



BEST PRACTICES & STATE-OF-THE-ART

Project deliverable D2.1

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LIST OF ABBREVIATIONS AND ACRONYMS

ACRONYM	MEANING
AI	Artificial Intelligence
ANPR	Automatic Number Plate Recognition
API	Application Programming Interface
AVL	Automatic Vehicle Location
CAM	Cooperative Awareness Message
CCAM	Cooperative, Connected and Automated Mobility
DENM	Decentralized Environmental Notification Message
EC	European Commission
EI	Expected Innovation
EDC	Eclipse Dataspace Connector
EMDS	European Mobility Data Space
ETA	Estimated Time of Arrival
FCD	Floating Car Data
FGSV	German Road and Transportation Research Association
FTAZ	Freight Traffic Analysis Zone
GA	Grant Agreement
GenAI	Generative Artificial Intelligence
GERS	Global Entity Reference System
GHG	Greenhouse Gas
GIMMI	Geometry InterMapMatching Extension
GIS	Geographic Information Systems
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HOT	High-Occupancy Toll
ICT	Information and Communication Technology
KoM	Kick-off Meeting
KPI	Key Performance Indicator
LaaS	Logistics as a Service
LLM	Large Language Model
MaaS	Mobility as a Service
MATs	Multi-Aspect Trajectories
MDC	Mobility Data Space
MNO	Mobile Network Operator
MTM	Multimodal Traffic Management
MTMC	Multimodal Traffic Management Cluster
OEM	Original Equipment Manufacturer
OSM	OpenStreetMap
PRM	Persons with Reduced Mobility
QoS	Quality of Service
RSU	Roadside Unit
TAZ	Traffic Analysis Zone
UAV	Unmanned Aerial Vehicle
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VM	Verification Means
VCS	Version Control Systems
VRU	Vulnerable Road User
WP	Work Package

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PROJECT EXECUTIVE SUMMARY

Lack of orchestration structured and standardized integration protocols and metadata descriptors, incorporation of real-world traffic complexities and nuances, underutilization of valuable resources, model uncertainties and integration of micro-mobility services and VRUs result in suboptimal performance in addressing complex issues related to the management of mobility services and infrastructure and a divergence from EU's sustainable mobility targets. FEDORA aims to pave the way towards advanced traffic and network management through the development of a federated spaces platform offering a holistic framework of innovative solutions and services that enable precise and proactive sensing of supply and demand, facilitate optimal operation of transport services and advance learning and evolution in complex environments. At the operational level, FEDORA offers a collaborative space of data that can realize advanced data alchemy processes using interconnected services and tools, a space of advanced traffic management optimisation services and a multi-modal simulation space to create and assess future mobility scenarios. The approach is validated in six thematic demonstrations in Vienna (Austria), the Basque country (Spain), Reggio Emilia (Italy), Nicosia (Cyprus), Budapest (Hungary) and Greater Copenhagen (Denmark), covering varying EU urban and rural contexts, infrastructure maturity levels, multimodal mobility services availability, organisation/operational structures and social conditions. Interaction with existing programmes on road mapping and recommendations at national, EU and global level will be promoted, allowing a multiplication effect of project's results.

Social Media Link:

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DELIVERABLE EXECUTIVE SUMMARY

This deliverable describes the best practice methods and the state-of-the-art of Multimodal Traffic Management (MTM). The purpose of this document is to provide a theoretical basis for the developments made during FEDORA. Scientific literature, categorized into three main areas, has been investigated to provide an overview of the relevant technologies and methods used in the context of MTM: (1) data, (2) modelling and simulation, (3) network management. Together, these three domains form the foundation for the coordination of multimodal transport. The deliverable also discusses MTM implementation and real-world pilots taken from EU-funded projects which demonstrate the ways in which data-driven coordination, artificial intelligence, and digital twins can improve the efficiency, safety, and sustainability of the network.

This deliverable includes:

- A review of the principles, methods, and challenges to multimodal traffic and network management, emphasizing the shift from single-mode optimization to integrated, data-driven coordination across modes.

