRoads Integrated Platform is instantiated in each pilot as a **purposeful composition of components**, aligned with concrete safety objectives and operational decision processes. Rather than presenting technologies as standalone artefacts, the intention here is to show how selected components are combined into an end-to-end workflow that transforms pilot inputs into safety-relevant decisions and implementable infrastructure actions. The mapping follows the shared decision chain introduced earlier (**Detection** → **Diagnosis** → **Prioritisation** → **Intervention Planning** → **Impact Assessment**) but emphasises that pilots differ in data sources, emphasis and intervention levers. The core explanatory pattern is therefore **inputs** → **platform services** → **decisions** → **interventions**, making it clear where each component contributes and why it is included. Importantly, this mapping also clarifies the architectural stance towards overlap: components are selected to be **complementary** (each providing a distinct capability), to enable **triangulation** (multi-source or multi-temporal reinforcement of confidence), and to avoid redundancy (no two components are intended to perform the same operational role without added value). In doing so, the subsection shows how the platform is assembled intentionally around pilot goals and constraints, and how each pilot can act as a credible demonstration of evidence-based infrastructure safety management.

4.2.3.1 MADRID PILOT: SMART ROAD MONITORING FOR PAVEMENT DEGRADATION

The Madrid pilot is designed to demonstrate a digital solution for **rapid and cost-effective pavement assessment** in **suburban and rural environments**, addressing a recognised gap in secondary and local road monitoring where investment and inspection practices are often limited. The operational objective is to produce a comprehensive overview of pavement conditions that supports early identification of deterioration and enables maintenance planners to prioritise where more detailed inspections are warranted. In the EvoRoads decision chain, Madrid's centre of gravity lies in converting high-coverage, vehicle-based sensing into consistent road-segment condition indicators that can withstand operational scrutiny and feed maintenance workflows. The pilot therefore focuses on the *Road Infrastructure* safety criteria

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category, with emphasis on pavement condition, deterioration patterns and network consistency, while also using contextual information (e.g. road geometry) to improve interpretability and targeting.

Inputs → platform services. The principal input stream is vehicle-based sensing: **vertical accelerometry and GPS** collected from (i) public transport fleets (historical/offline datasets initially sourced from Alicante for early functional testing of the workflow) and (ii) connected vehicles operating in Madrid, where data are transmitted through **5G-enabled V2X communications**. The pilot's workflow is explicitly designed to cope with heterogeneity: different vehicles, variable speeds, and diverse road conditions (including the Alcobendas corridor and the Colmenarejo rural road). This is reflected in the selection of components, where one component specialises in extracting reliable pavement signals and another specialises in structuring them into a network-operational representation.

Two core platform components are "married" to implement the workflow:

- **Probe-Vehicle pavement assessment system.** This component performs the observation-level analytics required for detection and initial characterisation. AI models fuse vertical accelerometer and GPS data to detect cracks, potholes and other surface defects and map them to location. Signal conditioning is a central design element: Kalman filtering and high/low-pass filtering isolate pavement-induced vibration from driving dynamics, enabling more reliable interpretation under real traffic conditions. This component is selected because it provides **coverage and sensitivity** at low marginal cost, allowing the pilot to detect early deterioration trends without relying on manual inspection as the primary mechanism.
- **GIS-backed road segment classification twin.** This component provides the network-level interpretation layer. It classifies road segments by condition and assigns alert codes, maintaining full context via segment identifiers and metadata so that outputs remain traceable and consumable by downstream tools. It is selected because it makes the output operationally actionable: maintenance planning rarely acts on individual vibration points; it acts on **segments**, ranked and contextualised, with clear codes that can be communicated and audited.

These two components are not overlapping; they are complementary by design. The probe-vehicle system generates evidence at fine granularity, while the GIS-backed twin converts that evidence into a structured representation aligned with how road authorities plan maintenance.

Decision-chain mapping (Madrid): *Table 23* below summarises how the selected components support the five decision stages while avoiding redundancy.

Table 23: Decision-chain mapping to Technologies for Madrid

Decision stage	Madrid instantiation (inputs / services / outputs)
Detection	Vehicle accelerometer + GPS streams; probe-vehicle analytics detect anomalies and compute roughness proxies (e.g. Z-axis energy peaks, RMS/IRI proxy indicators).
Diagnosis	GIS-backed twin contextualises detections by segment and corridor, linking anomalies to road links and associated metadata; optional enrichment with geometry/attributes to support interpretation.
Prioritisation	Twin outputs support ranking of segments by condition score and alert codes; multi-source aggregation (offline fleet history + live connected-vehicle feeds) supports stable prioritisation.
Intervention planning	Maintenance planners use ranked segment lists and map overlays to schedule inspections, plan resurfacing and generate maintenance tickets; interventions remain within existing authority processes.

Impact assessment	Post-intervention monitoring reuses the same sensing + twin pipeline to compare treated segments against baseline, supporting evidence of improvement and supporting iterative planning.

Triangulation and avoidance of redundancy. The Madrid pilot's architecture explicitly supports triangulation in two ways. First, it triangulates **across sources**: historical bus fleet data (offline) are used to validate the operational workflow and calibrate processing assumptions, while real-time connected-vehicle data (online) provide live monitoring in the selected Madrid corridors. The intent is not to "train" in one place and "test" in another, but to establish that the workflow remains interpretable and stable when moving from batch to streaming conditions and from one fleet to another. Second, it triangulates **across time**: repeated measurements on the same segments enable deterioration trending and post-intervention reassessment. Importantly, redundancy is avoided by keeping functions separated: the probe-vehicle system is responsible for signal-level detection and normalisation; the digital twin is responsible for segment-level classification, alerting logic and maintaining the link to contextual metadata. This separation also aligns with operational accountability: raw observations remain traceable to source streams, while decisions are expressed at the segment level where interventions are applied.

From decisions → interventions (operational realism). The Madrid pilot is explicitly structured around end-user decision-making roles, notably (i) a road safety operator monitoring corridors in near real time and (ii) a maintenance planner conducting inspection prioritisation and maintenance scheduling. In the first operational scenario, a user selects real-time connected-vehicle datasets; the system presents colour-coded corridor segments, highlights clusters of high-severity anomalies and generates alerts indicating likely surface degradation. In the second scenario, a maintenance planner filters and combines severity indices with road type, using aggregated alerts and historical data to produce a ranked list of segments with condition scores and contextual drill-down (e.g. anomaly frequency, timestamps, acceleration profiles). The intervention intent is therefore realistic and bounded: **prioritise inspections**, allocate resources, schedule resurfacing, and export actionable segment information into existing maintenance ticketing systems. The platform does not claim to replace asset management processes; it provides a defensible evidence layer that makes those processes more systematic and comparable.

To conclude, Madrid illustrates intentional assembly in a particularly clear way: scalable sensing inputs are converted into reliable pavement indicators; a GIS-backed classification twin translates those indicators into segment-level alerts and prioritisation; decisions feed practical interventions; and the same pipeline supports post-intervention reassessment. The resulting workflow supports early identification of deterioration and cost-effective targeting of inspections and maintenance; precisely the operational purpose the pilot is designed to demonstrate.

4.2.3.2 GALICIA PILOT: CONNECTIVITY-DRIVEN SAFETY READINESS ON RURAL AND SECONDARY ROADS

The Galicia pilot instantiates the EvoRoads platform around a rural and inter-urban safety objective that is fundamentally different from pavement- or asset-condition monitoring: it seeks to determine **where CCAM and V2X-enabled safety services can be offered reliably**, and where the current communication environment constrains such services. The pilot site is located in Pontevedra along the **N-550**, selected specifically because connectivity varies with terrain and road environment, creating a realistic basis for mapping service viability on secondary networks. The stated outputs are a **connectivity performance heatmap** derived from on-road measurements (latency, bandwidth, packet loss and related indicators) and a corresponding classification of road sections by **ISAD levels**, enabling identification of "viable", "marginal" and "non-viable" segments for CCAM/V2X services. In operational terms, Galicia's safety intent is expressed through *road network connectivity and continuity*: the platform is used to expose where digital infrastructure limitations could compromise cooperative safety functions (e.g., collision warnings or emergency notifications) and to support evidence-based prioritisation of digital infrastructure investment on rural and secondary roads.

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Inputs → platform services. The principal input stream is **network performance logging collected in motion** along the N-550 using a dedicated probe setup. A key enabling asset is the **OBU-equipped demonstration vehicle**, configured with three OBUs (each assigned to a different mobile network operator) and logging systems to capture network metrics under the same external conditions; this supports comparative assessment across operators and geographic zones. The pilot explicitly recognises that rural performance is shaped by geography and seasonality, and therefore designs data collection to cover varied road sections and conditions to produce a statistically meaningful and spatially representative dataset. These logs provide the raw evidence base for the connectivity products, which are then converted into actionable artefacts by a set of tightly-coupled platform services whose roles are intentionally separated to avoid overlap.

Three core components implement the connectivity assessment and readiness classification, each occupying a distinct position in the workflow:

- **CCAM service viability assessment module.** This component operationalises the measurement regime on rural roads by combining onboard collection with validation tooling (e.g., ping, iPerf) and converting observations into georeferenced indicators of service readiness. Its distinguishing function is to classify road sections by ISA/ISAD levels, identify blind spots and low-quality zones, and express these as decision-oriented outputs for stakeholders responsible for connectivity upgrades. This aligns directly with the pilot objective of determining where CCAM services can and cannot be offered.
- **CCAM connectivity performance heatmap generator.** This component provides the principal “boundary object” for infrastructure planning: it aggregates measured parameters (latency, bandwidth, packet loss) into a high-resolution heatmap and maps the results to ISAD-level readiness. The heatmap generator is selected because it enables systematic comparison across the corridor and can be consumed by both technical stakeholders and road authorities as a planning artefact.
- **Network digital twin for V2X connectivity analysis.** This component is not a second heatmap tool; it adds a different capability: it virtualises selected segments of the V2X network infrastructure, supports “what-if” analysis of future network states, and includes functions such as anomaly detection and congestion-risk analysis under operational degradation or cyber threats. It is selected to move beyond static mapping into a model-based interpretation layer that can support planning questions such as the expected impact of degradation patterns or targeted upgrades on service viability.

A fourth component provides an optional but strategically important link from assessment to user-facing safety operations:

- **Infrastructure-to-vehicle risk advertisement system.** This module generates and distributes IVI messages based on detected risks and system logs, using a hybrid communication model via short-range RSUs (linked to an ITS Centre) and long-range channels, with the explicit purpose of ensuring timely warnings even where coverage is limited. In the Galicia context, it is positioned as an exploratory capability that can translate connectivity limitations into actionable service-availability warnings for road users, rather than as the core evaluation output.

Decision-chain mapping (Galicia): *Table 24* below shows how the selected components support the shared workflow stages while maintaining complementarity and avoiding redundancy.

Table 24: Decision-chain mapping to Technologies for Galicia

Decision stage	Madrid instantiation (inputs / services / outputs)
Detection	OBU-equipped vehicle logs network parameters along the N-550; onboard validation tools capture latency/bandwidth/packet loss and related metrics under variable terrain and conditions.

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Diagnosis	Service viability module and heatmap generator transform logs into georeferenced performance indicators and segment-level readiness labels; ISAD levels are used to express service feasibility and to identify blind spots.
Prioritisation	Heatmap and ISAD classification identify connectivity-critical segments and underperforming zones (including operator-dependent patterns), supporting prioritisation of digital infrastructure investment where insufficient connectivity could compromise cooperative safety services.
Intervention planning	Network digital twin supports scenario and "what-if" analysis to evaluate likely benefits of targeted improvements or resilience measures, including under operational degradation; outputs inform upgrade planning rather than immediate physical maintenance.
Impact assessment	Repeated measurement campaigns (across road sections, time windows and conditions) enable before/after comparison of ISAD classifications and heatmap improvements following upgrades; risk advertisement can be revisited as coverage improves to confirm message relevance and delivery feasibility.

Complementarity, triangulation, and avoidance of redundancy. The Galicia composition is intentionally layered. The OBU-equipped demonstration vehicle provides controlled, comparable raw evidence across operators and conditions, avoiding the ambiguity that would arise from mixing heterogeneous device setups. The service viability assessment module and heatmap generator do not duplicate one another: the former provides assessment logic and readiness classification, while the latter provides the geospatial product designed for infrastructure planning and communication to stakeholders. Triangulation is achieved (i) across operators (capturing simultaneous measurements from multiple networks under the same external conditions) and (ii) across time and conditions, reflecting hypotheses that rural/semi-urban sections and weather/seasonality materially affect performance. The network digital twin adds a distinct diagnostic and planning capability by supporting forward-looking reasoning and risk analysis, rather than producing another static coverage map. Finally, the risk advertisement system is included to demonstrate how connectivity intelligence can be converted into operational messaging (e.g., warning that a CCAM feature may not be reliable in the next segment), without claiming that Galicia's primary evaluation is driver behaviour or real-time operational control.

From decisions → interventions (operational realism). Galicia's interventions are principally digital-infrastructure and service-readiness interventions rather than road-surface repairs: the pilot's outputs guide where upgrades, coverage improvements, or resilience measures are likely to be required before CCAM/V2X safety use cases can be deployed reliably on rural and secondary roads. This ensures the pilot remains operationally credible: it produces artefacts (heatmaps, ISAD classifications, and scenario-based assessments) that infrastructure and CCAM stakeholders can use to support investment decisions, readiness planning and policy development for connected mobility deployment in non-motorway contexts.

In this way, the Galicia pilot shows how EvoRoads supports safety not only by detecting physical defects, but also by identifying and addressing the digital conditions under which cooperative safety services can function as intended on rural networks.

4.2.3.3 RIGA PILOT: MICRO-MOBILITY-DRIVEN SAFETY MANAGEMENT ON URBAN CYCLING CORRIDORS

The Riga pilot instantiates the EvoRoads platform in an urban context where **micro-mobility and cycling have become dominant contributors to road safety risk**, particularly for vulnerable road users. The pilot's safety objectives align primarily with the *Vulnerable Road Users*, *Road Infrastructure* and *Roadside Safety Devices* categories of the EvoRoads safety criteria. The operational focus is on identifying surface defects, obstacles and legibility issues that disproportionately affect cyclists and e-scooter users, and on supporting targeted, low-cost interventions that can be deployed under

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municipal budget and seasonal constraints. Unlike pilots centred on network-scale asset management or digital connectivity, Riga emphasises **fine-grained, user-proximate evidence** that reflects how infrastructure is actually experienced by micro-mobility users during everyday travel.

Inputs → platform services. The Riga workflow begins with two complementary input streams that capture safety-relevant information at the scale of micro-mobility use. The first stream consists of **instrumented e-scooters** equipped with the **mountable sensory kit for micro-vehicles**, which continuously captures visual, inertial and positional data during normal operation. This input is designed to reflect real riding trajectories, speeds and manoeuvres, providing a detailed picture of surface condition and obstacle presence along cycling corridors. The second stream consists of **citizen-generated observations** collected through the **crowdsourced road defect reporting app [FixCyprus, FixRiga]**, which allows users to report infrastructure issues encountered during cycling or e-scooter trips. These reports extend spatial coverage beyond instrumented routes and capture perceived safety concerns that may not always be evident from sensor data alone.

A defining characteristic of the Riga pilot is that **initial detection occurs directly on the vehicle**. The **embedded road defect detection algorithm for micro-vehicles** processes live camera and sensor data on the scooter itself, identifying defects such as potholes or surface discontinuities and generating geo-tagged risk events in near real time. This design choice reflects both privacy and efficiency considerations, ensuring that only safety-relevant events are propagated upstream while raw data volumes are minimised.

The core platform components selected for the Riga workflow are therefore:

- **Mountable sensory kit for micro-vehicles.** This component provides the physical sensing capability required to capture road condition and ride dynamics from the perspective of micro-mobility users. By combining a multi-mode 3D camera, GPS, accelerometer and onboard computing, it enables systematic, repeatable observation of infrastructure at a scale and granularity not achievable through conventional vehicle fleets.
- **Embedded road defect detection algorithm for micro-vehicles.** Running directly on the scooter, this algorithm performs early filtering and detection of surface anomalies and obstacles. Its role is to elevate relevant events into the platform without embedding prioritisation or planning logic, thereby keeping onboard intelligence focused on detection rather than decision-making.
- **Crowdsourced road defect reporting app [FixCyprus, FixRiga].** This component captures user-perceived safety issues through geolocated reports and images, which are processed via an integrated management portal. Machine-learning-based duplicate filtering and categorisation improve data quality and ensure that citizen input complements, rather than overwhelms, sensor-based evidence.
- **Micromobility safety markings.** These constitute a physical intervention component rather than an analytical one. Specially designed road surface patterns are used to guide cyclists and e-scooter riders towards safer speeds and trajectories, offering a low-cost, rapidly deployable response to prioritised safety issues identified through the platform.

Decision-chain mapping (Riga). The interaction of these components across the shared decision workflow is summarised below in *Table 25*.

Table 25: Decision-chain mapping to Technologies for Riga

Decision stage	Riga instantiation (inputs / services / outputs)
Detection	Onboard sensing and embedded detection on micro-vehicles identify surface defects and obstacles; citizen reports add user-perceived hazards and contextual detail.
Diagnosis	Aggregation and classification of detections and reports distinguish recurring infrastructure problems from isolated events; duplicate filtering improves signal quality.

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Prioritisation	Spatial clustering and frequency analysis highlight corridors with high exposure of micro-mobility users and recurring issues, supporting ranking under budget constraints.
Intervention planning	Prioritised locations inform targeted maintenance, signage adjustments and deployment of micromobility safety markings on selected segments.
Impact assessment	Post-intervention micro-vehicle sensing and subsequent citizen reports are used to assess changes in detected anomalies and perceived safety along treated corridors.

Complementarity, triangulation and avoidance of redundancy. The Riga pilot demonstrates intentional assembly through the combination of **objective sensing** and **subjective reporting**. The mountable sensory kit and embedded detection algorithm provide repeatable, quantitative evidence of surface condition and obstacles under real riding conditions. The FixRiga reporting app captures experiential information, such as discomfort or perceived risk, that may not always correspond to clear physical defects. Triangulation occurs when these two streams converge spatially and temporally, increasing confidence that an issue is both technically significant and operationally relevant. Where they diverge, authorities gain insight into whether a problem is structural or perception-driven. Redundancy is avoided by clearly separating roles: detection is handled on the vehicle, perception capture is handled through citizen engagement, and prioritisation is handled centrally through aggregation rather than duplicated across components.

From decisions → interventions (operational realism). Interventions in Riga are designed to be **proportionate, low-cost and rapidly deployable**, reflecting municipal resource constraints and the need to respond quickly to emerging micro-mobility risks. Prioritised outputs from the platform support targeted maintenance where defects are confirmed, but also enable the deployment of **micromobility safety markings** in locations where behaviour guidance can reduce risk without extensive physical reconstruction. Because the same micro-vehicle sensing infrastructure remains active after intervention, impact assessment can be performed using comparable before-and-after evidence, complemented by renewed citizen feedback. This closes the decision loop and allows the city to iteratively refine both infrastructure treatments and prioritisation criteria.

In conclusion, the Riga pilot illustrates how the EvoRoads platform can be assembled intentionally to address micro-mobility safety challenges. By aligning onboard intelligence, citizen participation and low-cost physical interventions within a coherent decision workflow, the pilot demonstrates a practical and scalable approach to improving safety for vulnerable road users in dense urban environments.

4.2.3.4 ALBA IULIA PILOT: MULTI-SOURCE DEFECT DETECTION AND PRIORITISATION FOR MUNICIPAL ROAD SAFETY

The Alba Iulia pilot instantiates the EvoRoads platform in a **municipal-scale context**, where safety improvements must be achieved under tight resource constraints and where infrastructure management relies on selective, defensible intervention. The pilot's safety objectives align primarily with the *Road Infrastructure* and *Roadside Safety Devices* categories of the EvoRoads safety criteria, with particular attention to pavement defects, surface deformation and localised hazards that can escalate into safety risks if left unaddressed. Unlike network-scale pilots, Alba Iulia emphasises **early identification and prioritisation of a limited number of high-impact locations**, combining citizen input with aerial and satellite observations to build a coherent evidence base for maintenance planning. The operational challenge is therefore to consolidate heterogeneous observations into a small set of actionable decisions that can be implemented rapidly and justified within municipal governance processes.

Inputs → platform services. The Alba Iulia workflow deliberately combines **ground-level perception**, **low-altitude aerial inspection** and **satellite-based monitoring** to address both immediacy and coverage. The first input stream is provided by citizens through the **citizen road defect helpdesk smartphone app**, which allows residents to submit geo-referenced reports and optional photographs of infrastructure issues encountered in daily travel. This channel captures

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user-perceived defects and emerging hazards at minimal cost, reflecting the municipality's need to remain responsive to local concerns.

A second input stream is generated through **drone-based surveys**, which provide high-resolution visual coverage of selected road sections. These surveys are particularly suited for validating reported issues and for inspecting areas suspected of deterioration but not easily observable from ground level. A third, complementary stream is derived from **satellite-based InSAR measurements**, which detect subtle vertical displacements over time and highlight zones potentially affected by subsidence, rutting or ponding. This multi-scale input strategy ensures that Alba Iulia can detect both visible surface defects and less obvious structural changes that may precede safety incidents.

The platform components selected to operationalise these inputs are intentionally specialised and non-overlapping:

- **Citizen road defect helpdesk smartphone app.** This component provides the primary interface for citizen engagement and immediate issue reporting. By automatically capturing GPS coordinates and synchronising reports with the municipal portal via API, it ensures that citizen input is structured and traceable, serving as an early-warning mechanism rather than a standalone decision tool.
- **Drone-based infrastructure defect detection and annotation module.** This component processes high-resolution drone imagery to detect and annotate defects such as potholes and surface distress. Edge-detection algorithms accelerated through parallel processing extract defect contours efficiently, producing geo-referenced annotations that can be directly mapped and reviewed by technical staff. Its role is to validate and detail defects at locations flagged by other sources.
- **InSAR Infrastructure Deformation Detection module.** This module extends the temporal and spatial horizon of detection by analysing satellite SAR data (e.g. Sentinel-1) to identify millimetre-scale vertical displacements. It is selected to reveal latent or progressive infrastructure issues that may not yet manifest as visible defects, supporting proactive safety management.
- **Aerial pavement defect detection and classification models.** These computer vision models process overhead imagery from drones, satellites and complementary sources to identify cracks, surface distress and other defects at scale. Their role is comparative and diagnostic, enabling consistent assessment across multiple locations and supporting prioritisation decisions.

Decision-chain mapping (Alba Iulia). The interaction of these components across the shared decision workflow is summarised with *Table 26* below.

Table 26: Decision-chain mapping to Technologies for Alba Iulia

Decision stage	Alba Iulia instantiation (inputs / services / outputs)
Detection	Citizen reports identify perceived defects; InSAR analysis highlights deformation-prone zones; drone and aerial imagery provide high-resolution visual evidence.
Diagnosis	Drone-based annotation and aerial ML models classify defects and confirm severity; InSAR trends contextualise whether issues are isolated or progressive.
Prioritisation	Consolidation of citizen input, defect severity and deformation indicators identifies a small set of high-impact locations for action.
Intervention planning	Prioritised locations inform targeted maintenance and inspection scheduling within municipal workflows.
Impact assessment	Follow-up citizen feedback, repeat drone flights or updated InSAR measurements support before/after comparison of treated sites.

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Complementarity, triangulation and avoidance of redundancy. The Alba Iulia pilot demonstrates intentional assembly through **multi-source triangulation across scales**. Citizen reports provide immediacy and perception-based insight, but are not treated as sufficient evidence on their own. Drone-based inspection complements this by offering precise visual confirmation and annotation, while InSAR monitoring adds a longitudinal dimension that can reveal slow-onset deformation not captured by episodic surveys. Triangulation occurs when citizen-reported defects coincide with drone-observed surface damage or InSAR-identified subsidence trends, increasing confidence that intervention is warranted. Redundancy is avoided by assigning each component a distinct role: citizen reporting initiates attention, drone and aerial models diagnose and classify, and InSAR informs prioritisation by highlighting underlying structural behaviour rather than duplicating surface detection.

From decisions → interventions (operational realism). Interventions in Alba Iulia are necessarily **selective and proportionate**, reflecting municipal budgetary and staffing constraints. The platform's outputs support targeted maintenance actions (such as pothole repair, surface treatment or focused inspection) at locations where combined evidence indicates elevated risk. Importantly, the workflow supports defensible decision-making: each intervention can be traced back to citizen input, visual confirmation and, where relevant, deformation analysis. Impact assessment closes the loop by reusing the same mechanisms that initiated detection, enabling the municipality to verify whether reported issues have been resolved and whether deformation trends stabilise following intervention.

Overall, the Alba Iulia pilot illustrates how the EvoRoads platform can be assembled intentionally to support municipal infrastructure safety management. By combining citizen engagement with aerial and satellite analytics in a coherent decision workflow, the pilot demonstrates a scalable approach for small and medium-sized authorities to improve road safety through evidence-based prioritisation rather than reactive repair.

4.2.3.5 SANTA OLIVA PILOT: MAPPING PLATFORM COMPONENTS TO A HAZARD-AWARE SAFETY WORKFLOW

The Santa Oliva pilot instantiates the EvoRoads platform in a secondary and peri-urban road context where safety risks are shaped less by long-term structural degradation and more by **environmental conditions, roadside visibility and the timely communication of hazards**. The pilot's safety objectives align primarily with the *Road Infrastructure* and *Roadside Safety Devices* categories of the EvoRoads safety criteria, with particular emphasis on warning effectiveness, infrastructure readiness and safety under adverse or rapidly changing conditions. Operating in a low-density network with limited redundancy and constrained budgets, the pilot prioritises interventions that maximise safety impact without extensive physical redesign. The overarching intent is to detect safety-relevant hazards early, communicate them effectively to road users, and support selective maintenance or equipment deployment on risk-prone segments.