The literature review shows a transition from mode-specific traffic control to integrated, multimodal management. Coordination across cars, public transport, micromobility and freight can support more efficient, inclusive, and environmentally sustainable mobility. Challenges in this domain include the lack of standardized performance indicators, lack of cooperation between stakeholders and institutions and weak cross-modal service alignment. From an EU-perspective, there is a clear need for systems, that can manage multiple modes together, share control strategies across operators, and balance efficiency with societal objectives, such as safety and equity.

- A detailed review of data ecosystems, covering data types, governance frameworks, spatial and temporal characteristics, and the emerging concept of federated data spaces under the European Data Strategy.

Multimodal systems depend on diverse types of data, such as vehicle positioning, traffic volume, road conditions, passenger flow, and environmental conditions metrics. These data streams vary in format, frequency, and ownership, and often come from heterogeneous sources such as connected vehicles, roadside sensors, mobile apps, and transport operators. The review identifies a strong push toward interoperable data ecosystems, supported by expanding standards such as DATEX II, NeTeX, and linked data frameworks. Federated data spaces, where stakeholders retain control over their data, while allowing controlled access, are proposed as a solution to issues of data fragmentation, trust, and privacy.

- An overview of modelling and simulation approaches, emphasizing AI-based prediction, incident detection, and digital-twin applications for dynamic and adaptive management.

The state-of-the-art review includes a range of modelling tools that support both strategic planning and real-time traffic control. Traditional macroscopic and agent-based simulations remain important for long-term planning, and artificial intelligence is increasingly used for real-time applications such as travel time prediction, demand forecasting, and anomaly detection. Digital twins, real-time, virtual representations of transport networks, enable continuous monitoring and simulation-based decision-making. Several studies and pilot projects show that combining simulation with real-time data, AI, and machine learning leads to faster and more adaptive traffic management strategies.

- An analysis of management and optimization methods, including signal control, pricing and incentivization, freight and logistics coordination, and public transport optimization, with examples from ongoing and completed EU pilot projects within the MTM cluster and beyond.

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Practical implementations from recent EU-funded projects provide valuable insight into how MTM can be applied at city and regional levels. Examples include decentralized traffic control systems, dynamic pricing mechanisms to manage demand, real-time freight routing tools, and algorithms to improve public transport reliability and coordination. These pilots highlight the value of cross-modal architectures, user-centric services, and cooperative decision-making between public and private actors. They also show the importance of integrating physical infrastructure into digital platforms and institutional frameworks for effective, scalable deployment.

The main conclusions highlight that, although significant progress has been achieved in developing multimodal and cooperative traffic management systems, challenges remain regarding data interoperability, scalability of solutions, stakeholder coordination, and governance harmonization. The analysis also demonstrates the importance of integrating physical, digital, and institutional layers of the transport ecosystem through federated, AI-enabled, and simulation-supported frameworks. These insights constitute the situational awareness and baseline required for further work in FEDORA. This will ensure that the technical developments undertaken within the project are informed by current practices, reflect real operational constraints, and build on lessons learned from the broader European research community.

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1 INTRODUCTION

This deliverable lays the groundwork for all subsequent developments throughout the project by presenting a comprehensive review of the literature, existing solutions, best practices, and gaps identified across key dimensions of Multimodal Traffic Management (MTM). These elements are systematically organized and articulated according to FEDORA’s three core domains: data, simulation, and network management.

In addition, the deliverable explores the principal challenges and future directions in traffic management, alongside the diverse requirements and expectations of users and stakeholders. It also features a comparative analysis of recent scientific advancements, with a particular emphasis on real-world pilot implementations from EU-funded research initiatives within the MTM Cluster and beyond. This analysis highlights major outcomes, achievements, challenges encountered, and the strategies employed to address them. Ultimately, the deliverable aims to articulate FEDORA’s vision for the future of MTM, offering conceptual frameworks and strategic guidelines intended to inform researchers, practitioners, and operators about the innovations to be developed during the project.

Specifically, this deliverable includes a systematic literature review aligned with objectives and modules developed within the FEDORA project. Clear research and technical pathways that will be followed by FEDORA are thoroughly discussed. Additionally, deliverables and other relevant sources (e.g., scientific publications) from similar research projects are examined to extract insight into applied methodologies and implementation outcomes across various transport-related challenges. This facilitates the formulation of best practice and actionable recommendations.

1.1 MAPPING FEDORA’S OUTPUT

The purpose of this section is to map FEDORA Grant Agreement commitments, both within the formal Deliverable and Task description, against the project’s respective results, output and work performed (Table 1).

Table 1: Adherence to FEDORA GA Deliverable & Tasks Descriptions

FEDORA GA Component Title	FEDORA GA Component Outline	Respective Document Chapter(s)	Justification
DELIVERABLE			
EI 1.1	Knowledge base of existing systems, understand gaps	Chapter 3 and Chapter 4	Chapter 3 includes a thorough literature review concerning MTM aspects, while Chapter 4 includes a detailed presentation of existing systems, developed and tested within the framework of other EU-funded projects A knowledge base with related systems and best practice is created, presented and analysed
VM 1.1	>25 TM systems analysed, best practices	Chapter 4	
TASKS			

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All tasks of WP3		Section 3.1	Section 3.1 provides a thorough literature review for data-related topics, data spaces, etc.
T4.4, T4.6		Section 3.2.1	Section 3.2.1 includes literature review related to the developments of T4.4 and T4.6
T5.2, T5.3, T5.4		Section 3.2.2	Section 3.2.2 includes literature review related to the developments of T5.2, T5.3 and T5.4
T4.1		Section 3.3.1	Section 3.3.1 includes literature review related to the developments of T4.1
T4.2		Section 3.3.2	Section 3.3.2 includes literature review related to the developments of T4.2
T4.5		Section 3.3.3	Section 3.3.3 includes literature review related to the developments of T4.5
T4.3		Section 3.3.4	Section 3.3.4 includes literature review related to the developments of T4.3
T2.4		Section 3.3.5	Section 3.3.5 includes literature review related to the developments of T2.4

1.2 DELIVERABLE OVERVIEW AND REPORT STRUCTURE

The structure of the deliverable is as follows: In Section 2, a definition of Multimodal Traffic Management (MTM) is provided, along with the priorities of the EU, as well as Stakeholders’ and users’ needs and requirements. Also, the main areas of intervention are presented. Section 3 includes review of recent literature regarding aspects of MTM that are mostly related to the project, organized in three subsections: Data, Modelling and Simulation, Management. In Section 4, we analyse and discuss the main results of pilot/real-world demonstrations of relevant MTM systems from other EU-funded projects, including those belonging to the MTM cluster. Section 5 includes the vision of FEDORA, i.e., how we plan to go beyond the state-of-the-art in key areas related to MTM. Finally, in Section 6, we sum up and discuss the main conclusions.

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2 WHAT IS MULTIMODAL NETWORK AND TRAFFIC MANAGEMENT AND WHY DOES IT MATTER?

Multimodal Traffic Management (MTM) is the coordination of multiple transportation modes, such as cars, public transport, bicycles, pedestrians and rail to optimize the conditions of the entire network (MTMC, 2024). Instead of separately optimizing every mode of transport, it views the transport network as a whole. Traditional single-mode management approaches have typically been proven insufficient, as they tend to create inefficiencies and bottlenecks, which cannot be addressed through isolated single-mode approaches (Y. Jiang & Nielsen, 2022). On the other hand, multimodal management promotes coordination and interoperability between modes, enabling better use of infrastructure and smoother transition for users (Rongen et al., 2025).

2.1 EU PRIORITIES

In the European Union (EU), MTM has become a priority for achieving climate neutrality and sustainable mobility by 2030. EU strategies such as the European Green Deal (Fetting, 2020) and the Sustainable and Smart Mobility Strategy (European Commission, 2020b) support emission reduction and a shift towards cleaner modes of transport. For these aims to be achieved, transport systems must be managed in a multimodal way. MTM is supporting this shift by optimizing efficiency, reducing congestion and pollution, and strengthening connectivity across Europe, through new policies, data management schemes and new technologies.