Inputs → platform services. The Santa Oliva workflow begins with heterogeneous inputs describing the **current state of the road environment**. These include roadside sensor data and vehicle-derived observations capturing surface hazards, obstacles, degraded signs and environmental conditions such as puddles or reduced visibility. Unlike pilots focused on asset condition or connectivity planning, Santa Oliva's inputs are characterised by **temporal volatility**: hazards may emerge and dissipate rapidly, and their safety impact depends strongly on timely awareness.

The platform components selected to operationalise these inputs are:

- **Artificial intelligence algorithms for road hazard detection.** These algorithms apply computer vision and data fusion techniques to identify surface and roadside hazards, such as cracks, potholes, obstacles or degraded signage, and to generate structured hazard events suitable for downstream processing.
- **Hazard-aware infrastructure monitoring tool.** This component integrates roadside sensing and vehicle-based data streams, applying anomaly detection to distinguish safety-relevant events from background variability and to track hazard persistence or recurrence over time.

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- **On-the-edge processing and real-time C-ITS alerting module.** Deployed close to the road, this module receives raw sensor inputs, performs rapid hazard assessment and generates standardised C-ITS messages, enabling low-latency transmission of warnings to connected vehicles and systems.
- **Plastronics smart beacon system.** These durable, low-cost beacons translate detected hazards into intuitive visual warnings through dynamic light patterns and colours, providing infrastructure-level cues that do not rely solely on in-vehicle connectivity.
- **Smartphone nudging application.** This application delivers contextual, real-time safety prompts directly to road users, complementing infrastructure-based warnings and extending coverage to non-connected vehicles and vulnerable users.

Decision-chain mapping (Santa Oliva). The interaction of these components across the shared decision workflow is summarised below in *Table 27*.

Table 27: Decision-chain mapping to Technologies for Santa Oliva

Decision stage	Riga instantiation (inputs / services / outputs)
Detection	AI-based hazard detection and hazard-aware monitoring identify surface defects, obstacles and environmental risks from roadside and vehicle data.
Diagnosis	Contextualisation of detected hazards assesses severity, persistence and spatial extent, distinguishing transient anomalies from recurring risks.
Prioritisation	Hazards are ranked based on safety criticality, exposure and warning urgency, determining where alerts or follow-up actions are required.
Intervention planning	Prioritised hazards trigger proportional responses, including activation of smart beacons, generation of C-ITS messages and delivery of user nudges.
Impact assessment	System logs, repeated detections and user interactions are analysed to assess warning effectiveness and behavioural response over time.

Complementarity, triangulation and avoidance of redundancy. The Santa Oliva pilot demonstrates intentional assembly through the combination of **digital detection, edge processing and physical warning devices**. AI algorithms and the hazard-aware monitoring tool provide complementary detection and contextualisation functions, ensuring that hazards are identified reliably without over-alerting. Triangulation occurs when roadside sensor data and vehicle-based observations converge on the same hazard location, increasing confidence in the relevance of alerts. Redundancy is avoided by assigning distinct roles to each component: detection algorithms identify hazards, monitoring tools interpret their significance, edge modules ensure timely alert generation, and beacons and mobile applications deliver warnings through different but complementary channels. This separation ensures resilience and clarity in the safety workflow.

From decisions → interventions (operational realism). Interventions in Santa Oliva are designed to be **selective, low-cost and rapidly deployable**, reflecting the realities of secondary and peri-urban road management. Rather than relying on extensive reconstruction, the pilot focuses on improving situational awareness and warning effectiveness through smart beacons, C-ITS alerts and behavioural nudging. These measures allow authorities to respond proportionally to detected risks while preserving flexibility to escalate to maintenance or infrastructure upgrades where hazards persist. Impact assessment reuses the same detection and communication mechanisms, enabling iterative refinement of warning strategies and providing evidence of safety benefit without imposing additional monitoring burdens.

To summarise, the Santa Oliva pilot illustrates how the EvoRoads platform can be assembled intentionally to address hazard-driven safety challenges. By aligning detection, prioritisation and communication within a coherent decision

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workflow, the pilot demonstrates a practical approach to improving safety outcomes on low-density networks where responsiveness and warning effectiveness are critical.

4.2.3.6 TURIN PILOT: BEHAVIOUR-DRIVEN SAFETY DIAGNOSIS AND INTERVENTION IN CONNECTED URBAN ENVIRONMENTS

The Turin pilot instantiates the EvoRoads platform in a dense urban context where safety performance is strongly influenced by **road-user behaviour, traffic management practices and the readiness of infrastructure to support connected and automated mobility services**. The pilot's objectives align primarily with the *User Behaviour*, *Traffic Management* and *C-ITS / CCAM Operations* categories of the EvoRoads safety criteria. Rather than focusing on isolated defects or static hazards, Turin addresses **dynamic risk patterns** arising from interactions between vehicles, pedestrians and infrastructure at critical locations such as crossings and mixed-use corridors. The intervention intent is to support informed infrastructure adaptation and prioritisation - grounded in behavioural evidence - within a complex governance environment where safety measures must be consistent with broader urban mobility strategies and regulatory constraints.

Inputs → platform services. The Turin workflow is characterised by **multi-perspective behavioural observation**. Inputs are generated both from roadside sensing and from vehicles operating within the urban network. Roadside units equipped with LiDAR and high-resolution cameras capture detailed information on pedestrian movements, vehicle speeds, illegal parking and other behaviours that influence safety at crossings and along corridors. Complementary vehicle-based inputs are provided by on-board units installed on operational fleets, which capture signage condition, surface state and atypical driving behaviour while in motion. These inputs are further enriched by participatory data collected through structured surveys and feedback campaigns, reflecting user perception and acceptance of safety measures.

To operationalise these inputs, the Turin pilot combines a set of specialised platform components, each addressing a distinct stage of the safety workflow:

- **LiDAR and camera-enhanced Road-Side Units for behaviour surveillance.** These units provide real-time detection of pedestrian crossings, illegal parking, vulnerable road user interactions and mobility obstructions. Local processing ensures timely identification of safety-relevant events and supports immediate downstream actions.
- **Pedestrian crossing behaviour recognition algorithm.** Operating on roadside sensor inputs, this algorithm detects crossing-specific events such as pedestrian presence, vehicle approach speed and rule violations, producing structured signals that directly drive warning and feedback mechanisms.
- **Road user behaviour analysis algorithms.** These AI models extend behavioural detection beyond crossings, classifying speeding, unsafe lane usage, near-misses and other atypical behaviours from roadside and vehicle-based video and sensor data. Their role is to provide a broader behavioural context for diagnosis and planning.
- **Vision-based AI for traffic sign defect monitoring.** This component analyses road-user camera images to detect occluded or degraded signage, linking behavioural observations with infrastructure legibility and maintenance needs.
- **On-Board Units for signage condition and behaviour monitoring.** Installed on vehicles, these units capture signage condition and behavioural cues during normal operation, complementing fixed roadside sensing and improving spatial coverage.
- **Chimera data harmonisation platform.** This platform preprocesses and harmonises heterogeneous behavioural, infrastructure and perception datasets into a common reference model, ensuring semantic consistency and interoperability with the Digital Twin and data space services.
- **Road condition assessment system.** By analysing up-to-date inputs from sensors, connected vehicles and the Digital Twin, this system generates real-time infrastructure safety KPIs and ISAD levels, linking behavioural risk to infrastructure readiness for CCAM services.
- **Road risk identification and intervention support tool.** This AI-enabled tool assesses and classifies road segments based on accident risk and its evolution over time, supporting evidence-based prioritisation of safety interventions.

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- **Coney surveying toolkit.** This participatory platform captures structured feedback from users and stakeholders, supporting behavioural analysis, nudging evaluation and acceptance assessment.
- **Urban safety feedback display.** These roadside displays provide real-time visual feedback to drivers and pedestrians based on detected behaviours, closing the loop between observation and immediate behavioural influence.

Decision-chain mapping (Turin). The interaction of these components across the shared decision workflow is summarised below with *Table 28*.

Table 28: Decision-chain mapping to Technologies for Turin (Piemonte)

Decision stage	Turin instantiation (inputs / services / outputs)
Detection	Roadside LiDAR/camera units and vehicle OBUs detect pedestrian movements, vehicle behaviours, signage defects and atypical interactions in real time.
Diagnosis	Behaviour recognition algorithms and harmonised datasets contextualise detected events, linking behaviour patterns with infrastructure condition and traffic context.
Prioritisation	Risk identification tools and ISAD-based assessments rank locations and behaviours by safety impact and relevance to CCAM readiness.
Intervention planning	Evidence supports targeted infrastructure adaptation, signage maintenance, behavioural nudging strategies and traffic management adjustments.
Impact assessment	Repeated sensing, behavioural metrics, survey feedback and KPI evolution are analysed to assess the effectiveness of interventions over time.

Complementarity, triangulation and avoidance of redundancy. The Turin pilot demonstrates intentional assembly through the **combination of fixed roadside sensing, mobile vehicle observation and participatory input**. Behaviour recognition algorithms at crossings and corridor level provide complementary views of risk, while vehicle-based OBUs extend spatial coverage beyond instrumented locations. Triangulation occurs when behavioural events detected by roadside units align with vehicle-based observations and with user feedback captured through surveys, increasing confidence in diagnosis and prioritisation. Redundancy is avoided by clear role separation: detection is handled by sensing and AI components, harmonisation by Chimera, prioritisation by risk and readiness assessment tools, and behavioural influence by displays and nudging mechanisms.

From decisions → interventions (operational realism). Interventions in Turin are designed to be **data-driven and governance-aware**. Rather than enforcing rigid controls, the pilot supports informed adaptation of infrastructure (e.g. signage repair or repositioning), targeted deployment of feedback displays, and prioritisation of locations requiring further investment to support connected and automated mobility services. Behavioural nudging complements longer-term measures by providing immediate feedback to road users, while impact assessment relies on consistent before-and-after evidence from the same sensing and analysis pipeline. This approach enables Turin to integrate safety improvements into broader urban mobility planning, demonstrating how the EvoRoads platform supports dynamic, behaviour-centred safety management in complex urban environments.

In conclusion, the Turin pilot illustrates how the EvoRoads platform can be assembled intentionally to support **behaviour-driven safety management** in complex urban environments. By integrating roadside sensing, vehicle-based observation, behavioural analytics and participatory feedback within a coherent decision workflow, the pilot demonstrates how dynamic risk patterns can be detected, interpreted and acted upon in a way that aligns with both infrastructure readiness and connected mobility objectives. The combination of diagnostic depth and operational flexibility allows safety interventions to be prioritised and evaluated without disrupting broader urban mobility strategies. In this sense, Turin exemplifies how

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EvoRoads enables evidence-based safety improvement where behavioural dynamics, infrastructure condition and digital readiness must be considered jointly rather than in isolation.

4.2.4 CROSS-PILOT COHERENCE AND ARCHITECTURAL REUSE

This subsection consolidates the pilot-level analyses by examining how a single EvoRoads platform architecture is reused and adapted across diverse operational contexts. Although the six pilots differ markedly in geography, governance, safety focus and intervention levers (summarised in *Table 29* below), they do not represent six bespoke systems. Instead, they instantiate a shared architectural and operational framework, reusing core platform components and decision patterns while stretching them in different directions according to local needs. This cross-pilot coherence is essential to demonstrating that EvoRoads delivers a unified, generalisable solution rather than a collection of isolated demonstrations.

Table 29: Summary of functional requirements exercised per pilot

PILOT	**Turin instantiation (inputs / services / outputs)**
Madrid	Network-scale detection, prioritisation, maintenance planning
Galicia	Connectivity assessment, readiness classification, federation
Riga	Micro-mobility sensing, citizen input, low-cost interventions
Santa Oliva	Hazard detection, alerting, behavioural nudging
Alba Iulia	Multi-scale defect detection, selective prioritisation
Turin	Behaviour analysis, readiness assessment, decision support

Across pilots, several components recur as foundational building blocks, even when deployed with different emphases. Digital Twin services are used in Madrid, Galicia and Turin to structure observations into network- or segment-level representations that support decision-making. AI-based detection and classification algorithms appear in multiple forms across Santa Oliva, Riga, Alba Iulia and Turin, applied to different sensing modalities but following the same architectural role: converting raw observations into structured safety events. Data harmonisation and KPI-oriented assessment components underpin pilots that require comparability and justification at scale, such as Madrid and Turin, while federated data exposure and cataloguing mechanisms provide a consistent pathway for cross-pilot learning and external reuse. The reuse of these components confirms that the Logical View described earlier is not abstract, but actively instantiated in multiple contexts.

At the same time, the pilots reveal repeated architectural patterns with controlled variation. The shared decision chain - Detection, Diagnosis, Prioritisation, Intervention Planning and Impact Assessment - appears consistently, but pilots emphasise different stages depending on their role. Network-scale pilots prioritise detection and prioritisation to manage breadth and resource allocation, while urban behavioural pilots invest more heavily in diagnosis and impact assessment to support governance and acceptance. This variation does not fragment the platform; it demonstrates that the same logical structure can accommodate both proactive asset management and responsive, behaviour-centred safety interventions. Importantly, the pilots also illustrate how the platform can be stretched without breaking coherence. Rural and secondary road contexts such as Galicia and Santa Oliva push the platform towards resilience, coverage and warning effectiveness under constrained conditions. Urban contexts such as Turin and Riga stretch it towards behavioural interpretation, user interaction and fine-grained intervention. Municipal pilots such as Alba Iulia demonstrate that the same architecture can scale down to selective, cost-sensitive decision-making. In each case, stretching occurs through configuration and component selection, not through architectural divergence.

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Lessons emerging from individual pilots generalise naturally because they are expressed in shared artefacts: harmonised datasets, reusable KPIs, repeatable workflows and common interface concepts. This enables insights gained in one context—for example, the value of multi-source triangulation or the role of post-intervention assessment - to be transferred to others without reengineering the platform. As a result, EvoRoads supports both rural and urban safety management within a single architectural envelope.

Taken together, this cross-pilot analysis confirms the internal coherence of the EvoRoads platform as defined in the Logical View, while preparing the ground for the Process View that follows. The next section moves from structural and operational intent to runtime behaviour, detailing how data and control flow through the platform to realise the safety workflows described here in practice.

4.3 PROCESS VIEW: CONTROL AND DATA FLOW AT RUNTIME

The **Process View** of the EvoRoads Integrated Platform Architecture describes the dynamic behaviour of the system at runtime, focusing on how logical components interact through sequences of events and coordinated control and data flows. Building on the Logical View and the operational safety workflows introduced in Section 4.2, this view explains how observations originating from heterogeneous sources are propagated, transformed, combined and consumed to support timely and accountable safety decisions. The Process View captures key runtime concerns such as event sequencing, concurrency, synchronisation and latency, which are critical for handling both real-time and batch-oriented safety use cases. It illustrates how analytical services, decision-support functions and user-facing interactions are orchestrated under varying operating conditions, including fluctuating data volumes and partial system availability. Particular attention is given to fault tolerance and graceful degradation, ensuring that the platform maintains consistent behaviour and traceability even when individual components or data streams are temporarily unavailable. This view deliberately abstracts away from physical deployment choices and software implementation details, which are addressed in subsequent architectural perspectives. Instead, it provides a technology-neutral account of how the EvoRoads platform behaves as an integrated system, translating architectural intent into executable safety workflows. What is more, given the breadth of components and deployment contexts in EvoRoads, the Process View focuses on a set of representative runtime interaction patterns that collectively cover the platform's core operational behaviours, rather than exhaustively documenting all possible data flows.

4.3.1 EVENT-DRIVEN DATA INGESTION AND PREPROCESSING PATTERNS

This subsection describes the runtime patterns through which data enter the EvoRoads Integrated Platform and are prepared for downstream analytical and decision-support workflows. Given the diversity of data sources, operating contexts and latency requirements across pilots, EvoRoads adopts an event-driven ingestion approach that supports both streaming and batch-oriented data flows. Rather than documenting all possible ingestion paths, this section focuses on representative patterns that collectively capture the platform's ingestion behaviour under real-world conditions.

At runtime, ingestion serves two closely related purposes: first, to reliably accept data from heterogeneous producers operating under variable connectivity and performance constraints; and second, to perform initial preprocessing steps that ensure data are time-aligned, spatially referenced and suitable for harmonisation. Ingestion is therefore not treated as a passive data transfer step, but as an active control point where validation, buffering and basic transformation occur.

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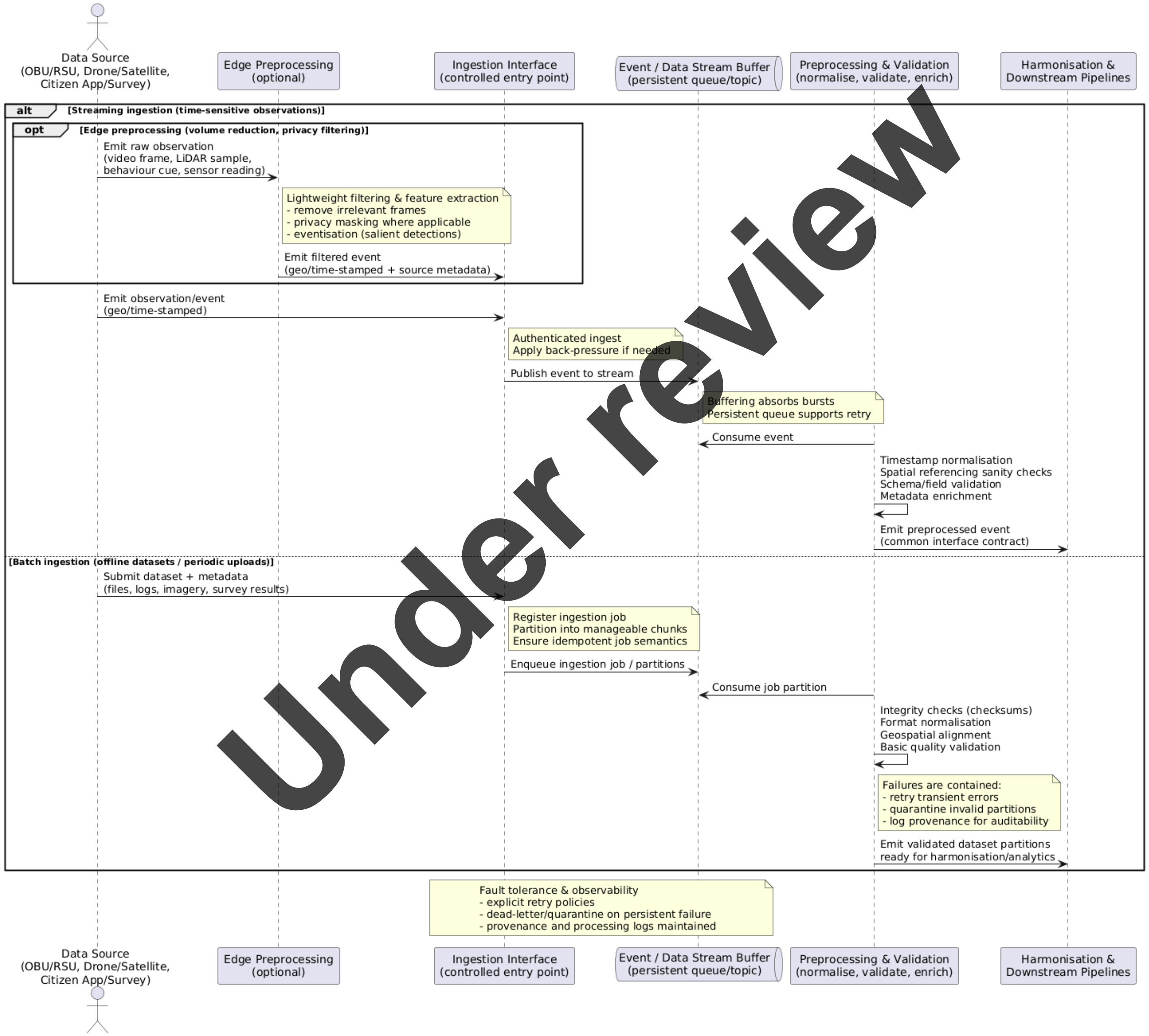

Figure 13: Event-driven data ingestion and preprocessing patterns

Two primary ingestion patterns are supported, both illustrated in the sequence diagram of ***Figure 13***. **Streaming ingestion** is used for time-sensitive observations, such as vehicle-based sensing, roadside monitoring and behavioural detection, where latency and continuity are critical. In this pattern, data producers emit events continuously or quasi-continuously, which are received by ingestion endpoints and placed onto internal event streams. Lightweight preprocessing is applied early in the pipeline, including timestamp normalisation, basic sanity checks and enrichment with source metadata. Where applicable, edge-level preprocessing reduces data volume by filtering raw signals into structured events before transmission. The ingestion layer implements buffering and back-pressure mechanisms to absorb bursts and to prevent upstream overload, ensuring that temporary connectivity degradation does not result in data loss or systemic failure.

Batch ingestion supports datasets that are collected or generated offline, such as historical vehicle logs, drone imagery, satellite-derived products, survey results or periodic infrastructure inventories. In this pattern, datasets are submitted explicitly through controlled interfaces and registered as ingestion jobs. Preprocessing steps include format normalisation, spatial referencing, integrity checks and partitioning into manageable units for downstream processing. Batch ingestion is designed to be idempotent, allowing safe reprocessing in case of partial failure or updated inputs. Although batch workflows are not latency-critical, they are subject to the same provenance and traceability requirements as streaming data.

Across both patterns, ingestion outputs are expressed as **pre-processed events or datasets** that conform to internal interface contracts and are ready for harmonisation and analytical processing. The ingestion layer explicitly decouples data producers from consumers, enabling downstream components to evolve independently and allowing pilots to introduce new data sources without destabilising existing flows. Fault tolerance is addressed through retry strategies, persistent queues and clear failure semantics, ensuring that ingestion failures are contained and observable rather than propagated silently. In summary, the ingestion and preprocessing patterns described here establish a robust foundation for the EvoRoads platform, balancing flexibility with control. By treating ingestion as an event-driven, first-class process, EvoRoads ensures that heterogeneous data streams can be integrated consistently, efficiently and safely across diverse operational contexts.

4.3.2 REAL-TIME SAFETY EVENT PROCESSING AND EDGE-CLOUD COORDINATION

This subsection describes how the EvoRoads Integrated Platform processes safety-relevant information under real-time or near-real-time constraints, and how responsibilities are coordinated between edge and cloud components. While the platform supports a wide range of analytical workflows, this section focuses specifically on runtime behaviours where timeliness, situational awareness and controlled latency are critical. The objective is not to enumerate all real-time use cases, but to document the recurring processing pattern that governs how safety events are detected, contextualised and propagated to decision-making interfaces.

Real-time safety processing in EvoRoads, explained in detail by ***Figure 14*** below, is organised around the principle of **edge-first responsiveness combined with cloud-level consolidation**. Events that may have immediate safety implications (such as surface hazards, behavioural anomalies, connectivity degradation or roadside risks) are detected as close as possible to their source. Edge components, including vehicle-mounted units and roadside processing modules, perform lightweight inference and filtering to transform raw sensor streams into structured safety events. This approach reduces communication overhead, preserves privacy by avoiding unnecessary transmission of raw data, and ensures that time-critical signals are not delayed by central processing queues.

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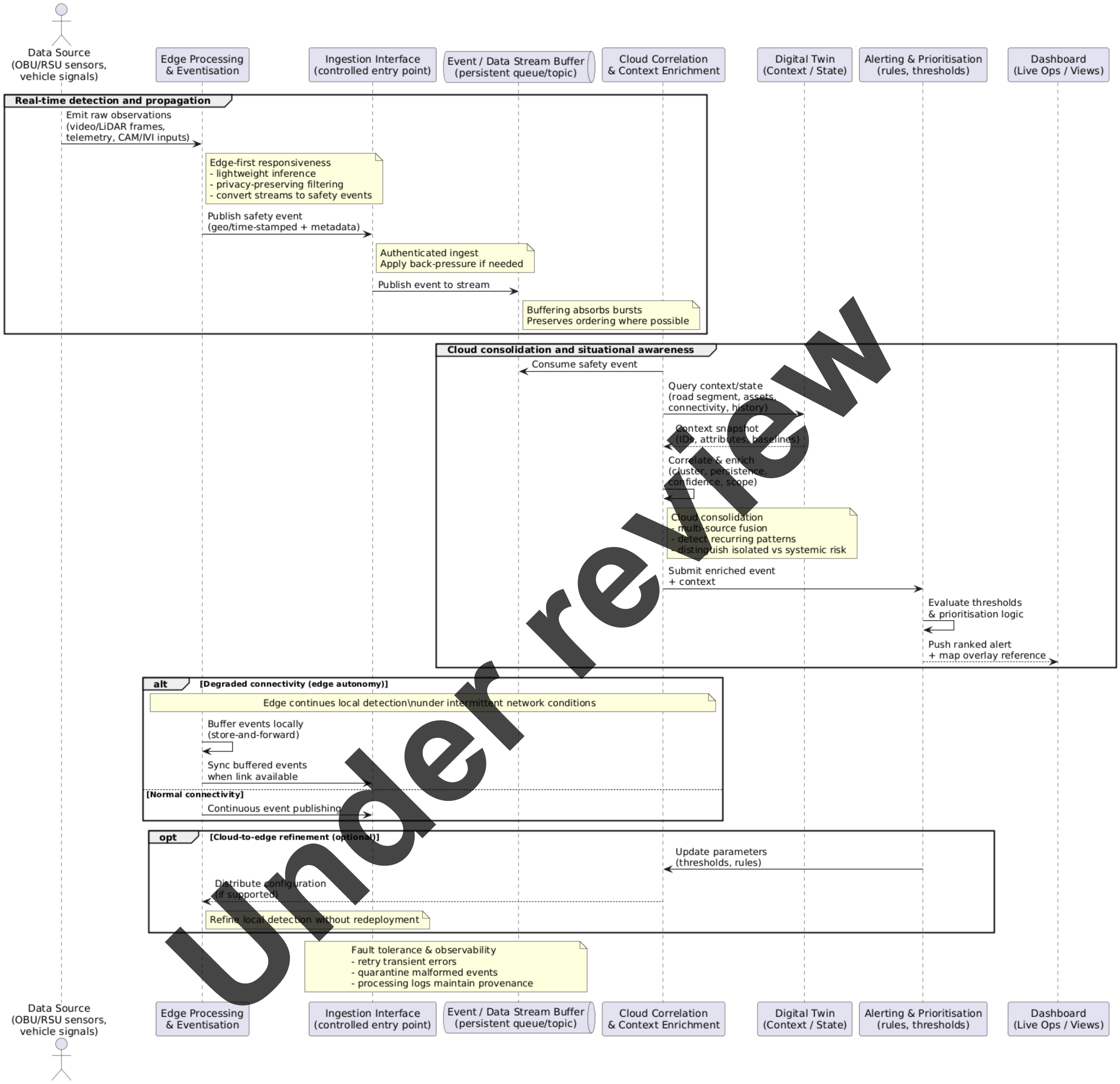

Figure 14: Real-time safety event processing and edge-cloud coordination

Once detected, safety events are forwarded to the cloud layer, where they are aggregated, enriched and correlated with broader contextual information. The cloud does not replace edge decision-making; instead, it provides **situational consolidation** across space and time. By combining events from multiple sources with digital twin state, historical observations and network context, the platform can assess persistence, spatial extent and potential escalation of safety conditions. This coordination allows the system to distinguish between isolated anomalies and patterns that warrant operational attention, such as emerging risk corridors or recurring behavioural conflicts. Control flow between edge and

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cloud components is explicitly designed to accommodate **variable connectivity and partial availability**. Edge components are capable of operating autonomously when network conditions are degraded, continuing to detect and locally act upon safety conditions within predefined bounds. When connectivity is restored, buffered events are synchronised with the cloud, preserving temporal ordering and provenance. Conversely, cloud-generated insights (such as updated thresholds, prioritisation parameters or contextual overlays) can be propagated back to the edge to refine local detection behaviour without requiring redeployment. From an operational perspective, real-time processing culminates in the presentation of **actionable safety information** rather than raw events. Alerts and indicators surfaced to users through the integrated dashboard are ranked, contextualised and scoped according to role and responsibility. This ensures that operators are not overwhelmed by high-frequency signals, while still retaining access to underlying evidence when deeper inspection is required. Importantly, real-time processing does not bypass governance or traceability: all events and derived signals are logged with sufficient metadata to support later analysis, validation and audit.

In summary, the real-time processing pattern in EvoRoads balances responsiveness with control by distributing intelligence across edge and cloud layers. This coordination enables the platform to react promptly to safety-critical situations while maintaining a coherent, system-level view of evolving conditions. The result is a runtime architecture that supports timely intervention without sacrificing robustness, accountability or architectural clarity.

4.3.3 ANALYTICAL WORKFLOWS AND DECISION-SUPPORT LOOPS

This subsection describes the runtime patterns through which the EvoRoads Integrated Platform transforms harmonised data and safety events into analytical outputs that support planning, prioritisation and intervention decisions. While real-time processing focuses on immediacy and situational awareness, analytical workflows operate over broader temporal and spatial scopes, enabling the systematic evaluation of infrastructure condition, risk evolution and intervention effectiveness. These workflows form the backbone of evidence-based decision-making within EvoRoads.

Analytical workflows **are initiated** through a combination of triggers, including scheduled execution, operator requests and the accumulation of sufficient new data to warrant re-analysis. Inputs to these workflows include pre-processed datasets from the ingestion layer, enriched safety events from real-time processing, and contextual state from the Digital Twin. The separation between data ingestion and analytics ensures that analytical jobs operate on stable, well-defined inputs, supporting reproducibility and traceability of results.

Within the analytics layer, diverse algorithms and models are executed to derive higher-level artefacts such as condition indicators, risk scores, connectivity readiness classifications and composite KPIs. These computations may span network-wide assessments or focus on specific corridors, assets or user groups, depending on the pilot context and decision need. Importantly, analytical workflows are designed to preserve linkage between derived outputs and their underlying evidence, including source datasets, parameter configurations and model versions. This linkage is essential for interpretability and for justifying decisions in operational and policy contexts. The **Digital Twin** plays a central role in analytical workflows by providing a structured representation of the infrastructure, its attributes and its temporal evolution. Analytical results are not produced in isolation; they are anchored to digital representations of road segments, intersections, roadside assets and network topology. This anchoring allows decision-makers to explore results spatially, compare scenarios and assess how conditions evolve over time. In addition, the Digital Twin supports the aggregation of analytical outputs across pilots and contexts, enabling consistent comparison while respecting local variation.

Analytical outputs are fed into **decision-support loops** that connect analysis to action. These loops are not automated control mechanisms; rather, they provide structured recommendations, ranked insights and explanatory context to human decision-makers. Outputs are surfaced through role-specific dashboard views, such as *Planning, Maintenance, Connectivity or Research views*, where users can explore trends, simulate scenarios and export results for downstream processes. The platform explicitly supports "why" explanations alongside "what" recommendations, ensuring that users understand the basis for prioritisation or intervention suggestions.

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Decision-support loops also extend beyond initial planning. Analytical workflows are re-executed following interventions or significant changes, enabling before-and-after comparison and impact assessment. This iterative use of analytics closes the decision loop, supporting learning and continuous refinement of strategies. By structuring analytical workflows around repeatable patterns rather than bespoke analyses, EvoRoads ensures that decision support remains coherent, auditable and adaptable across pilots.

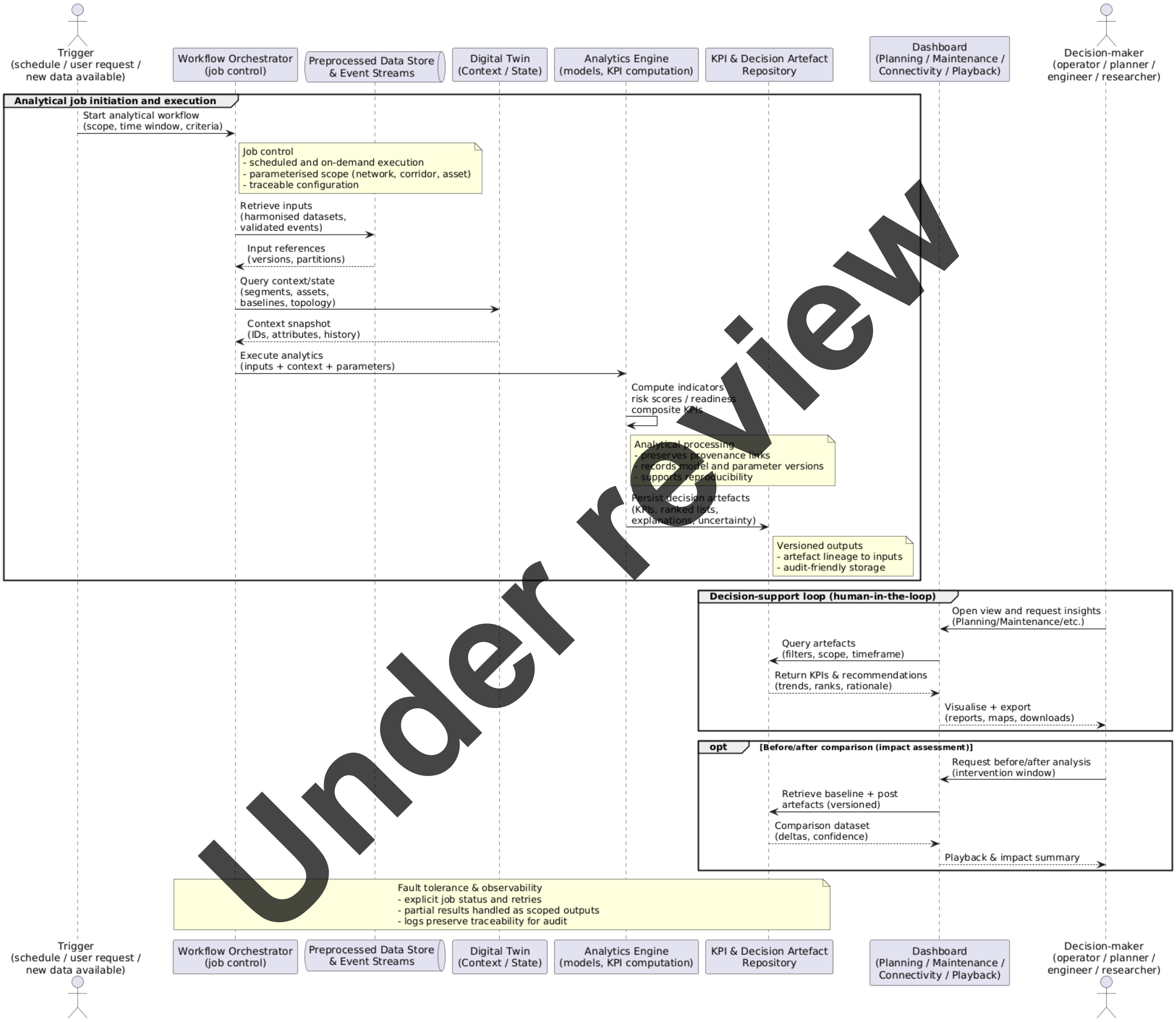

Figure 15: Analytical workflows and decision-support loops

In summary, analytical workflows in EvoRoads, whose blueprint is illustrated in ***Figure 15***, provide the mechanism through which data are converted into structured, defensible decision inputs. By integrating harmonised data, digital twin context and traceable analytics within a consistent runtime pattern, the platform supports informed decision-making without constraining local autonomy or operational judgement.

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4.3.4 USER INTERACTION, FEEDBACK, AND EXTERNAL DATA EXCHANGE PROCESSES

This subsection describes the runtime processes through which human users and external systems interact with the EvoRoads Integrated Platform. While preceding subsections focused on internal processing and analytical coordination, this section addresses how insights are consumed, acted upon and, where appropriate, shared beyond the platform boundary. These processes, documented with the assistance of ***Figure 16***, are essential for ensuring that EvoRoads functions not only as an analytical system, but as an operational decision-support environment embedded within real-world governance and collaboration structures.

User interaction within EvoRoads is mediated primarily through the integrated dashboard, which provides role-specific views aligned with distinct operational responsibilities. At runtime, users do not interact directly with raw data streams or analytical services; instead, they engage with curated representations such as ranked alerts, condition indicators, trends, maps and comparative analyses. Interaction patterns include exploratory navigation, filtering, temporal playback, and the explicit triggering of analytical workflows. Control flow is designed to be intentional and traceable: user actions result in well-defined requests to backend services, and responses are scoped to the user's role, permissions and geographic context.

Feedback processes form an integral part of these interaction patterns. Certain user interactions generate new inputs to the platform, such as citizen reports, survey responses, validation feedback or acknowledgements of alerts. These inputs are captured through dedicated interfaces and reintegrated into the platform via controlled ingestion pathways, ensuring that feedback is treated with the same governance and traceability as sensor-derived data. In this way, EvoRoads supports bidirectional information flow, allowing operational experience and user perception to inform subsequent analyses and decisions without compromising data integrity.

External data exchange is handled through a distinct runtime process that separates internal operation from outward-facing collaboration. Selected datasets and derived artefacts may be exposed to trusted external parties, such as researchers or other data spaces, under explicit policy and access controls. This exchange is initiated either by internal publication actions or by authorised external requests, and is mediated through the platform's federation and governance mechanisms. Importantly, external exchange does not introduce coupling into internal workflows: data products are shared as versioned, well-defined artefacts, preserving internal autonomy and operational stability.

Across user interaction, feedback and external data exchange, the EvoRoads platform maintains consistent logging and provenance tracking through explicit instrumentation of all runtime interactions. These interaction logs are linked to the corresponding analytical outputs and data versions, ensuring that decisions can be traced back to the evidence and configurations on which they were based. Similarly, feedback inputs originating from citizens, operators or stakeholders are ingested through controlled interfaces that apply validation, identity scoping and metadata assignment before the information enters downstream processing. This guarantees that feedback is not treated as an informal or opaque input, but as a governed contribution that can be referenced, re-analysed or excluded as appropriate. For external data exchange, publication and access events are logged at the point of contract establishment and data transfer, recording the scope, purpose and policy context under which data are shared.

By aligning logging and provenance mechanisms across internal interaction and external exchange, the platform enables reconstruction of decision pathways, assessment of accountability and support for post-hoc evaluation or audit.

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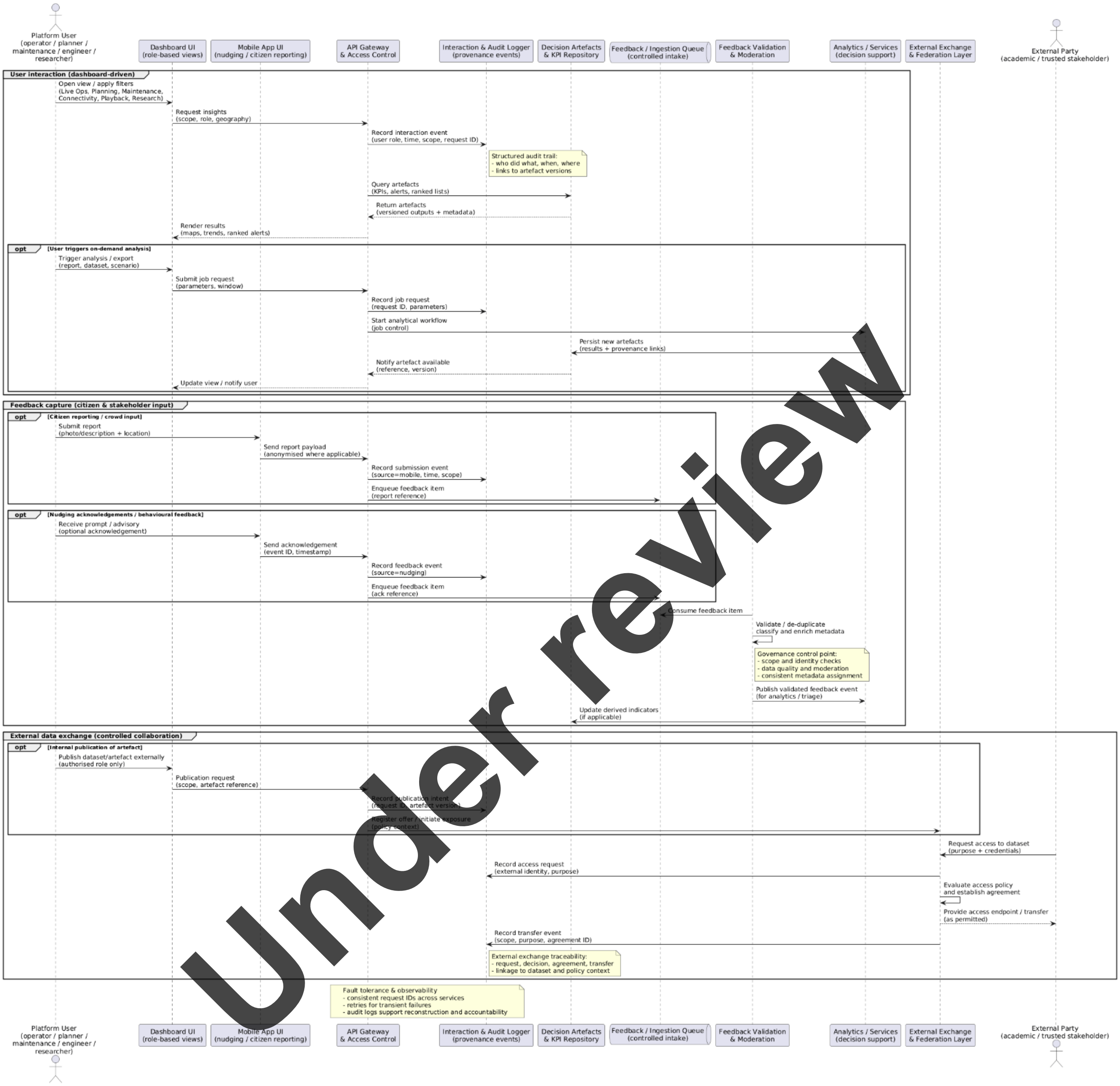

Figure 16: User interaction, feedback, and external data exchange processes

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4.3.5 CONCLUSION OF THE PROCESS VIEW

The Process View has described the dynamic behaviour of the EvoRoads Integrated Platform, focusing on how its components interact at runtime to ingest data, process safety-relevant events, execute analytical workflows and support user interaction and external exchange. By presenting a set of representative interaction patterns rather than an exhaustive enumeration of flows, this view has demonstrated that the platform's runtime behaviour is coherent, scalable and aligned with the diverse operational contexts of the pilots. The Process View complements the Logical View by showing not only what components exist, but how they cooperate under real-world conditions, including variable latency, partial connectivity and human-in-the-loop decision-making.

Importantly, the Process View highlights how EvoRoads balances responsiveness with control. Event-driven ingestion, edge-cloud coordination, traceable analytics and governed interaction mechanisms collectively ensure that safety-relevant information is processed in a timely yet accountable manner. The explicit inclusion of feedback loops and controlled external data exchange further illustrates how the platform integrates operational practice and collaboration without introducing tight coupling or undermining governance principles.

While the Process View concentrates on runtime interactions and control flow, it deliberately abstracts away from software packaging, code structure and development responsibilities. These aspects are addressed in the subsequent **Development View**, which focuses on how the platform is realised as a set of software components, services and interfaces. The Development View therefore builds on the behavioural patterns established here, explaining how they are supported through modular design, clear ownership boundaries and sustainable development practices across the EvoRoads consortium[1].

4.4 DEVELOPMENT VIEW: SYSTEM REQUIREMENTS AND COMPONENT SPECIFICATIONS

The Development View describes how the EvoRoads Integrated Platform is realised as a coherent set of software assets, services and deployment units, and how these are organised to support integration, evolution and reuse across heterogeneous pilot contexts. In contrast to the Logical and Process Views, which focus respectively on functional structure and runtime behaviour, the Development View addresses the **static organisation of software artefacts** and the principles governing their composition.

4.4.1 SCOPE AND INTENT OF THE DEVELOPMENT VIEW

Given the system-of-systems nature of EvoRoads, this view intentionally avoids repeating detailed implementation specifications of individual tools and algorithms. Such details are provided in dedicated WP EvoRoads deliverables (notably D2.1, D2.2, D3.1, D3.2, and forthcoming *"D2.3: Advanced infrastructure monitoring and predictive maintenance tools"* and *"D3.3: Advanced tools for implementing the 'Safe System' approach"*), where they can be treated with the appropriate depth and technical specificity. Instead, the Development View concentrates on how these assets are **assembled into an integrated platform**, how boundaries between components are defined and respected, and how the platform can evolve without destabilising existing deployments.

A central concern of this view is the coexistence of **pilot-specific development autonomy** with **platform-level coherence**. EvoRoads does not impose a monolithic software stack or a single development methodology. Rather, it

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[1] The sequence diagrams of Section 4.3 have been implemented in *PlantUML* (code available) and visualised using the online tool: https://www.planttext.com/ (Accessed December 2025).

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provides a set of architectural conventions - regarding packaging, interfaces, deployment boundaries and data contracts - that allow independently developed components to interoperate reliably. This section therefore focuses on software modularity, interface discipline, deployment alignment and extensibility, rather than on internal algorithmic design.

In addition to describing software organisation and integration mechanisms, the Development View captures a set of system-level and non-functional requirements that apply to the EvoRoads Integrated Platform as a whole. These requirements express quality attributes and operational constraints (such as scalability, deployment flexibility, data protection and evolvability) that arise from integration across pilots and WPs. They are intentionally defined independently of specific technologies or implementations, and complement the functional requirements introduced in the Logical View.

4.4.2 MODULAR COMPOSITION AND SOFTWARE PACKAGING ACROSS EDGE AND CLOUD

The EvoRoads platform is composed of modular software units deployed across two primary operational environments: **edge deployments**, which are pilot-specific and geographically distributed, and **cloud deployments**, which provide shared services and cross-pilot capabilities. This separation is a foundational development decision, reflecting both operational constraints and architectural intent.

Edge deployments host components that must operate close to data sources due to latency, bandwidth, privacy or regulatory considerations. These include sensor interfaces, on-board and roadside processing modules, privacy-preserving transformations (such as face and licence-plate blurring), and pilot-specific preprocessing pipelines. The precise composition of the edge environment varies across pilots, depending on available equipment, local regulations and safety objectives. From a development perspective, edge software units are packaged as self-contained services or applications that can be deployed independently, configured per pilot, and updated without requiring changes to the cloud environment. **Cloud deployments** host the collective and common services of the platform. These include the core data acquisition and processing pipelines, harmonisation services, Digital Twin infrastructure, analytics engines, cataloguing services, federation connectors, and the integrated dashboard. Cloud-based components are developed to be pilot-agnostic, supporting multiple data sources and contexts through configuration rather than code duplication. Packaging at this level favours services that can scale horizontally, accept inputs from multiple pilots, and expose stable interfaces to downstream consumers.

Across both environments, software components are organised to reflect the seven conceptual layers of the EvoRoads architecture. Sensor-facing and acquisition software aligns with the Sensor and Acquisition Layer, while edge-deployed analytics correspond to the Edge Processing and Filtering Layer. Harmonisation services and data engineering pipelines realise the Integration and Harmonisation Layer, and so forth up to the Interface and Application Layer. This alignment ensures that the development structure mirrors the logical architecture, reducing cognitive load and supporting consistent evolution.

Importantly, not all data follow identical paths through these layers. Certain batch datasets - such as satellite imagery or large historical collections - may bypass edge processing and be uploaded directly to cloud environments for analysis. The development structure explicitly supports such variations by allowing components to be composed flexibly, rather than enforcing a rigid pipeline. This composability is achieved through clear interface contracts and deployment-level separation, rather than through hard-coded assumptions about execution order.

4.4.3 INTERFACE CONTRACTS, DATA PIPELINES AND INTEGRATION MECHANISMS

Integration within EvoRoads is achieved primarily through explicit interface contracts and data pipelines, rather than through shared codebases or tightly coupled services. From a development perspective, this is a deliberate choice to preserve autonomy across WPs and pilot teams while ensuring predictable system behaviour.

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Data pipelines (materialised through Task 2.1) constitute the backbone of integration between components. Sensors and edge modules feed data into the data acquisition platform, where events and datasets are transported through streaming or batch mechanisms. At each stage of the pipeline, components interact through well-defined input and output schemas, ensuring that upstream and downstream services remain decoupled. Development teams are free to evolve internal implementations, provided that external contracts are respected.

The use of intermediate data stores - both at the edge and in the cloud - plays a critical role in this structure. Raw data repositories on the edge allow for local buffering, reprocessing and compliance with data-locality constraints. Processed data stores on the edge and in the cloud support staged transformation and validation, enabling partial pipelines to operate independently. From a development standpoint, these repositories act as integration buffers, reducing temporal and functional coupling between components. This concept will be explored in detail in a subsequent subsection pertaining to the Safe Mobility Data Space and will be visualised with a figure in Subsection 5.3.1.3.

Interfaces to the Digital Twin (developed under Task 3.1) are particularly significant. Rather than exposing raw datasets, upstream components publish structured representations of infrastructure state, events and indicators that can be anchored to digital objects such as road segments or assets. This abstraction allows analytical and decision-support components to interact with a consistent conceptual model, regardless of how underlying data were collected or processed. The Digital Twin therefore serves not only as a modelling tool, but as a development-level integration surface.

At the upper layers, APIs exposed to the dashboard and to external data space connectors are designed to be stable and versioned. These APIs encapsulate complexity behind clear service boundaries, allowing user-facing applications to evolve independently of backend analytics. From a development perspective, this separation supports parallel development streams and reduces the risk that changes in one area propagate unpredictably across the platform.

4.4.4 SYSTEM-LEVEL REQUIREMENTS APPLICABLE TO THE EVOROADS INTEGRATED PLATFORM

The following table summarises key system and non-functional requirements that guide the development and integration of the EvoRoads platform. These requirements apply across edge and cloud deployments and are validated collectively through the pilot activities, rather than through any single component implementation.

Table 30: System & non-functional requirements of the EvoRoads platform

ID	Requirement type	System requirement (technology-agnostic)
SR-01	Scalability	The platform shall support ingestion and processing of data from multiple pilots concurrently without requiring architectural changes.
SR-02	Deployment flexibility	Platform components shall be deployable on edge or cloud environments depending on pilot constraints and regulatory requirements.
SR-03	Modularity	Components shall be independently deployable and upgradable without requiring coordinated redeployment of the full platform.
SR-04	Interoperability	The platform shall expose stable, versioned interfaces for data exchange between components and with external systems.
SR-05	Latency tolerance	The platform shall support both real-time and batch processing workflows with clearly separated latency expectations.
SR-06	Fault isolation	Failures in pilot-specific components shall not propagate to other pilots or shared cloud services.