To that end, the EU invests in innovative technologies, data systems, and collaborative frameworks that enable coordinated management across all transport modes. The STRIA report on Network and Traffic Management identified ten priorities in three key phases to boost the specific domain, namely (Kearns et al., 2016): i. Design (architecture and concept of operations, multi actor organisational and business models, next generation multimodal NTM systems (including intra modal optimisation and development of interfaces), Integrated infrastructures, vehicles, systems and services), ii. Optimisation (multimodal demand capacity balancing, arbitration models for complex NTM scenarios and multi actor settings, conventional (semi-) automated and unmanned vehicles within a multimodal NTM system), and iii. Implementation (large scale demonstrations, resource and asset management optimisation, pilots NTM system across European hubs/nodes).

The CCAM Strategic Research and Innovation Agenda (SRIA, 2023) identified several research and innovation activities needed for CCAM enabled environments including infrastructure Support Levels for Automated Driving (ISAD) & fine-grained traffic regulations, integration of CCAM vehicles into the overall transport system (fleet & traffic management systems), data ecosystems and connectivity for traffic/transport operation, cross-modal and multimodal traffic and fleet management, advanced simulation, digital twins and network-wide control of traffic systems, as well as deployment readiness of traffic & mobility management systems.

The MTMC Roadmap (2024) argues that high-quality, real-time data and predictive tools are cornerstone importance for supporting informed decisions. The EU is also developing a European Mobility Data Space, which will provide secure and interoperable data sharing among all stakeholders (Vellinga & Hailevich, 2025). Another EU priority is the harmonization of policy and regulation to allow multimodal solutions, to work smoothly across cities and borders. Effective partnership between the public and private sectors is also fostered through governance frameworks that connect the local, national and cross-border efforts (Medeiros et al., 2021). Furthermore, EU funded research and innovation projects under programmes such as Horizon Europe, support pilot deployments and large-scale demonstrations of MTM concepts. Projects, such as DIT4Tram, ORCHESTRA and ACUMEN, research how artificial intelligence, digital twins, and vehicle connectivity data can assist in optimizing multimodal coordination and optimizing network performance. These activities facilitate the development of new methodologies, technologies and data architecture that support next-generation data-driven MTM systems in Europe.

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2.2 STAKEHOLDER REQUIREMENTS AND USER NEEDS

Effective MTM should consider the needs and priorities of many different stakeholders with different roles and goals. These stakeholders are public authorities (traffic management centres and transport regulators), network operators (public transport agencies, road authorities, and logistics providers), private mobility providers (rideshare and Mobility-as-a-Service platforms), and end users. For example, public authorities aim to reduce congestion and emissions. Network operators and private mobility providers focus on reliability and service efficiency. End users prioritize safety, convenience, and seamless journeys. Due to these differences, it is essential to align all perspectives through coordinated decision-making.

Research shows that collaboration and multi-criteria solutions are critical for the implementation of successful MTM. Mantouka et al. (2023) propose a group decision-making framework for MTM, which helps evaluate alternative strategies using criteria that represent the values of different stakeholders. In practice, this means involving stakeholders early in the planning process and ensuring that new traffic management measures address their real needs. Without such involvement, even technically advanced solutions may fail if they lack stakeholder support or do not match user expectations.