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SR-07	Data locality	Raw sensor data subject to volume or privacy constraints shall be processable locally at the edge.
SR-08	Privacy protection	Privacy-sensitive transformations (e.g. face or licence-plate blurring) shall occur before data leave the edge environment.
SR-09	Traceability	Derived data products and decision artefacts shall maintain traceable links to source data, configurations and processing steps.
SR-10	Auditability	User interactions, data exchanges and analytical executions shall be logged in a manner supporting reconstruction and audit.
SR-11	Configurability	Platform behaviour shall be adjustable through configuration rather than code changes wherever possible.
SR-12	Extensibility	New data sources, analytics or pilot deployments shall be integrable without modifying existing components.
SR-13	Performance isolation	High-volume data flows from one pilot shall not degrade the performance experienced by others.
SR-14	Governance separation	Internal operational data handling shall be decoupled from external data exposure mechanisms.
SR-15	Technology neutrality	The platform shall not impose programming language or framework choices on component developers.

4.4.5 DEVELOPMENT ALIGNMENT WITH WORK PACKAGES AND DEPLOYMENT REALITIES

Although ownership responsibilities are addressed elsewhere, it is important in the Development View to clarify how software organisation aligns with the **structure of the project and its deployment realities**. EvoRoads development is distributed across multiple WPs, each contributing assets that occupy specific positions within the overall architecture. ***Figure 17*** depicts the axes of the EvoRoads platform vision that dominate WPs 2 and 3:

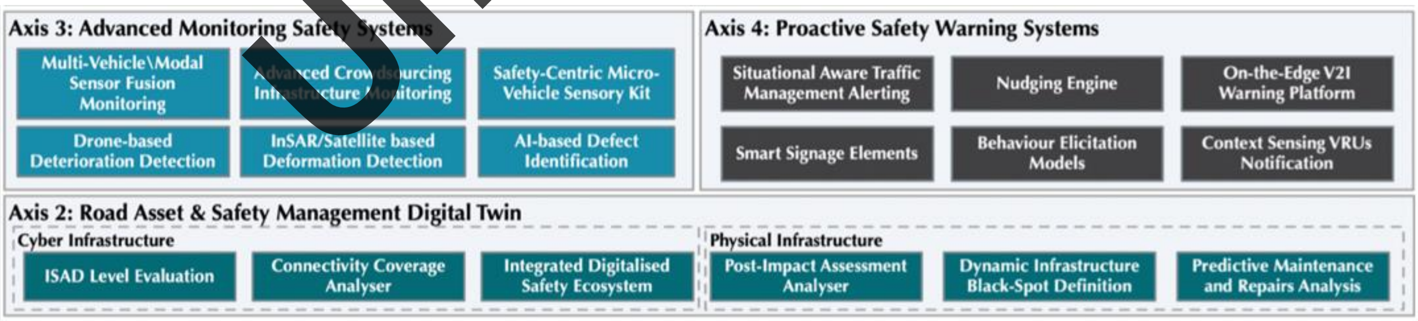

Figure 17: The Axes of the EvoRoads platform governing WP2 and WP3

WP2 focuses primarily on data acquisition, edge processing and infrastructure-level analytics. The software assets produced under this WP are primarily Cloud-deployed. WP 3 contributes Digital Twin models, behavioural analytics and hardware, which are typically (though not exclusively) deployed at the edge. WP1, and in particular Tasks 1.4 and 1.5, provide the integration fabric: harmonisation services, data space infrastructure and user-facing applications. From a development standpoint, this distribution necessitates careful coordination without centralisation. Integration is achieved through shared conventions - on data formats, metadata, APIs and deployment descriptors - rather than through a single development environment or code repository. This allows each WP to progress according to its own timelines and technical constraints, while still contributing to a coherent platform.

Deployment realities further influence development choices. Some pilots require fully local installations due to regulatory or connectivity constraints, while others can rely more heavily on Cloud services. Development practices therefore emphasise configuration-driven deployment, allowing the same software artefact to be instantiated differently depending on context. This approach reduces duplication and supports gradual scaling from pilot deployments to broader operational use.

The **dashboard components**, deployed centrally in the Cloud, exemplify this philosophy. They provide a unified interaction surface across pilots, while consuming data and services that may originate from very different edge environments. From a development perspective, this separation allows UX design to be decoupled from sensing and analytics development, improving maintainability and consistency.

4.4.6 EVOLUTION, EXTENSIBILITY AND LONG-TERM MAINTAINABILITY

A final concern of the Development View is how the EvoRoads platform can evolve over time, both during and beyond the project lifecycle. Evolution is expected at multiple levels: new data sources may be introduced, analytical methods refined, pilot deployments expanded, and interoperability requirements extended.

The **modular development** structure described above supports such evolution by isolating change. New sensors or edge processing modules can be introduced by extending ingestion pipelines, without requiring modification of cloud analytics. New analytical services can be added by consuming existing Digital Twin interfaces, without altering data acquisition mechanisms. Similarly, additional dashboard views or external data products can be developed on top of stable APIs.

Schema evolution is managed through versioned data contracts and metadata descriptors, allowing components to coexist across transition periods. From a development perspective, this reduces the need for coordinated “big-bang” updates and supports incremental improvement. The explicit separation between raw, processed and derived data stores further aids this process, allowing reprocessing or backfilling where necessary.

Avoidance of vendor or platform lock-in is another design consideration reflected in development choices. By relying on open interfaces, modular packaging and deployable services, EvoRoads ensures that components can be replaced or re-implemented without disrupting the overall system. This is particularly important for public authorities and infrastructure operators, for whom long-term sustainability and procurement flexibility are critical.

In summary, the Development View demonstrates that the EvoRoads Integrated Platform is not a fixed software product, but a structured ecosystem of components designed for controlled integration and evolution. By aligning development practices with architectural layers, deployment realities and interoperability principles, the platform establishes a credible foundation for continued use, extension and adoption beyond the duration of the project.

4.4.7 CONCLUDING COMMENTS FOR THE DEVELOPMENT VIEW

The Development View has described how the EvoRoads Integrated Platform is organised as a modular and composable set of software assets, and how integration, evolution and system-level requirements are addressed across heterogeneous components. By focusing on software structure, interface contracts and deployment flexibility, this view has established how independently developed assets can be assembled into a coherent platform without imposing centralised implementation constraints.

The subsequent Physical View builds on this foundation by examining how the platform is instantiated in concrete deployment environments. It addresses the mapping of software components to physical and virtual infrastructure, the

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distribution of functionality across edge and cloud resources, and the operational constraints that shape deployment choices at pilot sites. In doing so, the Physical View complements the Development View by shifting focus from software organisation to execution context, illustrating how architectural decisions are realised in practice across diverse geographic, regulatory and infrastructural settings.

4.5 PHYSICAL VIEW: DEPLOYMENT CONTEXT AND EXECUTION ENVIRONMENT

The **Physical View** describes the execution environment of the EvoRoads Integrated Platform, focusing on how architectural elements are hosted, secured and made operational across infrastructure resources. Unlike the Logical and Process Views, which abstract functionality and runtime behaviour, this view addresses the tangible constraints of computing environments, hosting models and deployment boundaries. Given the research-oriented nature of EvoRoads and the phased maturity of its technical assets, the Physical View does not currently attempt to prescribe final deployment topologies or optimisation strategies. Instead, it documents the concrete infrastructure assumptions, shared hosting services and security foundations that enable platform operation at this stage, while transparently identifying aspects that will be refined in later project phases and future deliverables.

4.5.1 CLOUD HOSTING ENVIRONMENT AND SHARED INFRASTRUCTURE SERVICES

The EvoRoads Integrated Platform relies on a centrally managed **cloud hosting environment** to provide the shared infrastructure services required for cross-pilot integration, analytics, data management and user interaction. This cloud environment constitutes the physical execution context for those platform components that are common across all pilots and that cannot be bound to a single geographic location or local operational authority. It enables the integration of heterogeneous pilot deployments into a coherent system while avoiding dependency on any single pilot's local infrastructure. The cloud environment hosts platform-level services that realise the upper layers of the EvoRoads architecture, including the data acquisition and harmonisation services, the Digital Twin infrastructure, analytics and decision-support components, cataloguing and data-space interfaces, and the integrated dashboard. These services require persistent availability, shared access and consistent configuration across pilots, making a centralised cloud deployment both appropriate and necessary.

4.5.1.1 CLOUD PROVIDER AND INFRASTRUCTURE MODEL

At the time of writing, the EvoRoads cloud infrastructure is provisioned using services offered by the Hetzner Cloud [2] provider. Hetzner provides an **Infrastructure-as-a-Service (IaaS) environment** that allows the project to instantiate virtual servers, attach persistent and ephemeral storage volumes, and configure network connectivity between services.

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This choice supports flexibility and scalability while maintaining clear responsibility boundaries. The cloud provider is responsible for the physical data centres, hardware maintenance and baseline availability, while EvoRoads partners retain full control over the configuration and operation of the virtualised resources. This model allows the platform to evolve incrementally as integration needs become clearer, without committing prematurely to fixed deployment topologies.

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[2] The official website of Hetzner is accessible via this link: https://www.hetzner.com/cloud (Accessed December 2025).

4.5.1.2 SHARED SERVICES AND MULTI-PILOT OPERATION

The EvoRoads cloud environment is designed to support multi-pilot operation through shared services rather than isolated, per-pilot cloud deployments. Logical separation between pilots is achieved through configuration, access control and data scoping, not through strict physical isolation of virtual machines.

This approach enables cross-pilot analytics, benchmarking and comparative assessments while preserving governance boundaries. Shared services such as the Digital Twin or analytics engines can operate over multiple datasets, with pilot-specific views enforced at the application and access-control layers. Where necessary, additional cloud resources can be provisioned to accommodate increased data volumes or computational demand without altering the overall architectural model.

4.5.1.3 SECURITY-BY-DESIGN AT INFRASTRUCTURE LEVEL

Several infrastructure-level security measures are already in place within the EvoRoads cloud environment.

All storage volumes attached to cloud-hosted virtual machines are **encrypted at rest** using mechanisms provided by the cloud provider. This ensures that data stored on physical media remain protected against unauthorised access in the event of hardware loss, decommissioning or compromise. Network access to cloud-hosted services is regulated through **firewall configurations** that restrict inbound and outbound traffic. Default-deny policies are applied unless specific communication paths are explicitly enabled. This reduces the exposed attack surface and ensures that only authorised users and systems can access platform services. **Reverse proxy components** are used to structure access to internal services. Rather than exposing backend services directly, reverse proxies act as controlled ingress points, terminating external connections and forwarding requests to appropriate internal components. This pattern simplifies service exposure, supports consistent security enforcement and allows internal service configurations to evolve without impacting external interfaces.

4.5.1.4 SECURE COMMUNICATION AND IDENTITY MANAGEMENT

All external communication with cloud-hosted EvoRoads services is performed over encrypted channels, typically using HTTPS/TLS. This ensures confidentiality and integrity of data exchanged between users, services and authorised external systems.

User authentication and authorisation are handled **centrally** using an identity and access management service based on Keycloak [3]. This enables role-based access control aligned with the personas defined within EvoRoads, such as road safety operators, planners, maintenance managers, researchers and public users. Centralised identity management ensures consistent enforcement of access policies across all shared services and avoids duplication of access-control logic within individual components. Role-based access control also supports the separation of operational and administrative responsibilities. Users are granted access only to the views, datasets and actions relevant to their role and geographic scope, while administrative functions are restricted to authorised personnel.

4.5.1.5 DEPLOYMENT MATURITY AND CURRENT LIMITATIONS

At the current stage of the project, detailed deployment diagrams mapping individual services to specific virtual machines or defining orchestration strategies have not yet been finalised. This is a deliberate and transparent choice. During the

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[3] The official website of the Keycloak open-source project is available here: https://www.keycloak.org/ (Accessed December 2025).

first phase of EvoRoads, emphasis has been placed on architectural integration, functional validation and end-to-end workflow coherence rather than on infrastructure optimisation.

Similarly, EvoRoads does not currently operate a fully automated continuous integration or continuous deployment pipeline for platform-level services. Integration activities are coordinated across WPs and partners, prioritising functional correctness and architectural alignment. More advanced automation, orchestration or scaling mechanisms remain potential evolution paths to be assessed as the platform matures and operational requirements become clearer.

In summary, the EvoRoads cloud hosting environment provides a secure and flexible physical foundation for shared platform services, grounded in a public IaaS offering and structured around clear hosting, security and access principles. While detailed deployment topologies and automation mechanisms are intentionally deferred, the current Physical View establishes the constraints and assumptions that govern cloud-based operation. This approach ensures technical credibility, avoids premature commitments, and prepares the ground for more detailed deployment specifications to be presented in subsequent deliverables, notably *D1.4*.

4.5.2 SECURITY, ACCESS CONTROL AND TRUST BOUNDARIES

Beyond the security characteristics of the hosting environment itself, the EvoRoads Integrated Platform defines a set of access control and trust boundaries that govern how users, services and external systems interact with deployed components. These mechanisms are designed to support secure operation across multiple pilots and stakeholders, while remaining compatible with the research-oriented nature of the project and the evolving state of deployment.

At platform level, access to cloud-hosted services is mediated through authenticated interfaces rather than direct infrastructure access. User-facing components, including the integrated dashboard and selected application services, are exposed through controlled entry points such as **reverse proxies**, ensuring that internal services and data stores are not directly reachable from external networks. This separation limits the attack surface and allows access policies to be enforced consistently across different services without requiring uniform deployment configurations at pilot level.

Authentication and identity management are handled centrally using a dedicated identity and access management service, with Keycloak serving as the primary identity broker. This enables the definition of distinct user roles corresponding to the personas addressed by the platform, such as road safety operators, maintenance planners, policy users and researchers. Authentication mechanisms are applied uniformly across web-based interfaces and APIs, allowing both human users and machine-to-machine interactions to be governed under the same identity framework. While full federation with external identity providers is not required at this stage, the chosen approach supports future integration should the platform evolve beyond the project lifecycle. **Authorisation** within the platform is based on **role-aware access** to services and data, rather than fine-grained per-component permissions. This reflects a deliberate design choice to balance security with manageability during the project phase. Access rights are scoped according to function and responsibility, ensuring, for example, that operational users can view and act upon safety alerts relevant to their jurisdiction, while research-oriented users may access aggregated or anonymised datasets through dedicated interfaces. Pilot-specific constraints and governance rules are respected by enforcing logical separation at service and data access level, rather than by duplicating infrastructure.

Trust boundaries are explicitly acknowledged between the cloud-hosted platform services and the pilot-level environments from which data originate. Data entering the cloud environment are assumed to have **undergone appropriate pre-processing and compliance checks** at source, particularly where personal or sensitive information is involved. Conversely, the cloud platform does not assume control over pilot-side systems or enforcement of local security policies. This delineation of responsibility ensures that pilot operators retain control over their infrastructure, while the integrated platform remains accountable for the security of shared services and exposed interfaces.

External access, including interaction with data spaces or third-party systems, follows the same principle of controlled exposure. APIs and data exchange mechanisms are designed to support authenticated and authorised access, with explicit governance over what data can be shared, under which conditions, and at what level of aggregation. This approach

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aligns with the broader EvoRoads data governance framework and avoids implicit trust relationships between the platform and external ecosystems.

Importantly, the security and access control mechanisms described here are (see also ***Figure 18***) intended to provide a robust baseline rather than a fully automated or self-adaptive security posture. Advanced capabilities such as continuous security monitoring, automated policy enforcement or dynamic trust evaluation are outside the scope of the current deployment phase and will be considered only where justified by future operational requirements. By clearly defining what is implemented and what remains prospective, EvoRoads maintains transparency while establishing a credible foundation for secure, multi-stakeholder operation.

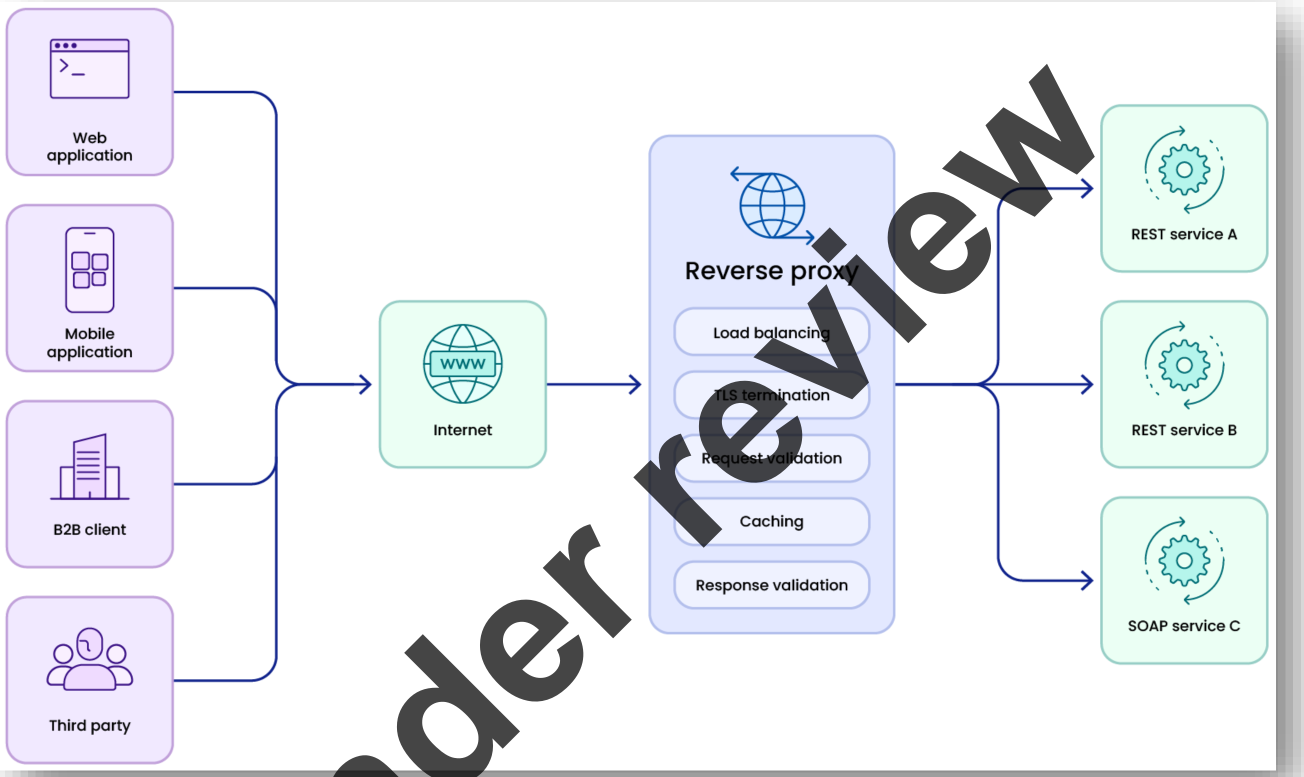

Figure 18: Access control approach of the EvoRoads platform

4.5.3 PHYSICAL CONSTRAINTS, ASSUMPTIONS AND EVOLUTION TOWARDS FINAL DEPLOYMENT

The Physical View presented in this deliverable reflects the current maturity stage of the EvoRoads Integrated Platform and is intentionally scoped to avoid premature or speculative deployment commitments. As a Research and Innovation Action, EvoRoads operates under evolving technical, organisational and regulatory conditions, particularly across pilot sites with heterogeneous infrastructure and governance requirements. Consequently, certain physical deployment aspects remain subject to refinement as implementation progresses and as integration activities mature.

A primary constraint concerns the incomplete finalisation of deployment topologies for both cloud and pilot-level environments. While shared cloud infrastructure assumptions have been established, the exact distribution of services across virtual machines, container runtimes and supporting middleware has not yet been fully defined. This is a deliberate

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outcome of the phased integration strategy adopted by the project, whereby component-level development and pilot-specific validation take precedence over early consolidation of a fixed deployment model. As a result, detailed deployment diagrams, resource sizing and orchestration strategies are deferred to a later stage.

Similarly, the physical installation and configuration of software components within pilot environments are influenced by factors that vary across sites, including available hardware, connectivity constraints, local operational practices and regulatory mandates. While common patterns for data ingestion, edge processing and cloud interaction have been identified, the precise mechanisms by which these are realised in each pilot are expected to differ. The present deliverable therefore avoids prescribing uniform installation procedures or edge deployment architectures, focusing instead on shared principles and interfaces.

Another important assumption relates to the progressive containerisation of algorithms and services. Although many components are designed to be containerised and exposed through APIs, the definition of these interfaces and the adoption of orchestration mechanisms are ongoing activities. At this stage, EvoRoads does not rely on fully automated deployment pipelines or continuous delivery processes. Integration and deployment are managed through coordinated integration cycles, with testing and validation activities conducted collaboratively across WPs. This pragmatic approach reflects the research-driven nature of the project and mitigates the risk of over-engineering early deployments.

Looking ahead, the evolution towards a consolidated final deployment will be addressed explicitly in Deliverable *D1.4*. That deliverable will document refined deployment architectures, including concrete diagrams, clarified integration points and updated security and access control configurations, based on lessons learned during pilot execution and system integration. By separating the foundational assumptions documented here from the final deployment specifications to be presented later, EvoRoads ensures transparency, technical credibility and a clear progression from architectural intent to operational realisation.

4.6 SCENARIOS VIEW: ARCHITECTURAL VALIDATION THROUGH EVOLVING OPERATIONAL NARRATIVES

The **Scenarios View constitutes the "+1" perspective** of the 4+1 architectural model and serves as a means to validate and contextualise the architecture by illustrating how it supports realistic system usage. In EvoRoads, this view is realised through a well-defined set of pilot-specific and cross-pilot use cases that describe how the integrated platform supports safety-oriented decision-making in real operational contexts. These scenarios reflect the actual workflows exercised during demonstrations and form a key instrument for validating both individual components and the platform as a whole.

In the context of the present deliverable, the Scenarios View is not described exhaustively. This is not due to any deviation from the classical interpretation of the 4+1 model, nor to an absence or abstraction of use cases within the project. On the contrary, EvoRoads has established concrete and detailed scenarios that guide pilot activities, integration efforts and evaluation planning. However, these scenarios are documented in dedicated WP deliverables - most notably within WP4 - and are already introduced from a user and operational perspective in Chapter 2 of this document. Reproducing them in full here would lead to unnecessary duplication and dilute the architectural focus of Chapter 4.

Instead, the role of the Scenarios View subsection within this chapter is to confirm that the architecture presented through the Logical, Process, Development and Physical Views is consistent with, and capable of supporting, the defined operational use cases. The scenarios exercised across pilots collectively span the full safety decision chain (from detection and diagnosis to prioritisation, intervention planning and impact assessment) and involve heterogeneous actors, data sources and temporal constraints. As such, they provide a comprehensive validation backdrop for the architecture, even when not restated in procedural detail. The architectural views presented earlier can be directly traced to scenario needs. The Logical View establishes the components and responsibilities required by the use cases; the Process View demonstrates how runtime interactions realise scenario workflows; the Development View ensures that integration across

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partners and technologies is feasible; and the Physical View grounds execution within realistic deployment constraints. Taken together, these views show that the architecture is not an abstract construct, but one that is explicitly shaped by and aligned with the scenarios exercised in the pilots.

In this sense, the Scenarios View plays its classical role: it validates architectural choices through concrete use, without redefining or substituting the scenario descriptions themselves. Detailed scenario narratives, step-by-step operational flows and evaluation criteria are therefore intentionally left to the deliverables where they are most effectively addressed and maintained as living artefacts throughout the project.

4.7 CONCLUSION

Chapter 4 has presented the EvoRoads Integrated Platform Architecture using the 4+1 model, demonstrating coherence across structural, behavioural, developmental and physical perspectives, and confirming alignment with the project's operational scenarios. Building on this architectural foundation, **Chapter 5 shifts focus to the Safe Mobility Data Space**, examining how data governance, interoperability and controlled data sharing are implemented to support both internal platform functions and interaction with the wider European mobility data ecosystem.

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5 SAFE MOBILITY DATA SPACE (SMDS)

Building upon the description of the integrated EvoRoads platform presented in the previous chapter, this chapter narrows the focus to the **Safe Mobility Data Space (SMDS)**, a core enabling component developed within the scope of Task 1.4. While the overall platform brings together sensing, analytics, digital twins and user-facing services, the SMDS constitutes the foundational layer through which data are systematically collected, harmonised, governed and made available for advanced safety assessment and decision support. The chapter provides a comprehensive overview of the SMDS as conceived and implemented in the EvoRoads project, situating it within the broader landscape of European initiatives on mobility data spaces and trusted data sharing. It first reflects on the state of the art in data space architectures for transport and mobility, highlighting emerging principles related to interoperability, federated access and secure data exchange. It then introduces the architectural design of the EvoRoads SMDS, describing how heterogeneous data sources - ranging from infrastructure monitoring and vehicle-based sensing to contextual and behavioural datasets - are integrated into a coherent and extensible data environment. Particular emphasis is placed on the mechanisms that enable semantic interoperability, data quality management and scalable integration across pilots and domains. In addition, the chapter discusses key cross-cutting concepts underpinning the SMDS, including data governance, trust, and data sovereignty, which are essential for ensuring compliance with European regulatory frameworks and for strengthening stakeholder confidence in data sharing processes. By articulating both the conceptual foundations and the practical implementation choices of the EvoRoads SMDS, this chapter sets the scene for a deeper examination of how data spaces can support safer, more resilient and more transparent mobility systems across diverse European contexts.

5.1 STATE-OF-THE-ART AND EXISTING PAN-EUROPEAN MOBILITY DATA SPACES

This subsection will provide an overview of existing pan-European mobility data spaces, focusing on initiatives and platforms that aim to aggregate and share mobility-related data across Europe. It will cover key developments in the field, discuss the integration of data from various sources, and highlight the benefits and challenges these data spaces face.

5.1.1 OVERVIEW OF SELECTED PAN-EUROPEAN MOBILITY DATA SPACE INITIATIVES

The notion of a *mobility data space* has emerged in Europe as a policy-driven response to a long-standing tension: the mobility sector generates vast volumes of potentially high-value data, yet the corresponding data landscape remains fragmented across modes, jurisdictions, and public–private boundaries. The European Commission explicitly frames the **Common European Mobility Data Space** (often abbreviated as **EMDS**) as an instrument to facilitate access, pooling and sharing of transport and mobility data from existing and future sources, thereby supporting digitalisation and a more interconnected multimodal system; the Commission further emphasises that fragmentation currently constrains innovation and limits the benefits of data-driven mobility [71]. This policy trajectory is reflected in a set of complementary initiatives; some targeting federation and governance, others providing deployment projects and technical building blocks, and others focusing on specific data domains (e.g., safety-related traffic information). The following overview highlights how the initiatives listed in this section collectively shape the contemporary state-of-the-art that informs EvoRoads' Safe Mobility Data Space (SMDS) design choices.

At the level of **EU policy and reference framing**, the Commission's "Creating a common European mobility data space" page [71] is particularly instructive as it articulates the problem statement and desired direction of travel. It links the EMDS ambition to broader strategic objectives such as sustainability, competitiveness and resilience, and positions data sharing and interoperability as prerequisites for achieving these ends. Importantly, the Commission's framing does not prescribe a single centralised platform; instead, it motivates a *federating* approach capable of connecting multiple data ecosystems

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and enabling reuse across passengers and freight contexts [71]. This is a foundational point for SMDS-like architectures: “data space” is not merely a repository concept, but a socio-technical construct combining shared rules, interoperability mechanisms, and trust/safeguards for controlled exchange.

From a **deployment and operationalisation** perspective, the **deployEMDS** initiative[4] can be read as a concrete step towards turning the EMDS policy ambition into an implemented infrastructure and community of practice. The project presents itself as co-funded under the EU Digital Europe Programme and explicitly states that it aims to help make the common European mobility data space a reality by cultivating a broad European ecosystem of data providers and users while facilitating adoption of “common building blocks”. Its public materials foreground three technical–organisational pillars: **data interoperability**, **data sovereignty and trust**, and **accessibility** (discoverability and availability); which collectively function as a pragmatic specification of the minimum properties expected from EMDS-aligned data exchange. Additionally, deployEMDS frames the EMDS as a “framework for interlinking and federating ecosystems”, signalling that interoperability in this context is expected to be multi-ecosystem and cross-border by design rather than limited to harmonisation within a single domain. For EvoRoads, this emphasis on common building blocks and federation is directly relevant when positioning SMDS as an extensible layer that can interoperate with external initiatives rather than compete with them.

Where deployEMDS focuses on deployment at ecosystem scale, **NAPCORE** addresses a closely related but historically distinct backbone: **National Access Points (NAPs)[5]**. NAPs are mandated under the EU ITS Directive and delegated regulations as national platforms for publishing and making available mobility-related data, notably for travel information services. NAPCORE identifies that NAPs have evolved heterogeneously, exhibiting differences in set-up, data access interfaces, and the standards and formats used across Europe; precisely the types of divergences that undermine pan-European interoperability if left unaddressed. It therefore positions itself as a coordination mechanism aimed at improving interoperability of NAPs through standard harmonisation and alignment, and at expanding access and availability through coordinated procedures and strategy. In this sense, NAPCORE provides an institutional and technical convergence layer for a key subset of public-sector mobility data exchange. For the EvoRoads SMDS, the relevance lies in two directions: (i) leveraging NAP-aligned standards, cataloguing approaches and quality practices where appropriate, and (ii) ensuring that EvoRoads data assets can be made visible and re-usable in ways compatible with NAP-based dissemination where governance permits.

A distinct, domain-specialised initiative[6] is **Data for Road Safety (DFRS)**, which presents itself as a *Safety Related Traffic Information (SRTI) ecosystem* supporting the exchange of safety-related traffic data and information at European scale. Its framing emphasises the need for mass involvement across vehicle manufacturers, traffic information service providers, suppliers and public authorities to achieve the critical mass of safety data required for impactful services, and it explicitly invites partners to join and exchange safety-related traffic data. In contrast to broader mobility data space efforts, DFRS is anchored in a specific safety data-sharing objective[7] and a set of associated artefacts (e.g., multi-party agreements and technical documentation) exposed through its “Key Documents” section. Conceptually, DFRS illustrates how a mobility data space can be instantiated as a *purpose-driven data ecosystem* with well-defined participants, governance arrangements, and operational data exchange, rather than as a general-purpose data marketplace. For EvoRoads SMDS, DFRS provides a valuable precedent: safety-oriented data exchange requires not only interoperability, but also explicit

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[4] The official website of the deployEMDS initiative is accessible here: https://deployemds.eu/ (Accessed December 2025).

[5] The official website of the NAPCORE initiative is accessible here: https://napcore.eu/ (Accessed December 2025).

[6] The official website of the Data for Road Safety initiative is accessible here: https://dataforroadsafety.eu/ (Accessed December 2025).

[7] An interactive map containing the DFRS-collected data is accessible here: https://dataforroadsafety.eu/dfrs-live-map (Accessed December 2025).

attention to trust, privacy, and liability considerations that are often encoded through contractual and procedural instruments alongside technology.

In parallel, initiatives such as **MobiSpaces**[8] illustrate the research and innovation strand of the European data space movement. MobiSpaces explicitly labels its mission as developing “new data spaces for green mobility” and characterises its platform as an ecosystem spanning the lifecycle of mobility data. It further contextualises its contribution through multiple real-life use cases across urban and maritime mobility domains, thereby illustrating how data space principles can be applied to heterogeneous operational environments rather than a single modal context. While the detailed technical scope differs across projects, the salient state-of-the-art contribution for SMDS is methodological: MobiSpaces exemplifies the coupling of data space concepts with edge-to-cloud data processing, modern data management practices, and a validation strategy grounded in concrete use cases (a pattern increasingly common across EU-funded data space projects).

Finally, the Mobility Data Space community[9] is illustrative of a *data space as an operational community and service environment*, explicitly convening organisations that “need data” and those who seek to monetise data assets. Notably, it positions itself within the **Gaia-X** context[10], and highlights institutionalisation aspects (e.g., a holding company structure and the link to a public-sector platform for exchanging digital information, established in 2025). For SMDS, this is a reminder that “data space maturity” is not solely measured in software components: sustainable data spaces typically require governance bodies, onboarding processes, and community mechanisms that support both public-interest and market-oriented participation. In aggregate, these initiatives provide the immediate European state-of-the-art backdrop for EvoRoads SMDS: a federated, standards-aware and governance-led approach to mobility data sharing, with sovereignty and trust treated as first-class design constraints rather than optional add-ons.

5.1.2 DATA-SHARING MODELS IN EXISTING MOBILITY DATA SPACE INITIATIVES

A defining characteristic of contemporary mobility data spaces is the manner in which data sharing is organised across organisational, national and sectoral boundaries. Existing European initiatives reveal a spectrum of data-sharing models, ranging from relatively centralised architectures to explicitly federated and decentralised approaches. These models are not mutually exclusive; rather, they reflect different trade-offs between governance control, scalability, data sovereignty and ease of access. Analysing these trade-offs is essential for positioning the EvoRoads Safe Mobility Data Space (SMDS) within the European state of the art and for ensuring technical and semantic alignment with established mobility data ecosystems.

Historically, centralised data-sharing models have played a prominent role in European transport data policy, particularly through the establishment of NAPs under the ITS Directive [72]. In this configuration, datasets are published and accessed via a single national platform, offering a clear point of responsibility and a uniform access mechanism. However, as the volume and heterogeneity of mobility data have increased, the limitations of strict centralisation have become evident. Central platforms often struggle to accommodate heterogeneous data lifecycles, real-time streams and evolving access policies, while cross-border interoperability remains dependent on sustained harmonisation efforts across multiple national systems.

The **NAPCORE** initiative directly addresses these challenges by focusing on convergence rather than replacement of existing NAP infrastructures. A cornerstone of this effort is the harmonisation of metadata through the adoption and

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[8] The official website of the MobiSpaces initiative is accessible here: https://mobispaces.eu/ (Accessed December 2025).

[9] The official website of the Mobility Data Space initiative is accessible here: https://mobility-dataspace.eu/ (Accessed December 2025).

[10] The official website of the Gaia-X initiative is accessible here: https://gaia-x.eu/ (Accessed December 2025).

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refinement of the **mobilityDCAT-AP** profile[11]. mobilityDCAT-AP provides a common semantic framework for describing mobility datasets, enabling consistent discovery, interpretation and reuse across national and European platforms. By standardising dataset descriptions rather than enforcing centralised data storage, NAPCORE supports a decentralised yet interoperable ecosystem in which data remain under the control of their original providers. This metadata-driven approach is highly relevant to EvoRoads SMDS, as it underscores the importance of semantic interoperability as a prerequisite for federated data sharing. Building on this foundation, EvoRoads (through T1.4, T6.4) has developed an **extension of mobilityDCAT-AP** tailored to the specific characteristics of its pilot environments and safety-oriented data assets. While mobilityDCAT-AP provides a robust baseline for dataset description, it does not natively capture several attributes critical for EvoRoads use cases, such as dynamic safety indicators, infrastructure condition assessments, sensor-derived features or links to composite safety KPIs. The EvoRoads extension addresses this gap by introducing additional metadata elements that preserve compatibility with the core profile while enabling richer semantic annotation of pilot-generated data. This approach ensures that EvoRoads datasets can be seamlessly exposed to external mobility data spaces while retaining the expressiveness required for advanced safety analytics.

Beyond metadata harmonisation, federated data-sharing models are increasingly recognised as the preferred architectural pattern for European data spaces. In federated configurations, data remain at source and are accessed through standardised interfaces governed by shared trust and governance frameworks. This paradigm aligns closely with the European data strategy’s emphasis on data sovereignty, allowing data providers to retain control over access conditions, usage rights and revocation. Federated models also enhance scalability and resilience, as participation does not depend on integration into a single central infrastructure. The **TN-ITS (Traffic and Navigation Information Services)** framework[12] provides a concrete example of decentralised data exchange in practice. TN-ITS enables road authorities to publish authoritative traffic and regulation data directly, while service providers retrieve this information through agreed interfaces and specifications. This model prioritises data freshness, legal authority and traceability, attributes that are particularly important for safety-critical information. At the same time, it demonstrates that decentralised publication can coexist with pan-European interoperability, provided that governance rules and technical specifications are clearly defined. For EvoRoads SMDS, TN-ITS offers a relevant reference point for the decentralised dissemination of authoritative infrastructure and safety-related data.

In practice, many European initiatives adopt **hybrid data-sharing models**, combining centralised coordination functions with decentralised data storage and access. Central services often include catalogues, identity management and governance coordination, while datasets themselves remain distributed. NAPCORE’s metadata catalogue strategy, grounded in mobilityDCAT-AP, exemplifies this hybrid approach, as does the broader vision of the Common European Mobility Data Space. Such models seek to balance discoverability and ease of access with respect for sovereignty and organisational autonomy.

The EvoRoads SMDS consciously adopts this federated–hybrid paradigm. Data generated across pilots are exposed through interoperable interfaces, described using mobilityDCAT-AP and its EvoRoads-specific extension, and governed by explicit access and usage policies. This design ensures alignment with existing European mobility data-sharing practices while extending them to accommodate novel safety data types and analytics outputs. By embedding metadata harmonisation, decentralised control and clear governance mechanisms at its core, SMDS positions EvoRoads as a technically and conceptually coherent contributor to the evolving European mobility data space ecosystem.

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[11] The technical specification and documentation of the mobilityDCAT-AP - Version 3.0.0 and specifically its unofficial draft 02 April 2025 is accessible here: https://mobilitydcat-ap.github.io/mobilityDCAT-AP/drafts/latest/index.html (Accessed December 2025).

[12] The official website of the TN-ITS platform is accessible here: https://tn-its.eu/ (Accessed December 2025).

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5.1.3 CHALLENGES AND GAPS IN CURRENT MOBILITY DATA SPACES

Despite the significant progress made through European initiatives on mobility data spaces, a number of persistent challenges and structural gaps remain. These challenges span technical, organisational, economic and temporal dimensions, and they have direct implications for projects such as EvoRoads that seek both to align with existing data space ecosystems and to deliver a self-contained, research-driven technical proposition. Understanding these limitations is essential not only for contextualising the EvoRoads Safe Mobility Data Space (SMDS) within the current state of the art, but also for articulating its added value and realistic pathways for integration or long-term interoperability.

A first major challenge concerns **temporal misalignment and sustainability** [73] [74] [75]. Many European mobility data space initiatives (including those funded under Horizon Europe, CEF Digital or Digital Europe) are constrained by fixed project lifecycles, typically spanning three to four years. While these timelines are sufficient for architectural design, piloting and early deployment, they are often insufficient for achieving stable integration with long-running operational ecosystems. In practice, data spaces mature over longer periods, requiring sustained governance, onboarding of participants, iterative refinement of standards, and trust-building between public and private actors. For EvoRoads, this creates a structural tension: the SMDS must demonstrate alignment and interoperability within the project's duration, while recognising that some target initiatives may evolve on different timelines or reach operational maturity only after EvoRoads has concluded.

A related gap arises from **asymmetries in organisational maturity and market positioning** [76] [77]. Certain initiatives, such as DFRS, operate as established ecosystems with long-term contractual arrangements, defined membership models and strong involvement from major industry players. Entry into such ecosystems typically requires not only technical compatibility, but also formal agreements, compliance with operational policies, and sustained commitments that extend beyond the scope of a research project. For EvoRoads, direct integration into these ecosystems during the project lifetime may therefore be constrained, not due to technical incompatibility, but due to governance and commercial realities. This highlights a broader challenge for research-driven data spaces: while they can align architecturally with operational initiatives, full integration often depends on post-project exploitation strategies rather than on technical readiness alone.

From a technical perspective, **heterogeneity of data models and semantic depth** remains a significant barrier [78]. While initiatives such as NAPCORE and mobilityDCAT-AP have advanced metadata harmonisation, many operational data spaces focus primarily on dataset discovery and access rather than on deep semantic integration of derived or analytical data. EvoRoads SMDS, by contrast, manages complex safety-related data products, including derived indicators, composite KPIs and outputs from advanced analytics and digital twins. Exposing these assets in a way that is both compliant with existing metadata standards and sufficiently expressive to preserve their meaning requires extensions and mappings that are not yet universally supported. This creates a gap between baseline interoperability and meaningful semantic interoperability, particularly when moving beyond raw or observational datasets.

Another challenge lies in **governance diversity and fragmentation** [79] [80]. Current mobility data spaces vary widely in their governance models, ranging from public-sector-led coordination (e.g. NAPs) to consortium-based ecosystems and market-oriented platforms. Each model defines its own rules for access control, liability, data quality assurance and dispute resolution. For EvoRoads SMDS, operating across multiple pilots and national contexts, aligning with all these governance regimes simultaneously is not feasible. Instead, SMDS must adopt a flexible governance-by-design approach, capable of interfacing with different external regimes while maintaining internal coherence and compliance. This reinforces the need for SMDS to function as a stand-alone data space that can selectively interoperate with external initiatives without being structurally dependent on any single one.

Trust and data sovereignty mechanisms also represent an area where gaps persist [81]. While the principles of data sovereignty are widely endorsed at policy level, their concrete implementation varies considerably across initiatives. Some ecosystems rely heavily on contractual trust, others on technical enforcement mechanisms, and others on institutional authority. EvoRoads SMDS must operate in this fragmented trust landscape while managing sensitive safety-related data that may have legal, ethical or reputational implications. Ensuring that data providers retain control over their assets, while

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enabling controlled sharing for cross-pilot and cross-domain analysis, is a non-trivial challenge; particularly when interoperability with external data spaces may require additional assurances or certifications not fully defined at present.

A further gap concerns **scalability and transition from pilot to operation** [82]. Many existing data spaces are still in pilot or early deployment phases, with limited numbers of participants and datasets. Conversely, initiatives that are already operational often prioritise stability over experimentation. EvoRoads SMDS occupies an intermediate position: it must support experimental, research-oriented use cases while also being credible as a foundation for future operational deployment. This dual role complicates both direct integration into mature ecosystems and alignment with early-stage initiatives whose architectures may still be evolving.

Taken together, these challenges suggest that a binary choice between direct integration and isolation is neither realistic nor desirable for EvoRoads SMDS. Instead, SMDS is positioned as a **stand-alone yet interoperable data space**, designed to align with European standards, principles and reference architectures, while remaining autonomous in governance and operation during the project lifecycle. This approach allows EvoRoads to contribute technically and conceptually to the European mobility data space landscape, even where immediate full integration is not feasible. At the same time, it preserves the flexibility required for post-project exploitation, whether through selective integration into established ecosystems, alignment with emerging initiatives, or continued independent operation. In this sense, the challenges and gaps of current mobility data spaces are not merely constraints for EvoRoads, but also key design drivers shaping the SMDS as a resilient, future-facing technical proposition.

5.2 OBJECTIVES, METHODOLOGICAL APPROACH AND ALIGNMENT PRINCIPLES OF THE EVOROADS SMDS

Building on the preceding analysis of the state of the art, this section introduces the Safe Mobility Data Space (SMDS) of EvoRoads by focusing on its core targets and the methodological approach adopted to achieve them. The SMDS is conceived not merely as a technical infrastructure, but as a strategic enabler for trusted, interoperable and safety-oriented data sharing across heterogeneous mobility domains. Accordingly, this section outlines the objectives guiding the design of the SMDS, the methodological principles through which these objectives have been translated into concrete design decisions, and the alignment mechanisms employed to ensure consistency with European mobility data space initiatives and stakeholder requirements. Together, these aspects provide the conceptual framing necessary for understanding the EvoRoads SMDS, before subsequent sections address its architectural and technical implementation in detail.

5.2.1 OBJECTIVES OF THE EVOROADS SAFE MOBILITY DATA SPACE

The Safe Mobility Data Space (SMDS) of EvoRoads has been designed with a clearly delimited set of objectives that respond directly to the technical, organisational and temporal challenges identified in the current mobility data space landscape. Rather than aiming to replicate or replace existing European initiatives, the SMDS is conceived as a project-level data space that enables coherent data integration, controlled sharing and analytical reuse across all EvoRoads pilot sites, while remaining interoperable with external ecosystems. These objectives are grounded in the practical requirements of road authorities, infrastructure managers and technology providers involved in the pilots, and they guide concrete technical deployment decisions.

A primary objective of the EvoRoads SMDS is to **provide a common data integration layer across heterogeneous pilot environments**. EvoRoads pilots span urban, peri-urban and rural contexts, multiple countries, and diverse sensing and data acquisition setups. The SMDS therefore aims to ingest, describe and expose data from infrastructure monitoring systems, vehicle-based sensing, environmental sources and contextual datasets in a uniform manner. This does not imply homogenisation of raw data, but rather the establishment of a shared integration framework through harmonised metadata, common access patterns and explicit documentation of data provenance and update cycles. By doing so, the

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SMDS ensures that data produced in one pilot can be understood, compared and reused in others, addressing fragmentation issues highlighted in subsection 5.1.3.

A second objective is to **support safety-oriented data products rather than only raw datasets**. EvoRoads generates derived outputs such as infrastructure condition indicators, behavioural metrics and composite safety KPIs that are central to decision-making by road operators. The SMDS is therefore designed to manage both primary data and derived artefacts, exposing their relationships, assumptions and dependencies. This objective directly responds to gaps in existing data spaces, which often prioritise dataset discovery while offering limited support for analytical outputs. For infrastructure and mobility specialists, this approach ensures that investments in data collection and analytics translate into actionable information rather than isolated data silos.

Closely related is the objective to **maintain decentralised control while enabling project-wide access**. Data ownership remains with the organisations operating the pilots or providing the data, reflecting legal, contractual and operational realities. The SMDS does not impose central data custody; instead, it enables controlled access through agreed interfaces and access policies. This design choice aligns with the sovereignty concerns discussed in subsection 5.1.3 and avoids dependencies on long-term contractual commitments that would be incompatible with the project's duration. At the same time, it allows EvoRoads to function as a coherent analytical environment during its lifecycle.

Interoperability with European mobility data space initiatives constitutes a further explicit objective. The SMDS adopts established metadata practices, notably mobilityDCAT-AP and its EvoRoads-specific extension, to ensure that datasets and data products can be exposed to external catalogues and platforms when appropriate. This objective is not framed as immediate full integration into ecosystems such as NAPs or DFRS, but as **technical readiness for interoperability**. In practical terms, this means that the SMDS produces data assets that are structurally compatible with external initiatives, even where governance or timing constraints prevent direct integration within the project timeframe.

Another key objective is **scalability beyond the initial pilots**. While the SMDS addresses all EvoRoads pilot sites equally, it is explicitly designed to be adaptable to additional cities, regions and road networks. This includes the ability to onboard new data providers, accommodate different sensing technologies, and reflect local infrastructure characteristics without re-engineering the data space. This adaptability is particularly relevant for rural road contexts, where data availability is often lower, infrastructure assets are more dispersed, and safety risks are less visible through traditional monitoring. By lowering the technical and organisational barriers to integrating rural road data, the SMDS supports more systematic safety assessment and prioritisation for networks that are typically underrepresented in data-driven mobility initiatives.

Finally, the SMDS aims to **support cost-effective decision-making for road authorities**. By consolidating access to diverse data sources and derived safety indicators, the data space reduces duplication of data collection efforts and facilitates evidence-based prioritisation of interventions. For infrastructure managers, this means that investments in sensing, analytics and data management are aligned within a single framework, improving transparency and reducing uncertainty in maintenance and safety planning.

Taken together, these objectives position the EvoRoads SMDS as a focused, technically grounded data space that addresses known gaps in current mobility data ecosystems, supports both urban and rural road safety needs, and provides a credible foundation for future extension beyond the project's initial scope.

5.2.2 METHODOLOGICAL APPROACH FOR THE DESIGN AND DEVELOPMENT OF THE EVOROADS SMDS

The methodological approach followed for the design and development of the EvoRoads SMDS is grounded in an iterative, evidence-driven process that combines state-of-the-art analysis, stakeholder engagement and cross-task technical co-design. During the first reporting period, Task 1.4 focused primarily on establishing the conceptual and methodological foundations of the SMDS, ensuring alignment with European data space initiatives while addressing the concrete data needs emerging from the EvoRoads pilots. This work was led by FRONT, with substantial contributions from consortium

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partners ERTICO and CEFRIEL, whose involvement in European mobility data ecosystems provided critical insight into operational practices and interoperability requirements.

A significant methodological step during the first period consisted of a structured review and analysis of existing European mobility data space initiatives and related frameworks. While the outcomes of this activity are synthesised in Section 5.1, the methodological relevance lies in how this analysis informed design decisions rather than in the descriptive results themselves. Through systematic comparison of architectures, governance models and data-sharing practices, Task 1.4 identified constraints that are particularly relevant for project-level data spaces, such as temporal misalignment with long-running initiatives and the limited feasibility of formal integration during a research project's lifecycle. These findings directly shaped the decision to position the EvoRoads SMDS as interoperable but operationally autonomous.

This analytical work was complemented by direct engagement with selected initiatives. Contacts and bilateral meetings were organised with representatives of initiatives such as the Mobility Data Space, while others - such as deployEMDS and TN-ITS - were presented to the consortium by ERTICO based on first-hand involvement of their experts. These exchanges served a dual methodological purpose: they validated assumptions derived from desk research and exposed practical considerations related to onboarding, governance and technical prerequisites that are not always visible in public documentation. For the SMDS, this translated into a pragmatic focus on technical compatibility and semantic alignment rather than on premature institutional integration.

In parallel, Task 1.4 adopted a **co-design methodology tightly coupled with other technical tasks**. The SMDS was not developed as an isolated data layer, but in continuous interaction with Task 2.1 (Data Acquisition and Processing) and Task 3.1 (Digital Twin). Methodologically, these three tasks form a functional pyramid: Task 2.1 defines how data are collected, cleaned and structured; Task 3.1 defines how data are modelled and exploited within digital representations of road infrastructure; and Task 1.4 defines how these data and derived products are exposed, governed and shared. Regular coordination meetings ensured that assumptions about data formats, update frequencies and semantics remained consistent across tasks, avoiding retrofitting at later stages.

A cornerstone of the methodological approach was the **co-design of the three-tier SMDS architecture**, led jointly by FRONT, LINKS and the KIOS Research and Innovation Center of Excellence (UCY). This work combined online technical meetings with targeted offline exchanges, allowing architectural decisions to be debated at both conceptual and implementation-oriented levels. Rather than starting from abstract reference models, the architecture was derived from concrete data flows observed in the pilots, ensuring that the SMDS reflects real acquisition, processing and consumption patterns. This approach was instrumental in addressing the heterogeneity of EvoRoads pilots, which differ significantly in sensing technologies, organisational setups and infrastructure contexts.

To ground architectural design in operational reality, Task 1.4 also relied heavily on **integration workshops with data providers and pilot leaders**, organised in collaboration with Tasks 1.5 and 6.2. These workshops mapped end-to-end data pipelines from edge data sources through processing components to user-facing services. Methodologically, this ensured that the SMDS is informed by actual data dependencies and interfaces rather than by assumed workflows. It also enabled early identification of constraints related to data ownership, access rights and update responsibilities, which are critical for the definition of data-sharing mechanisms.

Interoperability and data management considerations were systematically incorporated through close collaboration with CEFRIEL, particularly in relation to mobilityDCAT-AP and its EvoRoads-specific extension. CEFRIEL's role as Data Manager of EvoRoads and leader of Task 6.4 ensured that methodological choices in Task 1.4 were consistent with FAIR principles, ethical considerations and European interoperability guidelines. Rather than treating metadata and data governance as an afterthought, the methodology embedded these aspects early, influencing how datasets and derived artefacts are described and exposed within the SMDS.