Table 2: Stakeholders groups, roles, and key requirements for effective MTM

Stakeholder Group	Role/ Interest	Key Requirements for Network & Traffic Management
Road Authorities & Traffic Management Centers	Operate and monitor the road network; ensure safety and efficiency	<ul style="list-style-type: none"> • Real-time, high-quality multimodal data • Predictive and adaptive control tools • Interoperability across regions and systems (e.g. DATEX II) • Decision-support dashboards for proactive management • KPIs for congestion, safety, emissions, and resilience
Public Transport Operators	Manage buses, metros, trams, and multimodal operations	<ul style="list-style-type: none"> • Access to integrated multimodal data • Priority and coordination with traffic signals • Passenger flow prediction and demand management • Tools for service reliability, punctuality, and emissions tracking
City & Regional Authorities / Urban Planners	Strategic mobility planning and policymaking	<ul style="list-style-type: none"> • Insights from long-term simulations and digital twins • Impact assessment tools for policy interventions • Indicators for accessibility, inclusiveness, and sustainability • Interfaces to mobility data spaces and open platforms
Freight & Logistics Operators	Optimize goods movement across modes and corridors	<ul style="list-style-type: none"> • Synchromodal routing and congestion prediction • Integration with port, rail, and airport systems • Access to real-time traffic and infrastructure conditions • Fair and transparent access to traffic management services
Telecommunication & Cloud Service Providers	Enable data connectivity and low-latency communication	<ul style="list-style-type: none"> • Clear QoS and data exchange requirements (V2X, 5G/6G) • Edge-computing integration with transport nodes • Cybersecurity and privacy compliance frameworks • Interoperable APIs for data sharing with mobility systems
Transportation Companies (OEMs, MaaS, AV Operators)	Provide connected, automated, and shared mobility services	<ul style="list-style-type: none"> • Reliable, real-time network data for routing and control • Harmonized data standards and APIs for interoperability • Support for remote operation and CAV integration • Access to mobility management services (pricing, priority)

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Infrastructure Managers	Maintain and upgrade physical and digital road assets	<ul style="list-style-type: none"> • Predictive maintenance using sensor and traffic data • Integration with BIM and asset management systems • Real-time feedback on asset condition and utilization • Data models supporting infrastructure–vehicle cooperation
End Users (Travelers, Drivers, VRUs)	Use the transport system daily	<ul style="list-style-type: none"> • Reliable travel information (ETA, safety alerts, multimodal options) • Fair, transparent, and personalized mobility services • Protection of privacy and data ownership • Enhanced accessibility for vulnerable and PRM users
Research & Innovation Community	Develop, test, and validate new mobility and management concepts	<ul style="list-style-type: none"> • Access to open, anonymized datasets • Simulation and validation environments • Interfaces to digital twins and living labs • Feedback loops from real-world deployments
Policy Makers & Regulators	Define governance, standards, and frameworks	<ul style="list-style-type: none"> • Evidence-based decision support • Monitoring tools for compliance and impact assessment • Frameworks for data governance, ethics, and fairness • Tools supporting social, environmental, and economic objectives
Industry & Technology Providers (AI, ICT, Data Analytics)	Supply enabling technologies and algorithms	<ul style="list-style-type: none"> • Standardized, open interfaces for integration • Clear performance, latency, and reliability requirements • Mechanisms for co-development and testing with public partners • Validation and certification environments for innovation uptake

2.3 AREAS OF INTERVENTION

To enable MTM to work in practice, coordinated efforts in several areas are needed. The MTMC Roadmap (2024) defines eight priority areas of intervention:

1. Policy integration

Most challenges today are due to the regulatory fragmentation, as different regions and levels of government apply varying rules and standards, leading to inconsistent implementation (Gharehgozli et al., 2019). Furthermore, the lack of common standards in traffic management and intelligent transport systems set back interoperability. To address this, regulatory frameworks need to be developed at regional, national and EU levels for easy, secure, and equitable operations across modes.

2. Stakeholders' collaboration

Collaboration between stakeholders is crucial for the effective deployment of multimodal and intelligent transport systems. However, this process is often not possible because of the different interests of public authorities, private transportation service providers and end users. Ineffective communication and a lack of structured platforms for dialogue limit cooperation. Also, limited participation means that some stakeholder groups, such as community organizations or smaller operators, are not fully represented in decision-making. To that end, active participation and collaboration across all levels of governance should be promoted. Inclusive platforms, joint initiatives, co-funding schemes, and shared governance structures, where responsibilities and benefits are distributed fairly can enable such collaboration (Carteni et al., 2020). Additionally, ITS and transport planning requires engaging a diverse range of stakeholders, including community groups, academia, and government agencies, to ensure balanced and informed decisions (Katzilieris et al., 2024).