Looking ahead, the methodological focus in the remaining project period will gradually shift from conceptual alignment to **progressive operationalisation and validation**. Building on the established architecture, Task 1.4 will work closely with Tasks 2.1 and 3.1 to deploy the SMDS components in pilot environments, refine data-sharing interfaces, and test interoperability pathways with external initiatives where feasible. Continued engagement with European data space actors will support this phase, particularly to assess how EvoRoads data assets can be exposed beyond the project. Throughout this process, the methodology will remain iterative, using pilot feedback to adjust data models, access mechanisms and governance assumptions, ensuring that the SMDS evolves coherently until the end of the EvoRoads project.

5.2.3 ALIGNMENT THROUGH DESIGN-TIME COMPLIANCE AND SELECTIVE ADOPTION

The alignment of the EvoRoads Safe Mobility Data Space (SMDS) with European mobility data space initiatives is primarily achieved through **design-time compliance rather than runtime coupling**, in line with the scope and objectives of a Research and Innovation Action (RIA). Rather than pursuing live technical or institutional integration during the project lifecycle, EvoRoads internalises key European data space principles at the point of architectural and semantic design. This includes the adoption of recognised metadata standards, catalogue-oriented discovery mechanisms, and decentralised access assumptions that reflect prevailing European practices. By embedding these elements from the outset, the SMDS ensures that its data assets and interfaces are structurally compatible with external mobility data spaces, without presupposing their operational readiness, governance timelines or contractual frameworks. This approach directly mitigates the temporal and organisational constraints identified in Subsection 5.1.3, while remaining consistent with the exploratory and validating character of an RIA.

At the same time, EvoRoads applies a principle of **selective adoption** when engaging with European data space practices. As an RIA, the project prioritises the investigation, validation and demonstration of technically feasible approaches over the establishment of permanent operational or commercial arrangements. Accordingly, EvoRoads adopts those elements that can be realistically implemented and assessed within the project - such as metadata harmonisation, interoperability readiness and decentralised data exposure - while deliberately excluding mechanisms that presuppose long-term institutional commitments, fixed business models or stable governance entities. This selective approach ensures that alignment does not come at the expense of technical agility or pilot relevance. Instead, the SMDS is shaped as a coherent, self-contained data space that remains open to future integration pathways. In this sense, alignment in EvoRoads is expressed not through immediate connectivity, but through the conscious avoidance of architectural, semantic or governance decisions that would limit interoperability beyond the project's duration.

5.3 ARCHITECTURE OF THE EVOROADS SAFE MOBILITY DATA SPACE

This section presents the architecture of the EvoRoads Safe Mobility Data Space (SMDS), describing how its core components are structured and how they interact to support data ingestion, modelling, sharing and reuse across the project. Building on the objectives and methodological choices outlined in Section 5.2, the architecture is organised into a layered design that separates data engineering and ingestion processes, digital twin–based data structuring and analytics, and secure data exchange mechanisms. Particular emphasis is placed on the upper data-sharing layer, where the adoption of International Data Spaces Association (IDSA)-compliant Eclipse connectors[13] aligns the SMDS with the federated data exchange principles promoted by *deployEMDS* and the *Common European Mobility Data Space*. The section introduces these layers and the supporting services that enable dataset discovery, versioning and controlled access, notably through the use of a common catalogue. Together, these elements define a coherent architectural framework that underpins the operation of the SMDS across all EvoRoads pilot sites and establishes a technically credible pathway for interoperability with EMDS initiatives.

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[13] Eclipse Dataspace Components is available here: https://projects.eclipse.org/projects/technology.edc (Accessed December 2025).

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5.3.1 ARCHITECTURAL OVERVIEW AND DESIGN PRINCIPLES OF THE EVOROADS SMDS

This subsection presents a consolidated architectural overview of the EvoRoads SMDS and articulates the design principles that underpin its structure. The architecture has been conceived to accommodate heterogeneous data sources, diverse pilot constraints and evolving interoperability requirements, while remaining aligned with EU mobility data space principles. Rather than prescribing a single deployment pattern, the SMDS provides a modular and layered framework that supports different operational configurations across pilots, without compromising coherence at project level.

5.3.1.1 OVERVIEW OF THE THREE-LAYER ARCHITECTURE

At a high level, the EvoRoads SMDS is organised into three functional layers: (i) a **data engineering and ingestion layer**, (ii) a **digital twin layer**, and (iii) a **secure data exchange and federation layer**. Each one corresponds to a distinct set of responsibilities and is associated with specific tasks, ensuring clear ownership and traceability within the consortium.

The data engineering and ingestion layer is primarily realised through Task 2.1 and is responsible for collecting data from heterogeneous sources, performing initial processing, and transporting data across system boundaries. The digital twin layer, developed under Task 3.1, provides structured representations of road infrastructure, context and state, enabling data interpretation and analytical exploitation. The upper layer, designed under Task 1.4, implements secure data exposure and exchange mechanisms based on IDSA-compliant Eclipse connectors, acting as the interface between the EvoRoads data space and external ecosystems. Together, these layers form a coherent stack that supports the full lifecycle of data within the SMDS, from acquisition to controlled sharing. The concept of the three-layer architecture is illustrated in ***Figure 19***.

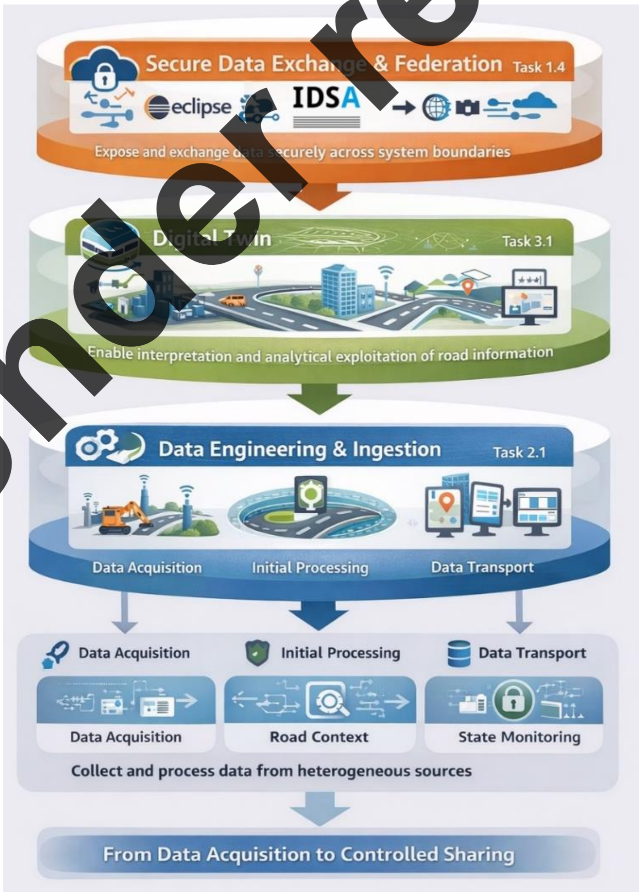

Figure 19: The three distinct layers of the EvoRoads SMDS architecture and correspondence to tasks that develop them

5.3.1.2 RATIONALE FOR A LAYERED ARCHITECTURE

The adoption of a layered architecture is driven by the need for **separation of concerns** in a complex, multi-stakeholder system. Data acquisition, semantic modelling and data sharing impose fundamentally different technical and organisational requirements. By isolating these responsibilities into distinct layers, the SMDS avoids tight coupling between components, reducing integration complexity and allowing each layer to evolve independently.

From a scalability perspective, this separation enables the system to accommodate varying data volumes and processing demands. For example, high-frequency sensor streams and video data can be handled at the ingestion layer without imposing constraints on the digital twin or data-sharing components. Similarly, changes in data-sharing protocols or federation mechanisms do not require modifications to upstream acquisition pipelines. This design choice directly addresses challenges identified in Section 5.1.3, where rigid architectures and premature coupling were shown to hinder adaptability.

Interoperability is another key motivation. By defining explicit interfaces between layers, the SMDS can align with external standards and initiatives at the appropriate level. The digital twin layer can focus on domain semantics and analytical relevance, while the upper layer can align with European data space protocols and governance frameworks, such as those promoted by deployEMDS, without forcing these concerns into lower-level components.

5.3.1.3 DATA PLANES: EDGE, CLOUD AND PAN-EUROPEAN EXPOSURE

Complementing the layered architecture, the SMDS operates across three planes of data storage and processing: the edge plane, the cloud plane and the pan-European plane. These planes are orthogonal to the functional layers and reflect deployment and operational considerations rather than logical responsibilities.

At the **edge plane**, data are collected directly from sensors, vehicles and local monitoring systems. Initial processing takes place as close as possible to the data source, including filtering, frame selection and privacy-preserving transformations such as the blurring of faces and vehicle licence plates. This approach reduces data volumes, addresses legal and ethical constraints, and enables pilots with limited connectivity or strict data localisation requirements to participate fully in the SMDS.

The **cloud plane** hosts the main data processing and analytics activities, including algorithms developed under WP2 and WP3 for infrastructure assessment, behaviour analysis and safety indicator computation. Here, data are aggregated, enriched and analysed at scale, producing derived artefacts that feed into the digital twin. Importantly, several configurations of the Task 2.1 and Task 3.1 components have been prepared, allowing this plane to be deployed either centrally or on-premise, depending on pilot-specific legal and organisational constraints.

The **pan-European plane** corresponds to the exposure of selected datasets and data products to external stakeholders, including academic users and European initiatives. This plane is realised through the federation layer based on IDSA Eclipse connectors and associated catalogue services. It represents the point at which the SMDS interfaces with the broader European mobility data space landscape, without requiring full centralisation of data.

Figure 20 below illustrates a conceptual abstraction of the EvoRoads data flows across the aforementioned three planes. Further it illustrates data transformation to the data schemas proposed by the initiatives discussed in Subsections 5.1.1 and 5.1.2.

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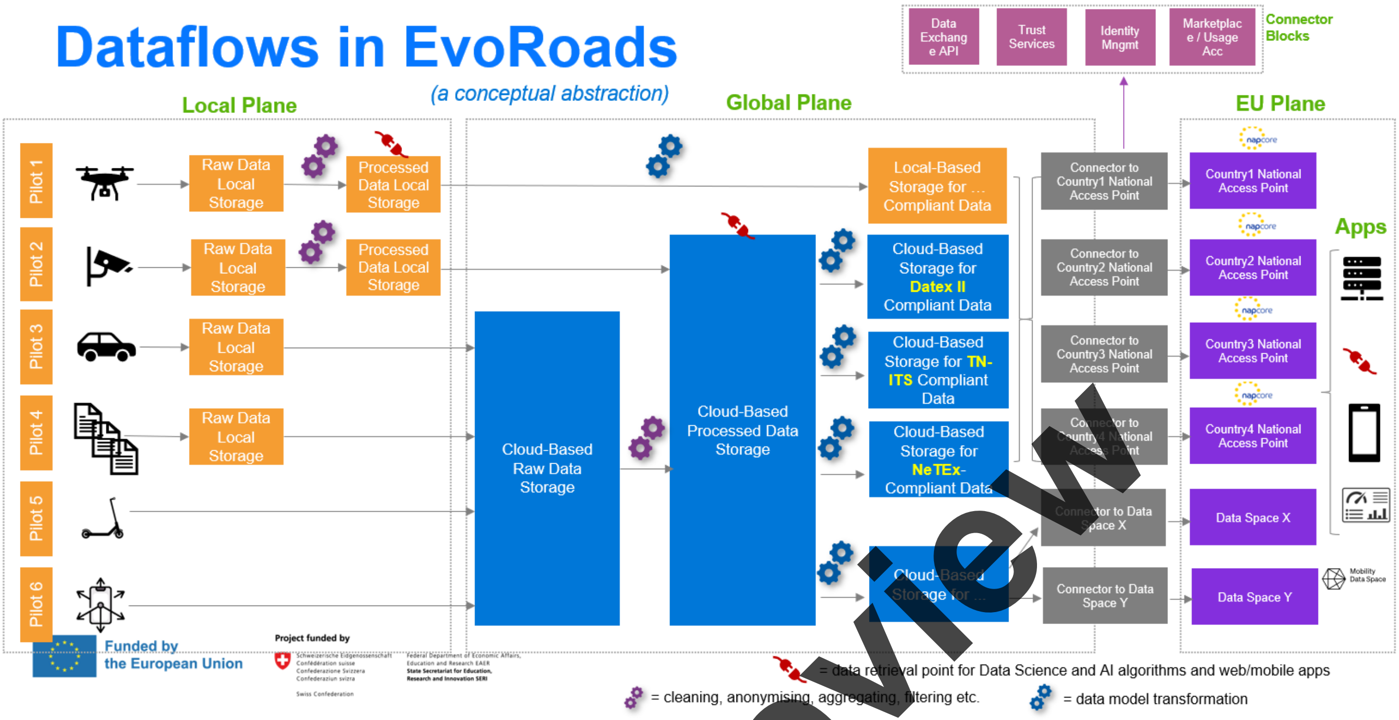

Figure 20: Conceptual abstraction of the EvoRoads data flows across the Edge, Global (Cloud) and pan-EU planes

5.3.1.4 DATA ENGINEERING AND INGESTION LAYER

The data engineering and ingestion layer, implemented under Task 2.1, forms the foundation of the SMDS. It is responsible for ingesting data from diverse sources, including roadside sensors, mobile platforms, UAVs and external datasets. Apache Kafka[14] is employed as the core backbone for data streaming and pipeline management, enabling reliable, scalable and asynchronous data transport between components and across planes.

This layer supports both streaming and batch workflows, reflecting the diversity of data types involved in EvoRoads pilots. It also acts as the primary mechanism for moving data between the edge and cloud planes, enforcing data quality checks and ensuring consistent data packaging. By centralising these functions within a dedicated layer, the SMDS avoids duplicating ingestion logic across downstream components.

5.3.1.5 DIGITAL TWIN LAYER

The digital twin layer, developed under Task 3.1, provides a structured and contextualised representation of road infrastructure and its operational state. Rather than serving as a mere visualisation tool, the digital twin acts as an intermediate semantic layer that links raw and processed data to infrastructure entities, spatial contexts and temporal states.

Within the SMDS, the digital twin exposes data and derived indicators through well-defined interfaces, enabling downstream services and users to access information in a meaningful and consistent manner. This layer is central to the generation and interpretation of safety-related insights, as it connects analytical outputs from WP2 algorithms to concrete

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[14] Documentation of the open-source Apache Kafka ecosystem of technologies is available here: https://kafka.apache.org/ (Accessed December 2025).

infrastructure elements and operational scenarios. By positioning the digital twin as a distinct layer, the architecture ensures that analytical logic and data semantics are decoupled from both acquisition mechanisms and data-sharing protocols.

The first version of this layer has already been documented in detail in the EvoRoads "D3.1.

5.3.1.6 DATA SHARING, CATALOGUING AND FEDERATION LAYER

The upper layer of the SMDS, realised under Task 1.4, implements secure data exposure and federation mechanisms. Internally, Comprehensive Knowledge Archive Network (CKAN)[15], an open-source data management system, is employed as a data lake and catalogue service, supporting dataset storage, search, versioning and access through its API. CKAN is used strictly for internal project purposes and does not constitute a public-facing platform. The metadata profiles collected and managed within CKAN are subsequently used to feed the OpenAIRE Argos platform[16], which is employed for the preparation and publication of the project's final DMP under Task 6.4. All datasets and data products are described using mobilityDCAT-AP and its EvoRoads-specific extension, ensuring consistent metadata and facilitating future interoperability.

For external data sharing, the SMDS adopts IDSA-compliant Eclipse connectors, which provide controlled data exchange based on usage policies and sovereignty principles. This design aligns with the federated data exchange model promoted by deployEMDS and the Common EMDS, positioning EvoRoads as technically compatible with emerging European data space infrastructures. The use of Eclipse connectors allows data to be shared selectively and securely, without transferring ownership or requiring centralised storage.

5.3.1.7 DESIGN PRINCIPLES AND ALIGNMENT WITH DATA SPACE CONCEPTS

Across all layers and planes, the SMDS architecture embodies key data space principles, including **federation, decentralisation and data sovereignty**. Data remain under the control of their original providers, reflecting the legal, organisational and operational realities of the EvoRoads pilots. Access to data and derived products is mediated through explicit technical mechanisms rather than implicit assumptions, allowing providers to define how, when and under which conditions their assets may be used. Interoperability is achieved through standardised interfaces, shared metadata models and agreed data exchange patterns, rather than through the aggregation of data into a single central repository. This approach ensures that participation in the SMDS does not require the relinquishment of ownership or control, a consideration that is particularly relevant for public authorities and infrastructure operators.

The architectural separation between ingestion, digital twin and federation layers further reinforces these principles. By decoupling data acquisition and processing from data exposure and sharing, the SMDS enables different components to evolve at different paces and under different governance constraints. This is especially important in a multi-pilot project where legal requirements, data sensitivity and technical maturity vary significantly across sites. The use of flexible deployment planes - edge, cloud and pan-European - allows the architecture to accommodate these differences without fragmenting the overall data space, ensuring that all pilots are supported within a common framework. By combining a layered architecture with flexible deployment options and federated exchange mechanisms, the EvoRoads SMDS provides a technically grounded and adaptable framework for safety-oriented mobility data sharing. It supports diverse pilot configurations, including urban and rural road contexts, and enables the integration of heterogeneous data sources and analytical outputs into a coherent environment. At the same time, the alignment of the upper data-sharing layer with IDSA-based federation concepts establishes a credible pathway for interoperability with European mobility data space initiatives. Within the scope of a Research and Innovation Action, this architecture balances ambition with feasibility,

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[15] The official documentation of CKAN is available here: https://ckan.org/ (Accessed December 2025).

[16] The official website of the OpenAIRE Argos technological proposition is available here: https://argos.openaire.eu/portal/ (Accessed December 2025).

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delivering a coherent and manageable data space that is compatible with European practices while remaining responsive to the practical constraints of real-world deployments.

5.3.2 DATA INGESTION, ENGINEERING AND DIGITAL TWIN LAYERS

The data engineering, ingestion and digital twin layers together form the operational core of the EvoRoads SMDS, linking raw data acquisition to meaningful, safety-oriented information products. While their detailed technical implementation is documented extensively in the deliverables of WP2 and WP3, this subsection provides a high-level view of their role within the SMDS and clarifies how they jointly enable controlled data entry, structuring and analytical exploitation.

The data engineering and ingestion layer, developed under Task 2.1, defines how data enter the SMDS in a controlled and traceable manner. Its primary role is to handle heterogeneous data streams originating from a wide range of sources, including roadside and embedded sensors, mobile sensing platforms, UAVs, infrastructure inventories, environmental services and selected external datasets. The ingestion pipelines are designed to support both streaming and batch data flows. Streaming pipelines are employed for time-sensitive or high-frequency data, such as sensor measurements or video feeds, while batch processes are used for periodic uploads of inspection results, inventories or contextual datasets. Apache Kafka constitutes the backbone of this layer, enabling asynchronous, scalable and resilient data transport across system components and deployment planes.

A key function of the ingestion layer is data validation, pre-processing and enrichment prior to downstream use. Validation mechanisms ensure that incoming data conform to expected formats and basic quality constraints, reducing the propagation of errors. Pre-processing activities include filtering, aggregation and transformation of raw data, as well as privacy-preserving operations such as the blurring of faces or vehicle licence plates at the edge. Enrichment may involve the attachment of spatial, temporal or contextual attributes that are required for subsequent analysis. Through these mechanisms, Task 2.1 ensures that data entering the SMDS are technically consistent, legally compliant and fit for further processing.

The digital twin layer, implemented under Task 3.1, builds upon these prepared data streams to provide structured, contextualised representations of road infrastructure and its operational state. Within the SMDS, the digital twin does not function as an end-user visualisation tool, but as a semantic and organisational layer that links data to infrastructure entities, locations and temporal contexts. Data are modelled in relation to road assets, network segments and operational conditions, enabling consistent interpretation across pilots and analytical components. This structuring is essential for integrating heterogeneous data types and for maintaining coherence between raw observations and higher-level assessments. A central role of the digital twin layer is its interaction with analytics and KPI generation processes developed in WP1, WP2 and WP3. Analytical outputs - such as infrastructure condition metrics, behavioural indicators or risk-related features - are anchored within the digital twin, ensuring that derived artefacts can be traced back to specific assets and contexts. These outputs feed into the computation of safety indicators and composite KPIs, which constitute the primary decision-support products of EvoRoads. By mediating between ingestion pipelines and analytics, the digital twin layer ensures that data become meaningful and actionable for road authorities and infrastructure managers, while remaining accessible to the upper SMDS layers for controlled sharing and interoperability.

5.3.3 DATA ACCESS, CATALOGUING AND EXPOSURE THROUGH CKAN

This subsection describes how CKAN[17] is employed within the EvoRoads Safe Mobility Data Space (SMDS) as the central internal mechanism for dataset discovery, cataloguing, versioning and metadata management. CKAN is not positioned as a public dissemination portal, but as an enabling service that supports structured data exchange, governance and reuse

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[17] The official documentation of CKAN is available here: https://ckan.org/ (Accessed December 2025).

across tasks, pilots and technical components of the project. Its role is therefore architectural rather than presentational, forming a bridge between data production, analytical exploitation and controlled exposure to external systems.

5.3.3.1 CKAN AS A CATALOGUE AND INTERNAL DISCOVERY SERVICE

Within the SMDS, CKAN functions primarily as a dataset catalogue, providing a unified view of the data assets generated and managed across all EvoRoads pilot sites. Each dataset - whether raw, processed or derived - is registered as a first-class entity, accompanied by rich metadata that describe its scope, provenance, spatial and temporal coverage, update frequency and access conditions. This catalogue-oriented approach ensures that datasets remain discoverable across the consortium, even when physically stored or processed in different deployment planes (edge or cloud).

CKAN's API-centric design is central to this role. All interactions with the catalogue -dataset creation, update, querying and retrieval - are performed programmatically, allowing other components of the SMDS and the user interfaces to integrate seamlessly with the catalogue. This enables analytical workflows, validation processes and data-sharing mechanisms to reference datasets consistently, avoiding ad hoc or undocumented data exchanges. In this sense, CKAN acts as the authoritative inventory of SMDS data assets, supporting internal transparency and traceability.

5.3.3.2 VERSIONING AND DATASET EVOLUTION

A key requirement of the EvoRoads SMDS is the ability to manage datasets that evolve over time, either through periodic updates or through the refinement of processing and analytics. CKAN supports this requirement by enabling explicit versioning of datasets, allowing multiple versions to coexist while preserving their relationships. New versions may correspond to updated data captures, reprocessed datasets using improved algorithms, or revised analytical outputs.

Within EvoRoads, versioning is used to ensure reproducibility and auditability of results. Analytical outputs and safety indicators can be linked to the exact dataset versions from which they were derived, reducing ambiguity when results are compared across pilots or over time. CKAN's support for dataset metadata updates and resource-level granularity allows changes to be documented clearly, while older versions can be retained or deprecated in a controlled manner. This approach avoids silent overwriting of data and provides a clear lifecycle for each dataset.

5.3.3.3 CKAN AS A METADATA REGISTRY

Beyond dataset listing, CKAN serves as the central metadata registry of the SMDS. All datasets registered in CKAN are described using structured metadata profiles, ensuring consistency across pilots and tasks. The adoption of metadata-as-infrastructure is a deliberate design choice: metadata are not treated as documentation artefacts, but as operational elements that drive discovery, interoperability and governance.

The SMDS adopts mobilityDCAT-AP as the baseline metadata profile, complemented by an EvoRoads-specific extension developed under Task 6.4. This extension captures attributes that are essential for safety-oriented use cases but are not fully addressed in the core profile, such as links to infrastructure assets, references to derived safety indicators, and relationships between primary data and composite KPIs. CKAN's extensibility allows these additional fields to be integrated without breaking compatibility with the underlying DCAT-AP model.

By enforcing the use of harmonised metadata at dataset registration time, CKAN ensures that all data assets are semantically aligned from the moment they enter the SMDS. This reduces the burden of later interoperability mapping and supports automated discovery and filtering based on spatial, temporal or thematic criteria.

5.3.3.4 DATASET LIFECYCLE MANAGEMENT

CKAN plays a central role in managing the lifecycle of datasets within the SMDS. This lifecycle encompasses dataset creation, update, versioning, potential deprecation and eventual archival. Lifecycle states are reflected through metadata attributes and version relationships, enabling users and systems to distinguish between active, superseded and deprecated datasets.

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For EvoRoads, lifecycle management is particularly important given the iterative nature of data production across pilots. As sensing configurations evolve, algorithms are refined and analytical methods mature, datasets may be replaced or updated. CKAN provides a structured environment in which these changes can be managed transparently, ensuring that downstream users are aware of dataset status and suitability for reuse. This approach directly supports the project's emphasis on traceability and controlled data reuse.

5.3.3.5 ENABLING DISCOVERY AND REUSE ACROSS THE SMDS

The combined use of cataloguing, versioning and harmonised metadata positions CKAN as the primary mechanism through which data are discovered and reused within the SMDS. Researchers, analysts and system components can query the catalogue to identify relevant datasets, assess their applicability and retrieve them through standardised interfaces. This reduces duplication of data collection and encourages reuse of existing assets across tasks and pilots.

Importantly, CKAN supports fine-grained access control and integration with external services, allowing datasets to be selectively exposed to other SMDS layers or external systems without making the catalogue itself public. This aligns with the project's governance model, where internal sharing is prioritised during the project lifecycle, while external exposure is mediated through the federation layer based on IDSA Eclipse connectors.