3. Integration of modes

Multimodality is connecting different transport modes such as road, rail, biking, walking and car-sharing in one system for both passengers and freight (Katzilieris et al., 2024; MTMC, 2024) In practice this is possible with measures such as unified ticketing,

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multimodal hubs and trip planning platforms. These systems allow users to combine buses, trains, and other modes easily and make seamless transfers. Better coordination between modes supports accessibility and reduces travel time. It also helps lower environmental impacts and the overall cost of mobility for all users (Alessandretti et al., 2023).

4. Innovative solutions

The move toward advanced mobility systems is still slow. Technologies like ITS, C-ITS, MaaS, and connected vehicles face high costs and resistance to change. Pilot projects often work well on a small scale but face problems when expanded to full networks. Developing tools such as digital twins and real-time models is also difficult because they need high-quality data and complex methods. Recent studies show that most transport digital twins are still in early stages and used only in small areas (Nag et al., 2025). New technologies like artificial intelligence and multi-agent reinforcement learning can improve traffic flow and public transport efficiency (Kampitakis et al., 2024; Katzilieris et al., 2023). However, to apply these solutions successfully, they need to be tested carefully, adjust them to local needs, and make sure all stakeholders support their use.

5. Infrastructure enhancement

Most urban centres still rely on outdated infrastructure that cannot support multimodal mobility. There is also a lack of coordination between physical and digital systems, as smart sensors, IoT devices, and data platforms are not evenly deployed. The adoption of new technologies, such as AI and connected vehicles, is difficult and require investments and technical knowledge. At the same time, digital infrastructure adoption increases cybersecurity risks that should be addressed (Siraparapu & Azad, 2024). Future efforts should focus on enhancing both physical and digital networks, following EU-wide standards and ensuring that new technologies are safe and universally compatible (Cucor et al., 2022).

6. Data reliability, management, use and sharing

Developing data governance frameworks that ensure the secure exchange of multi-source data among all stakeholders. This means creating federated data spaces and establishing common standards so that data from all transport modes can be used for real-time management and predictive analysis (Vellinga & Hailevich, 2025).

7. Resilience and adaptability

Developing resilient and adaptable multimodal transport networks is requires ensuring continuity and reliability under planned and unplanned disruptions (Mattsson & Jenelius, 2015). Road networks still lack response and recovery plans, which makes managing disruptions, such as accidents, extreme weather, or infrastructure failures, reactive rather than proactive. Uncoordinated communication between transport authorities, operators, and emergency services further weakens system response, leading to longer recovery times and increased user impacts. Traffic and mobility management should embrace resilience principles to increase readiness. This involves developing systems with the ability to maintaining a minimum level of service. Digital technologies such as real-time monitoring, scenario modelling, and predictive analytics can support adaptive decision-making (Papadatou et al., 2025). Resilience also requires data exchange and communication protocols among all the stakeholders in multimodal networks.

8. Public engagement and acceptance

Building public acceptance and engagement is important for the successful implementation of multimodal transport systems and new mobility solutions (Kyriakidis et al., 2023). But without incentives, people are discouraged to participate in pilot programs or provide feedback on new solutions. Most people also do not have awareness of the benefits of multimodal transport, such as reduced congestion, emissions, and accessibility. Moreover, findings from pilot demonstrations are not properly communicated and that creates a gap between technological progress and user perception. To achieve wider acceptance, advanced technical outcomes must be communicated in simple and clear terms highlighting practical advantages, such as time-saving or greater comfort (Rindone et al., 2024). Participation can be increased through campaigns, public consultations, and pilot projects to demonstrate the benefits of MTM and address any concerns from the public.