5.3.3.6 INTEGRATION WITH OPENAIRE ARGOS AND DATA MANAGEMENT PROCESSES

Finally, CKAN acts as a feeder system for the OpenAIRE Argos platform[18], which is used for the preparation and publication of the project's DMP under Task 6.4. Metadata profiles collected and maintained in CKAN are reused to populate Argos, ensuring consistency between operational data management practices and formal reporting obligations. This integration reduces manual effort, minimises discrepancies between declared and actual data assets, and reinforces the role of CKAN as the single source of truth for dataset metadata within EvoRoads.

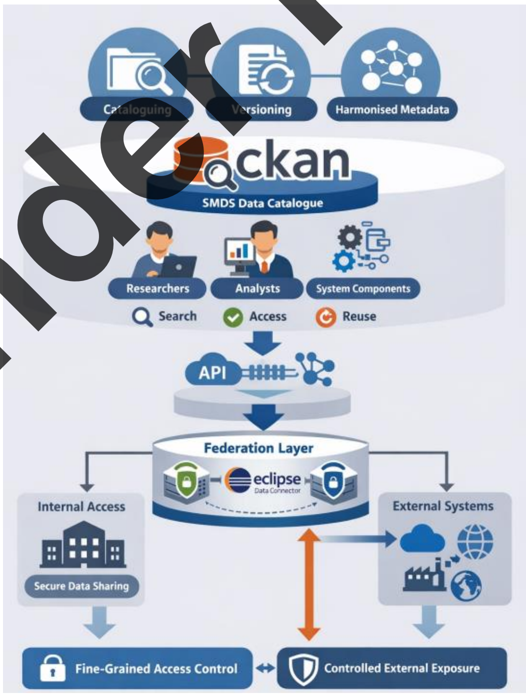

Figure 21: CKAN positioned within the EvoRoads data cataloguing and sharing services

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[18] OpenAIRE Argos technological proposition is available here: https://argos.openaire.eu/portal/ (Accessed December 2025).

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In summary, CKAN is leveraged within the EvoRoads SMDS as a multifunctional internal service that underpins data discovery, version control, metadata governance and reuse. Its position within the context of EvoRoads SMDS and the manifested dependencies with the Eclipse infrastructure are summarised below through ***Figure 21***. By embedding CKAN into the architectural fabric of the SMDS, EvoRoads ensures that data assets remain accessible, traceable and interoperable throughout the project lifecycle, while maintaining flexibility for future alignment with external mobility data space initiatives.

5.3.4 SECURE DATA EXCHANGE AND FEDERATION THROUGH IDSA-COMPATIBLE ECLIPSE CONNECTORS

This subsection describes the **secure data exchange and federation layer** of the EvoRoads SMDS, which enables controlled data sharing beyond the project boundary. This layer is implemented using **IDSA-compatible Eclipse Connectors**, specifically leveraging the Eclipse Data Connector (EDC) framework, and is aligned with the architectural propositions promoted by deployEMDS for the Common European Mobility Data Space. Its role is to ensure that data can leave the SMDS in a secure, policy-driven and sovereign manner, without compromising ownership, governance or legal constraints established at pilot or organisational level.

5.3.4.1 FEDERATION REQUIREMENTS AND DEPLOYEMDS REFERENCE COMPONENTS

The deployEMDS initiative identifies a set of core building blocks required to support federated data exchange at European scale (especially by NAPs), notably: **Data Exchange APIs**, **Trust Services**, **Identity Management**, and **Marketplace services**. Together, these components, depicted in ***Figure 22*** below, define the minimum functional capabilities needed for participants to publish, discover, negotiate and consume data across organisational boundaries. Importantly, deployEMDS does not prescribe a single implementation, but rather a set of interoperable roles and interfaces that can be realised using different technologies.

Within EvoRoads, the secure data exchange layer has been designed to cover these functional requirements through the adoption of IDSA-compatible Eclipse Connectors. The EDC provides a modular, extensible framework that implements the core concepts of the International Data Spaces Association, including sovereign data exchange, usage control and federated trust. By aligning with this framework, EvoRoads ensures that its SMDS is technically compatible with deployEMDS-aligned ecosystems, while remaining deployable and manageable within the scope of a Research and Innovation Action.

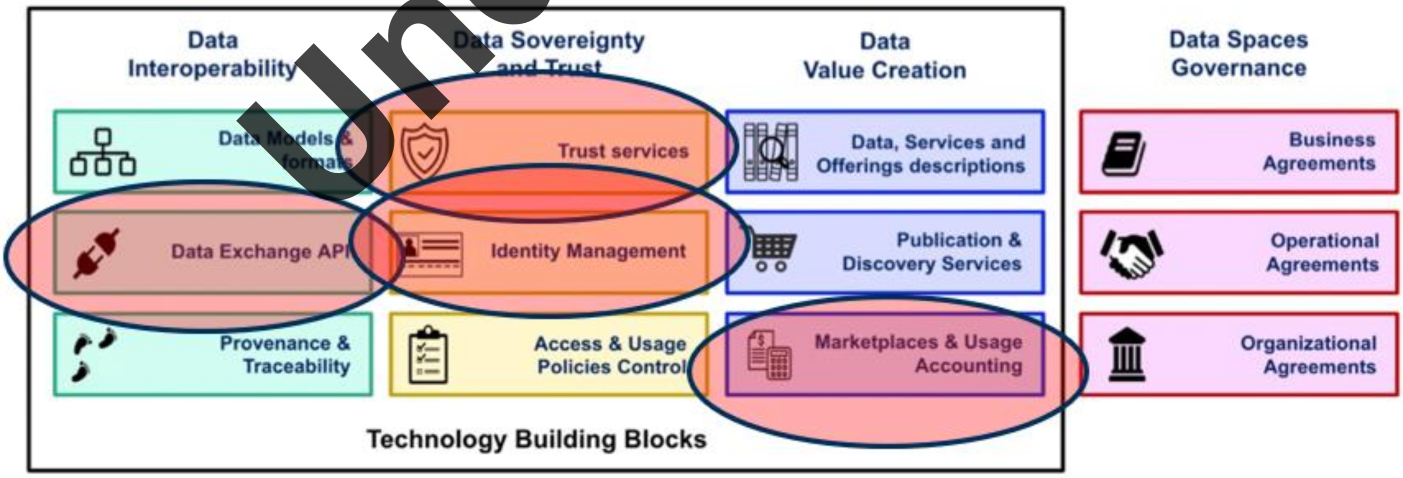

Figure 22: The building blocks NAPs are expected to maintain as recommended by the deployEMDS initiative

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5.3.4.2 ROLE OF IDSA-COMPATIBLE ECLIPSE CONNECTORS IN EVOROADS

In the EvoRoads architecture, Eclipse Connectors constitute the **gateway through which data exit the SMDS**. They sit above the internal cataloguing and data management services (notably CKAN) and mediate all external data exchanges. Rather than exposing datasets directly through open APIs, the SMDS requires that any external access is negotiated and enforced through connector-to-connector interactions.

Each organisation participating in EvoRoads may operate one or more connectors, depending on its role as a data provider, consumer or both. This decentralised deployment model reflects the federated nature of the SMDS and avoids the need for a central data broker. The connectors interact using standardised protocols to advertise data offers, negotiate contracts and transfer data, ensuring that exchanges are auditable and policy-compliant.

5.3.4.3 TECHNICAL BUILDING BLOCKS AND CONNECTOR ARCHITECTURE

From a technical perspective, the EDC is built as a set of loosely coupled services that can be deployed independently and configured to suit different operational contexts. Key components relevant to EvoRoads include[19]:

- **Data Plane** components, which handle the actual transfer of data between providers and consumers using secure communication channels.
- **Control Plane** components, which manage contract negotiation, policy enforcement and lifecycle management of data exchanges.
- **Extension mechanisms**, which allow custom integration with internal systems such as CKAN, digital twin services or analytics platforms.

Within the SMDS, connectors are integrated with the internal catalogue to reference datasets and data products that are eligible for external sharing. Metadata describing these assets are mapped from mobilityDCAT-AP–compliant records into connector-compatible data offers. This separation ensures that internal dataset management remains decoupled from external exposure, while still enabling automated discovery and negotiation.

5.3.4.4 DATA EXCHANGE APIS AND CONTROLLED ACCESS

The **Data Exchange API** provided by the connectors defines how data consumers can request access to specific datasets and how providers respond to such requests. In EvoRoads, this API is not publicly exposed; instead, it is accessible only to authenticated and authorised counterpart connectors. This design ensures that data exchanges occur exclusively within a trusted federation.

Data transfer may involve direct access to datasets, provision of data snapshots, or access to derived products, depending on the negotiated agreement. The connectors support both pull- and push-based exchange patterns, allowing flexibility in how data are shared. Crucially, the Data Exchange API enforces the outcome of contract negotiations, ensuring that only permitted operations are executed.

5.3.4.5 TRUST SERVICES AND IDENTITY MANAGEMENT

Trust and identity are foundational to federated data spaces. In EvoRoads, the Eclipse Connectors integrate with **identity management and trust services** that establish the authenticity and legitimacy of participants. Each connector is associated with a verifiable identity, which can be validated using certificates or other trust anchors aligned with IDSA principles.

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[19] For more information developers may consult the “Developers Handbook” published by Eclipse: https://github.com/eclipse-edc/docs/blob/main/developer/handbook.md (Accessed December 2025).

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This identity layer enables participants to verify who they are interacting with before initiating data exchange. It also supports fine-grained access control, where different organisations - or even different roles within the same organisation - may have different permissions. By embedding identity verification into the exchange process, the SMDS avoids ad hoc trust assumptions and supports scalable federation.

5.3.4.6 USAGE CONTROL, ACCESS POLICIES AND DATA SOVEREIGNTY

A defining feature of IDSA-compatible EDC is their support for **usage control policies**, which extend beyond traditional access control mechanisms such as authentication and role-based authorisation. Within the EvoRoads Safe Mobility Data Space (SMDS), these policies provide a formal and enforceable way for data providers to define the conditions under which their data may be accessed and used by external parties. Rather than granting blanket access, providers specify constraints related to purpose of use, temporal validity, data scope, and restrictions on onward sharing. This capability is essential in a safety-oriented context, where data may carry legal, ethical or operational sensitivities.

From a technical perspective, Eclipse Connectors implement usage control through **machine-readable policy definitions** that are associated with data offers published by a provider connector. These policies are typically expressed using a policy language aligned with IDSA and Gaia-X concepts and are interpreted by the connector's **policy engine**. When a data consumer requests access to a dataset, the request triggers a **contract negotiation process** between the consumer and provider connectors. During this process, the provider's policies are evaluated against the consumer's declared usage intent and credentials. Only if the conditions are satisfied is a contract agreement established, explicitly binding both parties to the negotiated terms. Once a contract is in place, policy enforcement continues throughout the **entire data exchange lifecycle**. The Eclipse Connector's control plane ensures that data transfers are initiated only in accordance with the agreed contract, while the data plane enforces technical constraints on how data are delivered (e.g. one-off transfer versus continuous access). Policies may include time-based constraints, allowing access to expire automatically, or purpose limitations that restrict use to predefined categories such as research, validation or infrastructure assessment. In addition, policies can prohibit redistribution, ensuring that data cannot be forwarded to third parties without explicit authorisation [83] [84].

Figure 23 summarises the concept of policy-driven usage control with Eclipse Connectors:

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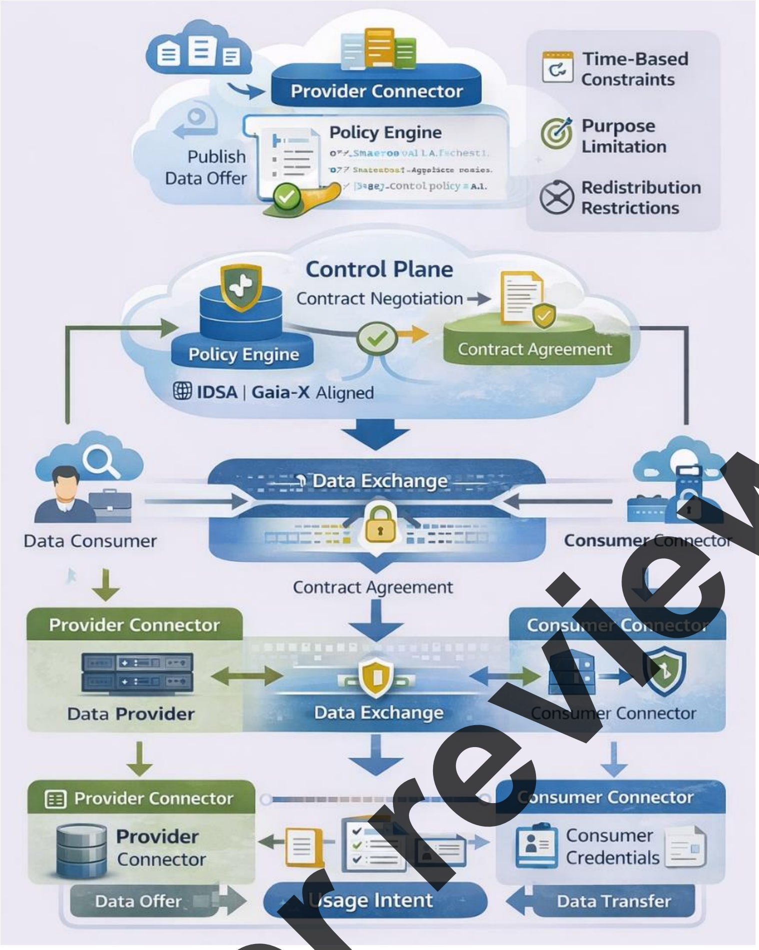

Figure 23: Policy driven usage control with Eclipse Connectors

An important aspect of this approach is that **policy enforcement does not end at the point of data transfer**. The contract agreement, together with associated policies, remains active and auditable, allowing providers to track how their data have been shared and under which conditions. Eclipse Connectors support logging and monitoring mechanisms that can be used to demonstrate compliance, an aspect that is particularly relevant for public authorities participating in EvoRoads. In cases where access conditions change, contracts can be revoked or allowed to expire without requiring manual intervention or renegotiation of system-level permissions.

From a technical perspective, policies are ODRL serialized as JSON-LD. Thus, an example would look like this (***Figure 24*** [83]):