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3 FUNDAMENTALS OF NETWORK AND TRAFFIC MANAGEMENT

3.1 DATA

3.1.1 TYPES OF DATA AND DATA SOURCES

Traffic management systems rely on a wide range of data types and sources to capture different aspects of mobility, infrastructure and user behaviour. Traffic flow data, collected from loop detectors, radar, or cameras, is fundamental for monitoring congestion, estimating travel times, and managing real-time operations at the local or corridor level. Vehicle data, often sourced from connected vehicles via GNSS and onboard diagnostics, provides detailed insight into position, speed, and driving behaviour, enabling applications such as cooperative manoeuvres and safety interventions. Infrastructure data, including road geometry, signal status, and Roadside Unit (RSU) information, supports predictive maintenance and ensures coordination between vehicles and their environment. Control data, such as signal timings and lane management, feeds adaptive control strategies, while incident and environmental data support dynamic responses to hazards, closures, or weather conditions. Demand and service-level data, often derived from aggregated mobile or public transport usage, provide essential input for strategic planning and performance monitoring at broader spatial scales. An overview of data sources can be found in Table 3 below.

Table 3: Types of transport and traffic data for MTM

Category	Data Type	Purpose / Use	Typical Spatial Coverage
Traffic Flow Data	Flow rates, vehicle counts, speeds, lane occupancy	Traffic control, congestion management, travel-time estimation	Local to corridor-level (detector zones, intersections, highways)
Vehicle Data	Position (GNSS), speed, heading, acceleration, braking, diagnostics	Vehicle tracking, safety, cooperative maneuvers	Per-vehicle, aggregated to network level through fleet data
Infrastructure Data	Road geometry, lane markings, signal states, RSU status	Infrastructure monitoring, predictive maintenance	Fixed-point / segment-level, along equipped roads
Communication Network Data	Latency, packet loss, signal strength, handover events	Network optimization, QoS assurance for CCAM	Cell-level to regional, depending on mobile network coverage
Environmental Data	Weather, road surface condition, visibility, air quality	Hazard prediction, route adaptation	Local (sensor stations) to regional/national (weather models)
Incident Data	Accidents, roadworks, closures, emergency events	Incident response, rerouting	Localized (point) events, with network impact propagation
User / Demand Data	Origin-destination flows, trip purposes, mode shares	Demand modeling, planning	Zonal to regional, depending on data aggregation
Control Data	Signal timing, ramp metering, lane control	Adaptive control, network optimization	Local (intersection) or corridor level
Service-Level Data	Travel times, delays, reliability metrics	KPI monitoring, service quality evaluation	Link, route, or network-wide aggregation

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These data types are collected through various sources with different spatial, temporal, and technical characteristics. Roadside infrastructure, such as inductive loops or CCTV, offers continuous but localized observations. Connected vehicles and C-ITS platforms provide scalable, dynamic coverage, transmitting CAM and DENM messages enriched with real-time sensor input. Traffic management centers aggregate data across networks, often integrating signal timing, incident reports, and flow statistics. Public transport systems contribute AVL, ticketing, and occupancy data, vital for modeling passenger demand and system reliability. Mobile devices and telecom networks enable the generation of floating car data (FCD) and crowd-sourced metrics at large scales. Additionally, drones and weather sensors allow task-specific or environmental observations. To complement real-world data, simulation tools and digital twins generate synthetic datasets for foresight and validation purposes. Integrating these diverse sources is essential for generating high-resolution, multimodal datasets that support operational and strategic MTM decision-making (Vlahogianni, 2015).