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```
{
  "@context": {
    "edc": "https://w3id.org/edc/v0.0.1/ns/"
  },
  "@type": "PolicyDefinition",
  "policy": {
    "@context": "http://www.w3.org/ns/odrl.jsonld",
    "@type": "Set",
    "duty": [
      {
        "target": "http://example.com/asset:12345",
        "action": "use",
        "constraint": {
          "leftOperand": "headquarter_location",
          "operator": "eq",
          "rightOperand": "EU"
        }
      }
    ]
  }
}
```

Figure 24: Sample data access policy as JSON-LD

For EvoRoads, this policy-driven approach to data sharing is central to preserving **data sovereignty**. Infrastructure operators and public authorities can participate in federated data exchange without relinquishing control over their assets, while still enabling meaningful reuse of safety-related data. By embedding usage control into the connector-based federation layer, the SMDS ensures that data leave the system under explicitly defined and enforceable conditions, supporting trust, accountability and long-term interoperability with European mobility data space initiatives.

5.3.4.7 MARKETPLACE CONCEPTS AND DISCOVERY BEYOND THE PROJECT

While EvoRoads does not operate a standalone marketplace during the project, the connector-based architecture is compatible with **marketplace-style discovery mechanisms** promoted by deployEMDS. Data offers published by connectors can, in principle, be indexed by external catalogue or marketplace services, enabling discovery by authorised participants beyond the consortium.

This positioning ensures that the SMDS is future proof with respect to EMDS developments. Should EvoRoads datasets be exposed post-project to wider communities (such as academic researchers or European stakeholders) the necessary technical hooks are already in place. Importantly, this exposure can be selective and policy-driven, avoiding wholesale publication.

5.3.4.8 POSITIONING TOWARDS EXTERNAL DATA SPACES

Through the adoption of IDSA-compatible Eclipse Connectors, the EvoRoads SMDS positions itself as a **federated node** within the broader EMDS ecosystem. Rather than acting as a central hub, the SMDS participates as one data space among others, capable of both providing and consuming data under agreed conditions.

This approach directly addresses the challenges identified in Subsection 5.1.3, where full integration into long-running or market-driven ecosystems may not be feasible within a project lifecycle. By focusing on technical compatibility and sovereign exchange, EvoRoads ensures that its data can be shared safely and credibly, while preserving autonomy during the RIA.

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5.3.4.9 SUMMARY: SAFE DATA EGRESS BY DESIGN

In summary, the secure data exchange and federation layer of the EvoRoads SMDS ensures that data leave the system safely, transparently and under the control of their owners. The use of IDSA-compatible Eclipse Connectors provides a concrete implementation of deployEMDS-aligned principles, covering data exchange APIs, trust and identity, usage control and future marketplace integration. By embedding these mechanisms into the architecture, EvoRoads delivers a technically robust and governance-aware pathway for external data sharing, without compromising the integrity or autonomy of the SMDS.

5.4 OPERATIONAL AND INTEROPERABILITY ASPECTS OF THE SMDS

This subsection describes how the Safe Mobility Data Space (SMDS) operates in practice across EvoRoads pilot sites and how it interacts with external ecosystems. The focus is on deployment patterns, operational roles and interoperability pathways, clarifying how the architectural choices described in Section 5.3 translate into day-to-day operation. The intent is to demonstrate that the SMDS supports all pilots in a consistent manner while remaining flexible enough to accommodate local constraints and future integration scenarios.

5.4.1 DEPLOYMENT ACROSS EVOROADS PILOT SITES

The SMDS is instantiated across EvoRoads pilot sites following a common architectural blueprint combined with pilot-specific configurations. Core services - such as metadata management, data governance logic and federation mechanisms - are defined at project level to ensure consistency, while data acquisition and processing components are deployed according to local technical and legal conditions. This approach ensures that all pilots are treated equally from a data space perspective, even when their operational environments differ significantly.

From an operational standpoint, the SMDS supports both centralised and distributed deployments. Where feasible, data processing components associated with Tasks 2.1 and 3.1 are deployed on shared cloud infrastructures, enabling economies of scale and simplified management. In pilots with stricter data localisation requirements or limited connectivity, equivalent components can be deployed on-premise or at the edge (consult ***Figure 20***), with the same interfaces and data models. This dual deployment strategy avoids fragmentation while respecting local constraints.

5.4.2 COMMON SERVICES AND PILOT-SPECIFIC COMPONENTS

A clear distinction is maintained between common SMDS services and pilot-specific services.

Common services include the internal catalogue, metadata profiles, interoperability interfaces and federation logic, which are uniform across all pilots. These services provide the backbone of the SMDS and ensure that datasets and data products can be discovered, accessed and interpreted consistently.

Pilot-specific components relate primarily to data sources, ingestion pipelines and local processing configurations. Differences in sensing technologies, infrastructure assets and organisational workflows are accommodated within the data engineering layer without affecting the higher layers of the SMDS. As a result, pilot-specific diversity is contained where it belongs, while interoperability and governance remain harmonised at project level.

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5.4.3 ILLUSTRATIVE USE CASE: END-TO-END DATA DISCOVERY, PROCESSING AND EXTERNAL SHARING

To illustrate how the SMDS operates in practice, this subsection describes an end-to-end use case drawn from an EvoRoads pilot scenario, focusing on dataset discovery, processing and controlled external sharing. The scenario is representative of both urban and rural deployments and demonstrates how the different SMDS layers interact in an operational workflow.

The use case begins with a **pilot user accessing the EvoRoads dashboard** provided under Task 1.5. The user requests an overview of available datasets relevant to a specific road segment or area of interest, for example to assess recent safety conditions or infrastructure performance. Rather than querying raw data repositories directly, the dashboard issues a structured request to the **digital twin layer** (Task 3.1), which acts as the semantic entry point to the SMDS. The digital twin contextualises the request based on spatial extent, infrastructure assets and temporal scope, and forwards a metadata query to the internal catalogue.

The **CKAN service** is then consulted to retrieve the relevant dataset catalogue entries. Using its API, CKAN returns a list of datasets and dataset versions that match the query criteria, described using mobilityDCAT-AP and the EvoRoads extension. This catalogue response is passed back through the digital twin to the dashboard, where the user is presented with a structured and intelligible list of available data assets, including their provenance, update status and applicability.

The user selects a specific dataset for further analysis. This triggers the **Task 2.1 data acquisition and ingestion platform**, which retrieves the selected dataset and initiates the appropriate processing pipeline. Depending on the pilot configuration, this may involve streaming or batch ingestion via Apache Kafka. The data are then processed in the cloud plane by algorithms developed in WP2 and WP3, for example to compute updated infrastructure condition indicators or safety-related metrics.

Once processing is completed, a **new derived dataset** is produced. This dataset is registered in CKAN as a new version or as a linked analytical output, with metadata that explicitly relate it to the original input data. The digital twin layer incorporates the results by associating them with the relevant infrastructure entities and contexts, making them immediately available to the dashboard. The user can then visualise the results, inspect indicators or use them to support decision-making.

In the final step of the scenario, the resulting dataset is designated for **external sharing with an academic stakeholder**. Rather than exporting the data manually, the dataset is exposed through the SMDS federation layer using an **IDSA-compatible Eclipse Connector**. Access conditions are defined by the data provider, and a controlled data exchange is established with the external party. In this way, the use case demonstrates how data move seamlessly from internal discovery and processing to secure, policy-driven sharing beyond the project, highlighting the practical interoperability of the SMDS architecture.

5.4.4 RURAL AND URBAN DEPLOYMENT CONSIDERATIONS

The operational design of the SMDS explicitly accounts for the differences between urban and rural road contexts. Urban pilots often generate higher data volumes and benefit from existing digital infrastructure, enabling near-real-time processing and richer contextual data integration. Rural pilots, by contrast, may rely on sparser sensing, intermittent connectivity and lower-cost monitoring solutions. The SMDS accommodates these differences by supporting asynchronous data flows, local pre-processing at the edge and flexible update cycles.

Importantly, the data space does not prioritise one context over another. Safety-related data from rural roads are integrated, described and exposed using the same mechanisms as urban data, ensuring comparable visibility and analytical treatment. This is a key factor in enabling evidence-based safety assessments for road networks that are traditionally underrepresented in data-driven mobility systems.

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5.4.5 INTEROPERABILITY AND INTERACTION WITH EXTERNAL ECOSYSTEMS

In operational terms, interoperability with external data spaces within EvoRoads is achieved through selective exposure rather than continuous or hard-wired integration. The SMDS interfaces with external ecosystems exclusively through its federation layer, where datasets and derived data products can be shared under explicitly defined technical and governance conditions. This approach allows data providers to determine what is shared, with whom, for which purpose, and for how long, without exposing internal services or disrupting ongoing pilot operations. Depending on stakeholder needs, exposure may concern raw datasets, processed outputs, or higher-level analytical artefacts such as safety indicators, enabling interaction at different levels of granularity. Importantly, this model avoids the need for synchronised lifecycles or permanent coupling between EvoRoads and external initiatives, a constraint that has been identified as a key challenge for research-driven data spaces.

Operationally, this means that pilot deployments remain self-contained and stable, while interoperability is realised at the boundary of the SMDS through standardised interfaces and policy-driven exchange mechanisms. External interactions are therefore additive rather than intrusive, preserving the integrity of local data pipelines and respecting legal or organisational constraints that may vary across pilots. At the same time, the use of common metadata profiles and federated exchange protocols ensures that exposed datasets are intelligible and usable by external parties without bespoke adaptation.

To conclude, this operational design allows the EvoRoads SMDS to function as a coherent data space across all pilots, while remaining adaptable to diverse local conditions and evolving European data space ecosystems. By balancing shared services with decentralised operation, the SMDS establishes a practical and scalable model that supports internal collaboration during the project and provides credible pathways for external reuse and integration beyond its lifetime.

5.5 MAINTENANCE, EVOLUTION AND EXTENSIBILITY OF THE SMDS

This concluding subsection addresses how the EvoRoads Safe Mobility Data Space (SMDS) is designed to be maintained, evolved and extended beyond its initial implementation, and outlines the future steps planned during the remainder of the project. The focus is on ensuring that the SMDS delivers long-term value by remaining adaptable to new stakeholders, new contexts and evolving technical requirements, while preserving architectural coherence.

5.5.1 TRANSITION FROM DESIGN TO FULL DEPLOYMENT

During the first 18 months of the EvoRoads project, SMDS-related activities concentrated on state-of-the-art analysis, requirement elicitation, component selection, architectural design and systematic mapping of data sources across pilots. This period also included the partial definition of end-to-end data pipelines, validated progressively through integration workshops and continuous interaction with pilot leaders and data providers. The remaining project period will shift the emphasis towards **full development, deployment and operational validation** of the SMDS components. This includes completing data pipelines from edge to cloud and federation layers, stabilising interfaces between Tasks 2.1, 3.1 and 1.4, and validating operational workflows across all pilot sites.

5.5.2 ONBOARDING NEW DATA PROVIDERS

A core requirement for long-term sustainability is the ability to onboard new data providers with minimal overhead. The SMDS architecture supports this through well-defined ingestion interfaces, standardised metadata requirements and decentralised deployment options. New providers can be integrated by configuring ingestion pipelines within the Task 2.1 layer and registering their datasets in the internal catalogue using the established metadata profiles. Crucially, onboarding

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does not require changes to the overall architecture or to existing pilot deployments, ensuring that growth can occur incrementally and without disruption.

5.5.3 EXTENDING TO NEW CITIES AND REGIONS

Beyond the initial EvoRoads pilots, the SMDS is designed to be adaptable to additional cities, regions and road networks. This extensibility is achieved through the separation of common services from pilot-specific configurations. New locations can adopt the same architectural blueprint, selecting deployment options that match local legal, organisational and technical constraints. This approach is particularly relevant for rural and secondary road networks, where digital maturity and data availability may differ significantly from urban contexts, yet where the need for systematic safety assessment remains high.

5.5.4 MANAGING SCHEMA AND DATA MODEL EVOLUTION

Schema evolution is an inherent challenge in data-intensive systems, especially where analytical methods and data sources evolve over time. The SMDS addresses this through explicit dataset versioning, metadata-driven documentation and controlled lifecycle management within the internal catalogue. Changes to data schemas or derived data products are introduced as new versions rather than as breaking updates, preserving backward compatibility and analytical reproducibility. This approach allows the SMDS to evolve while maintaining continuity for existing users and workflows.

5.5.5 AVOIDING VENDOR AND PLATFORM LOCK-IN

Long-term viability also depends on avoiding dependency on proprietary technologies or single vendors. The SMDS architecture deliberately relies on open standards and open-source components and exposes functionality through documented interfaces rather than embedded integrations. This design choice allows individual components to be replaced or upgraded as technologies evolve, without requiring a complete redesign of the data space. It also ensures that future adopters can deploy and operate the SMDS using infrastructures and providers of their choice.

5.5.6 OUTLOOK AND CONCLUDING REMARKS

In summary, the EvoRoads SMDS is conceived not as a static project artefact, but as an evolving data space that can grow in scope and relevance over time. The methodological groundwork laid during the first half of the project provides a stable foundation for full deployment and validation in the second half, while the architectural choices support extensibility beyond the project's duration. By addressing onboarding, geographic expansion, schema evolution and technology independence, the SMDS offers a credible pathway towards sustained impact. This concludes the Data Space chapter, situating the SMDS as a practical, adaptable and future-oriented component of the EvoRoads technical framework.

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6 CONCLUSIONS

The present final chapter draws together the main findings, highlighting conclusions, lessons learnt, challenges encountered, and the alignment of the deliverable with European transport safety goals, while outlining the steps foreseen for the next project phases.

6.1 SUMMARY OF KEY POINTS

This deliverable has presented a comprehensive account of the conceptual, methodological and architectural foundations of the EvoRoads platform, reflecting the work undertaken during the first phase of the project. Its overarching contribution lies in articulating a coherent framework that connects user needs, safety criteria, data-driven analytics and system architecture into a unified proposition for infrastructure-focused road safety improvement.

Chapter 1 established the scope and objectives of the deliverable, positioning it within the broader EvoRoads project and clarifying its role as a foundation-setting document rather than a final system specification. The methodological approach adopted throughout the work emphasised traceability, cross-work-package coordination and iterative refinement, recognising the research and innovation character of the project.

Chapter 2 addressed the user-facing dimension of EvoRoads by introducing the five planes of UX. This chapter demonstrated how strategic objectives, user personas and operational needs were progressively translated into interaction concepts, functional views and interface designs. Rather than treating the user interface as a downstream concern, the work positioned UX as a structuring element that informs platform functionality and decision-support logic across roles such as road operators, planners, maintenance managers and policy stakeholders.

Chapter 3 focused on the development of dynamic KPIs, providing a structured pathway from safety criteria to measurable, actionable indicators. By grounding KPIs in a shared safety framework and explicitly considering temporal resolution and decision context, the project established a mechanism for transforming heterogeneous data into insights that can support both operational and strategic interventions. This work forms a critical bridge between raw observations and evidence-based decision-making.

Chapter 4 presented the integrated platform architecture using the 4+1 architectural model. Through the Logical, Process, Development and Physical Views, the deliverable described the structure, runtime behaviour, integration strategy and deployment assumptions of the EvoRoads platform. The inclusion of an operational perspective highlighted how architectural components support safety-oriented workflows across diverse pilots. Importantly, the chapter balanced architectural clarity with transparency regarding the evolving state of implementation, avoiding premature commitments while demonstrating coherence and design discipline.

Chapter 5 examined the Safe Mobility Data Space as a central enabling element of the platform. It detailed the design principles, metadata models and interoperability mechanisms that allow EvoRoads to manage data sovereignty, controlled sharing and alignment with EMDS initiatives. This chapter positioned the data space not as an isolated technical artefact, but as an integral part of the platform's ability to operate across organisational and national boundaries.

Taken together, the deliverable demonstrates that EvoRoads is progressing towards a coherent, user-driven and safety-focused platform architecture. The work carried out so far establishes a solid conceptual and technical baseline upon which further development, integration and validation activities can build, while maintaining alignment with European priorities in road safety and data interoperability.

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6.2 LESSONS LEARNED AND CHALLENGES

The work documented in this deliverable has yielded a number of lessons that are characteristic of large-scale, multi-partner research and innovation projects operating across heterogeneous technical and organisational contexts. These lessons are closely linked to the challenges encountered during the initial project phase and have informed both architectural choices and methodological approaches.

One of the primary challenges has been managing **heterogeneity across pilot sites**. EvoRoads operates in environments that differ significantly in terms of infrastructure characteristics, governance structures, data availability and operational practices. A key lesson has been the importance of defining common conceptual frameworks (such as shared safety criteria, decision workflows and architectural layers) while allowing sufficient flexibility for local adaptation. Attempting to enforce uniform solutions too early would have risked misalignment with pilot realities and reduced the relevance of the platform outputs.

A second challenge relates to **integration across WPs and technical domains**. The platform brings together sensing technologies, data engineering pipelines, digital twins, analytics, user interfaces and data space components, each developed by different partners with distinct expertise. The experience to date has shown that architectural coordination and continuous dialogue are as critical as technical interfaces. Clear architectural views and shared artefacts have proven essential for avoiding fragmentation and ensuring that components evolve in a compatible manner.

The treatment of **deployment and operational aspects** has also presented challenges. While there is a strong need to demonstrate technical credibility, premature specification of deployment topologies, orchestration mechanisms or automation pipelines would have introduced risks and potentially constrained innovation. A key lesson has been the value of explicitly documenting assumptions and constraints, rather than attempting to present an artificially complete picture. This approach supports transparency and allows the architecture to evolve in response to evidence gathered during pilot execution.

From a data perspective, **balancing innovation with governance and compliance** has required careful consideration. The need to support advanced analytics and cross-pilot learning must be reconciled with data protection, ownership and sovereignty requirements. The work on the Safe Mobility Data Space highlighted the importance of embedding governance considerations into technical design from the outset, rather than treating them as an external constraint.

Finally, the **iterative nature of user engagement** has underscored the importance of maintaining a feedback loop between conceptual design and practical validation. User needs and expectations evolve as prototypes become available and as stakeholders gain a clearer understanding of platform capabilities. Capturing these insights without destabilising the architectural baseline has been a recurring challenge, reinforcing the need for modularity and composability.

Overall, the lessons learned during this phase emphasise the value of architectural discipline, transparent scoping and continuous alignment across technical and organisational boundaries. These insights will inform the next phases of EvoRoads, supporting more focused integration, validation and refinement as the platform progresses towards its subsequent iterations.

6.3 ALIGNMENT WITH EU GOALS

The EvoRoads project is closely aligned with the strategic objectives and policy directions set by the European Union in the domains of road safety, smart mobility and data governance. At its core, EvoRoads responds to the EU's long-term commitment to reducing road fatalities and serious injuries, while supporting the transition towards more data-driven, coordinated and preventive approaches to infrastructure safety management.

A central point of alignment is the **Vision Zero ambition** [85], which underpins the EU Road Safety Policy Framework 2021-2030. Vision Zero establishes the ethical principle that no loss of life or serious injury on Europe's roads is acceptable and calls for a systemic approach to safety that goes beyond individual behaviour. EvoRoads contributes to this objective by focusing explicitly on infrastructure-related safety risks and by enabling early detection, prioritisation and evaluation of interventions. Rather than treating accidents as isolated events, the platform supports continuous monitoring of infrastructure condition, connectivity and operational readiness, thereby reinforcing the Safe System approach promoted at EU level.

EvoRoads also aligns with the EU's intermediate target of **reducing road deaths and serious injuries** by 50% by 2030 [86]. The project addresses a critical gap identified in EU policy discussions: the limited availability of consistent, comparable and timely data on secondary, rural and peri-urban road networks, where a disproportionate share of fatal accidents occurs. By enabling scalable data collection, harmonised indicators and cross-pilot learning, EvoRoads strengthens the evidence base required for targeted interventions on precisely those parts of the network where safety challenges are most acute.

Beyond road safety, the project supports broader EU objectives related to **smart and sustainable mobility** [87]. The platform architecture and operational workflows are designed to integrate heterogeneous data sources, including those related to connectivity and emerging mobility services, thereby supporting informed decision-making in contexts where digital readiness and safety are increasingly interdependent. This is particularly relevant for policies addressing connected and automated mobility, where infrastructure quality, network performance and safety assurance must evolve in parallel.

A further dimension of alignment with EU policy objectives lies in EvoRoads' explicit focus on **rural and secondary road networks** [85] [88], which remain a persistent safety challenge across Europe. EU road safety statistics consistently show that a disproportionate share of fatalities and serious injuries occur on non-motorway roads, particularly in rural and peri-urban areas, where infrastructure quality, maintenance cycles and digital coverage are often uneven. EvoRoads addresses this gap directly by prioritising sensing, analytics and decision-support mechanisms tailored to these contexts, including large-area monitoring, connectivity-aware safety assessment and scalable prioritisation of interventions under resource constraints. By enabling road authorities to better understand degradation patterns, connectivity limitations and risk concentration on secondary networks, the platform supports more targeted and equitable safety improvements. This focus complements Vision Zero and Safe System principles by extending data-driven safety management beyond primary corridors and urban centres, contributing to a more balanced and inclusive approach to road safety across the European road network.

From a data policy perspective, EvoRoads is aligned with the EU's ambition to establish **common European data spaces** [89], including the Common European Mobility Data Space [71]. The Safe Mobility Data Space developed within EvoRoads adopts principles of data sovereignty, interoperability and controlled sharing, ensuring that data providers retain control while enabling cross-organisational and cross-border reuse. This approach reflects the EU's emphasis on trusted data sharing frameworks as articulated in the European Data Strategy and related legislative initiatives.

The project also contributes to EU goals on **digitalisation of public services and infrastructure management**. By providing decision-support tools that are usable by public authorities with varying levels of digital maturity, EvoRoads supports the uptake of advanced analytics and digital twins in everyday infrastructure management. This aligns with EU efforts to modernise public administration, improve transparency and enable evidence-based policymaking at local, regional and national levels.

Importantly, EvoRoads does not pursue alignment through abstract policy mapping alone. The platform's design explicitly incorporates EU-relevant standards, safety criteria and governance principles, ensuring that alignment is realised in technical artefacts and operational practices rather than remaining declarative. The focus on interoperability, comparability of indicators and scalability across contexts positions EvoRoads as a practical contributor to EU objectives, capable of informing both future deployments and policy refinement.

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In summary, EvoRoads supports the EU’s road safety and mobility agenda by operationalising Vision Zero principles, strengthening the data foundations for infrastructure safety management and contributing to the development of trusted mobility data ecosystems. Through its integrated platform and data space approach, the project provides a concrete pathway from European policy objectives to actionable tools and methods that can be adopted and extended beyond the project’s lifetime.

6.4 FUTURE STEPS AHEAD OF VERSION 2

The work documented in this deliverable establishes the conceptual, architectural and methodological foundations of the EvoRoads platform. The next project phase focuses on consolidating these foundations into a fully integrated and operational system, informed by real pilot data, iterative validation and cross-work-package coordination. The transition from architectural baseline to Version 2 of the platform will therefore be driven by targeted integration, refinement and deployment activities rather than by the introduction of new conceptual layers.

A first priority is the **finalisation of the full integration blueprint** across the platform. This includes detailing the remaining interfaces, data flows and harmonisation rules that connect data acquisition and processing activities in WP2, analytical and digital twin components in WP3, and the Safe Mobility Data Space. While the present deliverable has established clear architectural roles and interaction patterns, the next phase will formalise these into complete, end-to-end pipelines that are exercised consistently across pilots.

As pilots progress into operational phases with live and batch data, the **system architecture will be refined based on empirical feedback**. Real data volumes, latency characteristics and user interaction patterns will inform adjustments to dependencies, module interactions and KPI computation pathways. This refinement process is expected to be iterative, ensuring that architectural decisions remain grounded in observed behaviour rather than static assumptions.

In parallel, **user interfaces will be finalised and validated** across pilots. This work will ensure that dashboard views and companion applications remain consistent with pilot-specific needs, with the semantics and constraints imposed by the Safe Mobility Data Space, and with the overall design approach introduced in this deliverable. Particular attention will be given to clarity, interpretability and alignment between analytical outputs and decision-making contexts.

The next phase will also place emphasis on **documentation and demonstration readiness**. Technical documentation, integration guides and demonstration narratives will be prepared to support external showcases during the second pilot round and during the project’s dissemination and clustering events. These materials will translate architectural and technical achievements into accessible evidence of impact for stakeholders beyond the project consortium.

A central milestone will be the **completion of the full Safe Mobility Data Space implementation**. This includes finalising ingestion and exposure pipelines, metadata mappings and semantic transformations across all pilots, ensuring that data products can be governed, discovered and shared in a controlled and interoperable manner. The deployment of additional architectural components - such as identity management services, sovereign data-sharing modules, marketplace elements and a unified data-exchange API - will further strengthen the platform’s readiness for interaction with external ecosystems.

These activities are closely aligned with the project’s forthcoming deliverables. At component level, *“D2.3: Advanced infrastructure monitoring and predictive maintenance tools”* and *“D3.3: Advanced tools for implementing the ‘Safe System’ approach”*, both due in September 2026, will provide mature technical capabilities feeding into the integrated platform. At platform level, “*D1.4: KPIs quantification methodologies, data space, user interfaces and integrated platform V2*”, due in February 2027, will document the consolidated architecture, refined KPIs, completed data space and validated user interfaces.

The first verification phase in pilots will conclude in March 2026, providing early evidence to guide integration and refinement, while the second verification phase will run until March 2027, supporting full validation of Version 2. Together,

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these steps ensure a structured progression from architectural foundation to operational maturity, positioning EvoRoads for sustained impact beyond the project lifetime.

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ANNEX

ANNEX 1: AI ACT COMPLIANCE IN THE EVOROADS PROJECT

To guarantee the responsible development and use of AI, the European Union has defined the concept of Trustworthy AI based on three fundamental pillars: compliance with existing laws and regulations (Lawful), adherence to fundamental human values (Ethical) and technical security and resilience against risks (Robust). As outlined in the **Ethics Guidelines for Trustworthy AI**[20], these principles have been translated into practical requirements, such as transparency, human oversight, data protection, and fairness.

The **AI Act**[21] is a European regulation that integrates the Ethics Guidelines for Trustworthy AI into a binding regulatory framework, establishing concrete rules, classifying AI-based systems, and imposing stringent requirements for high-risk applications. The regulation introduces a risk-based classification system for AI-based systems, dividing them into four main categories:

- *Unacceptable risk*: Prohibited systems, such as those employing subliminal manipulative techniques or social scoring;
- *High risk*: Applications impacting critical sectors (e.g., healthcare, infrastructure, mobility) that are subject to strict compliance requirements;
- *Limited risk*: Systems that require transparency obligations, such as chatbots or deepfakes;
- *Minimal risk*: Unregulated systems, such as spam filters or AI-powered video games.

The AI Act seeks to balance technological innovation with the protection of fundamental rights, promoting the responsible use of AI. It includes human oversight, data security, and non-discrimination provisions while supporting AI-based research and development in strategic sectors.

EvoRoads Project is committed to fully complying with the EU AI Act, its core principles, and the Trustworthy AI criteria, ensuring that all developed AI-based technologies are lawful, ethical, robust, and respectful of human rights and values.

The EvoRoads project involves multiple entities, meaning any subject (company, individual, or public body) engaged in developing, distributing, or using an AI-based system. Depending on their role, each entity has specific obligations and responsibilities to ensure compliance with European AI regulations. The key entities involved in the EvoRoads Project include:

- **Provider**: A company, public entity, or individual that develops an AI-based system or a general-purpose AI model and places it on the market or into service under its own name or brand;
- **Deployer**: Any entity using an AI system under its authority (e.g., companies, public bodies), except for personal, non-professional use.

To correctly classify the role of each EvoRoads beneficiary and the characteristics of the AI-based systems being developed, used, or distributed, the project will leverage the **EU AI Act Compliance Checker**[22] .

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By answering a series of questions, this tool will support EvoRoads beneficiaries in identifying the risk level of EvoRoads AI-based system and being informed about specific articles of the AI Act to be considered to be fully compliant with trustworthy AI principles. The results provided by the tool will be documented in project deliverables dedicated to the EvoRoads AI-based solutions.

By leveraging the EU AI Act Compliance Checker, the EvoRoads project will ensure full compliance with European AI regulations, fostering the development and adoption of safe, ethical, and reliable AI-based systems in road transport.

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ANNEX 2: DELIVERABLE CONTEXT MAPPING

The purpose of this section is to map EvoRoads' Grant Agreement (GA) commitments, both within the Deliverable 1.3 content and Tasks 1.3, 1.4 & 1.5 descriptions, against the project's respective outputs and work performed.

Table 31. Adherence to EvoRoads GA Deliverable & Tasks Descriptions

EVOROADS GA COMPONENT TITLE	EVOROADS GA COMPONENT OUTLINE	RESPECTIVE DOCUMENT CHAPTER(S)	JUSTIFICATION
DELIVERABLE			
D1.3 KPIs quantification methodologies, data space, user interfaces and integrated platform V1	*The first release of the KPIs quantification methodologies, ...*	Chapter 3	Chapter 3 addresses the development of dynamic KPIs, detailing the process through which safety-related criteria are transformed into measurable indicators capable of supporting interventions at different temporal resolutions.
D1.3 KPIs quantification methodologies, data space, user interfaces and integrated platform V1	*… the mobility data space, …*	Chapter 5	Chapter 5 focuses on the safe mobility data space, describing its design principles, data models, and role in ensuring interoperability and trust across heterogeneous sources.
D1.3 KPIs quantification methodologies, data space, user interfaces and integrated platform V1	*… the mobile and web applications …*	Chapter 2	Chapter 2 presents the design of the user-facing elements through the five planes of user experience, showing how the interfaces were shaped from strategic intent to final surface design.
D1.3 KPIs quantification methodologies, data space, user interfaces and integrated platform V1	*… and the integrated platform with components from WP2 and WP3.*	Chapter 4	Chapter 4 then turns to the technical architecture of the platform, adopting the 4+1 methodology to present the system from multiple perspectives and including a discussion of access control and security mechanisms.
D1.3 KPIs quantification methodologies, data space, user interfaces and integrated platform V1	*The first release of the KPIs quantification methodologies, the mobility data space, the mobile and web applications and the integrated platform with components from WP2 and WP3.*	Chapter 6	Chapter 6 draws together the main findings, highlighting conclusions, lessons learnt, challenges encountered, and the alignment of the deliverable with European transport safety goals, while outlining the steps foreseen for the next project phases.
TASKS			

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T1.3	*The outcomes of T1.1 and T1.2 will be exploited as the cornerstone of this task's activities, which will involve the investigation and development of methodologies for the dynamic quantification of safety criteria and related KPIs. A large focus is on criteria/KPIs that can be updated and changed in real-time to allow for fast adaptation of the traffic system to enhance the safety level, but also post-processing of data and KPIs are considered. Correlations between traditional traffic safety KPIs and road attribute KPIs are considered to propose new safety KPIs that combine both safety measurements and road attribute safety levels. Further, new data collection methods for detecting unsafe behaviour, such as video-detection, probe vehicle data etc. are assessed for proposing and quantifying enhanced traffic safety KPI's. The approaches are based on, but not limited to mathematical, ML and statistical methods, and traffic flow theory-based methodologies to (a) assess the influence of road attributes, collected through new technologies and data sources (with a special focus on dynamic road attributes that can be updated and change frequently or in real-time) on the severity and frequency of road crashes. Road crash prediction models, including also other contributing factors (e.g. traffic volumes, road congestion, road geometries and other road static attributes), will be developed and tested, based on both statistical and ML approaches, to compare the model efficiency and accuracy; (b) identify thresholds (that can vary depending on the context, e.g. country, type of road, type of users involved in accidents etc.) and criteria to integrate the impact of newly collected road attributes in the evaluation of infrastructure safety ranking; (c) establish procedures for road network monitoring and road attributes KPIs collection (e.g. frequency of monitoring, best technologies for data collection) to guarantee an appropriate update of road safety levels.*	Chapter 3	**Chapter 3** addresses the development of dynamic KPIs as a central mechanism for translating safety-related criteria into measurable, actionable insights. Building on the user needs and safety frameworks introduced in Chapter 2 and on the baseline safety criteria defined in Deliverable D1.1, the chapter describes a structured process through which heterogeneous safety signals are transformed into indicators capable of supporting operational, tactical and strategic interventions. The chapter focuses on methodologies that allow KPIs to evolve over time, reflecting changes in infrastructure condition, network performance and contextual factors.
T1.4: Safe Mobility Data space and knowledge	*This task will be responsible for the development a Safe Mobility Data Space (SMDS) aggregating the EvoRoads data sources while providing*	Chapter 5	**Chapter 5** focuses on the design and role of the **Safe Mobility Data Space (SMDS)** within the EvoRoads platform. The chapter positions the SMDS as a key enabling element that supports

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discovery services	*methodologies to fuse, combine and integrate, harmonize multidisciplinary safety databases and assessment frameworks and sensor data. EvoRoads foresees to provide a comprehensive and extendible EU wide data space including able to host static and streamed heterogeneous data, ranging from structured connected vehicles data to semi-structured video streams of traffic to variable-size unstructured qualitative data from social innovation instruments. An initial set of sources of data to be included have been described in Section 1.2.8. For processing and storing the corresponding safety related data, a big-data architecture will be established, also relying on and extending the work of the International Data Spaces (IDS) association. The EvoRoads approach will ensure high degree of interoperability, data trustworthiness and secure sharing with the use of IDS Connectors. Data integration and harmonization will rely on smart data models in the form of multi-dimensional and semantically coded data structures capable of supporting representations for various data to be generated and utilised by the EvoRoads platform. Moreover, a pipeline mechanism for the creation of pre-processing steps focused on the data quality will be designed, starting from the existing open-source Chimera project. The outcome will be a containerized software application for easy deployment at EvoRoads pilots. Additionally, data enrichment capabilities in the form of knowledge discovery services will be provided, where the goal is to generate (from the observed data) additional derived attributes/features using either external background knowledge or internal relationships within of data. This could include the use of external ontologies, statistical properties (modes) of data and/ or temporal characteristics of data.*		secure data integration, interoperability and controlled data sharing across heterogeneous sources, stakeholders and geographic contexts. It situates the EvoRoads SMDS within the broader European mobility data space landscape, identifying both alignment opportunities and existing gaps. The chapter outlines the architectural principles underpinning the SMDS, including federation, decentralisation, data sovereignty and governance by design. It describes how data are ingested, catalogued and exposed using harmonised metadata models, including mobilityDCAT-AP extensions tailored to EvoRoads pilot characteristics. Particular emphasis is placed on the management of derived and analytical data products, ensuring that safety indicators and digital twin outputs remain discoverable and reusable without loss of semantic meaning. By addressing governance, interoperability and technical enforcement mechanisms together, Chapter 5 demonstrates how the SMDS enables EvoRoads to function as a stand-alone yet interoperable data space.
Task 1.5: EvoRoads integrated platform for safer urban and rural environments	*The aim of this task is to develop the EvoRoads detailed use cases and to conceptualize the EvoRoads framework architecture and design approach to be followed by WP2 and WP3 for implementing integrated and interoperable safety services for all road users. The resulting architecture will provide a conceptual and non-*	Chapters 2 and 4	Chapters 2 and 4 together articulate the central design principle of EvoRoads: that technical architecture and user experience are not developed independently, but co-evolve as mutually reinforcing elements of a single platform. **Chapter 2** establishes the user-facing foundations of the project by identifying personas, operational contexts and user requirements through the five

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	technical specification of the solutions: actors and roles, process models showing interactions, conceptual information models and open services that support interoperability between loosely coupled systems. Existing frameworks and models, where appropriate, and interoperability and information demands will be considered to develop the necessary service interfaces. Moreover, this task will undertake the required activities for the integration of the various EvoRoads solutions as a single technological offering. Models and tools developed within the frame of WP2 and WP3 will be integrated, where applicable, in the form of software services in the context of this task. Software testing and evaluation will be based on a method such as STEP (Systematic Test and Evaluation Process), a well-established industry methodology for testing and evaluating activities in software projects. It should be mentioned that within this task testing will be performed to verify the proper functioning and performance of the integrated EvoRoads Platform. Lastly this task will provide the various client interfaces for smartphones and web applications, which will provide the users of the platform the entry point for accessing the various services. The EvoRoads applications will be tailored to the needs and requirements of different road users and stakeholders, including needs for VRUs, drivers, maintenance operators, policy makers, etc.		planes of user experience, ranging from strategic intent to concrete interface interactions. This work ensures that the platform addresses real decision-making needs of road safety operators, planners, maintenance leads, policy stakeholders, researchers and other actors involved in infrastructure safety management. **Chapter 4** translates these user-driven insights into a coherent technical architecture. The Logical View defines components and responsibilities that directly reflect user needs, such as real-time monitoring, prioritisation support, impact assessment and data governance. The Process View demonstrates how runtime interactions support user workflows, ensuring that safety-related information flows from sensing and analytics layers to dashboards and applications in a timely and interpretable manner. The Development and Physical Views further ensure that integration practices and deployment assumptions remain compatible with the diversity of pilot contexts and user environments identified earlier. Taken together, these chapters demonstrate that EvoRoads is designed as a user-centred, safety-driven platform in which architecture serves decision-making needs rather than dictating them.

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