Table 4: Data source types for MTM applications

Source Type	Examples	Description of Captured Data	Typical Spatial Coverage
Roadside Infrastructure	Inductive loops, radar, LIDAR, CCTV, ANPR	Traffic flow, occupancy, vehicle classification	Fixed-point (tens of meters); aggregated over corridors
Connected Vehicles (C-ITS)	CCAM, DENM, V2V/V2I data, onboard sensors	Vehicle state and event data	Dynamic, moving coverage; scalable to network-wide with high penetration
Traffic Management Centers	Control systems, central databases	Aggregated network state, signal timing, events	Urban or regional network coverage
Public Transport Systems	AVL, ticketing, occupancy sensors	Vehicle positions, schedules, passenger data	Line or network level (city or metropolitan region)
Mobile Devices & Apps	Navigation apps, MNO data	Floating car data, crowd-sourced speeds	Network-wide, depending on user density
Telecommunication Networks	4G/5G QoS data, edge/cloud metrics	Latency, throughput, coverage	Cellular network coverage area (up to national level)
Drones / Aerial Platforms	UAV video, orthophotos	Incident detection, large-area observation	Flexible, task-specific (0.5–5 km ² per mission)
Weather & Environmental Sensors	RWIS, meteorological stations	Road weather, visibility, air conditions	Point-based, interpolated to regional models
Data Brokers / Open Data Platforms	National Access Points, DATEX II, OpenStreetMap	Standardized and aggregated traffic datasets	National / cross-border scope
Simulation & Digital Twins	Traffic and network simulation, synthetic sensors	Predictive or test data	Scalable, from intersection to national network

However, to make this data operationally useful, particularly for modelling, simulation, and strategic planning, it must be organized within a coherent spatial framework. One of the most common approaches to structuring mobility data geographically is the use of Traffic Analysis Zones (TAZs). The division of a geographical region into smaller areas, such as TAZs, is an essential part of transport system planning and modelling. Defining TAZs is often a difficult and time-consuming task, requiring extensive local knowledge of

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both the territory and the transport network. Traditionally, TAZs tend to be aligned with existing administrative divisions, but each administration defines its own TAZs, making it difficult to establish consistency between different sources. Moreover, heterogeneous entities and operators involved in the management of the transportation services, often rely on custom geographical subdivisions and different location references

To address these challenges, several approaches have been developed to automate data-based TAZ definition. These methodologies aim to overcome the limitations of administrative divisions by creating more homogeneous areas in terms of travel behaviour or congestion patterns, thereby improving the accuracy of transport models. For instance, Du et al (2024) consider it as a multi-objective optimisation problem, seeking a more homogeneous distribution between trip characteristics and residents' actual behaviour. Castiglione et al. (2025) merge satellite image data, OpenStreetMap (OSM) layers, and Floating Car Data (FCD) to create homogeneous zones in terms of activity, network characteristics, and land coverage. Nagy & Horváth, (2024) use WAZE-generated congestion data to define TAZs automatically, reliably, and quickly. Chandra et al. (2020) propose an automation approach to planning freight transport (Freight Traffic Analysis Zone - FTAZ) using Geographic Information Systems (GIS) and public data, focusing that definition of zones on freight transport.

The automated definition of TAZs, relying on dynamic big data sources (FCD, WAZE), requires that zone locations and boundaries can be reliably referenced across different maps and platforms. However, like zoning, there is no unique standard for location. This creates difficulties when identifying the same location on different maps, due to a variety of discrepancies inherent in cartographic data. To address this problem, *OpenLR* (2012) developed a method for map agnostic location. *OpenLR™* is a standard for dynamic location referencing (DLR), royalty free and open source (*OpenLR*, 2012). Similarly, Ebendt & Touko Tchoumadjou (2017) propose GIMME (Geometry InterMapMatching Extension), another approach to dynamic location referencing. Protocols such as GIMME and *OpenLR* are essential in the knowledge infrastructure of smart cities for the continuous updating of location-based information, which is vital for transport services that may use or be linked to defined zones.

DLR protocols resolve referencing between locations identified by different techniques, but the notion of place lacks standards in the digital realm. While location refers to geographic coordinates on maps, places such as roads, buildings, or cities are human-defined entities. To this purpose, the Overture Maps Foundation has proposed the Global Entity Reference System (GERS), a standard for assigning unique identifiers to real-world entities, making it easier to link and integrate data from different platforms (Breunig, 2024; Overture Maps, 2025)

The transportation infrastructure (road network and the offered services) as well as the available data providing sources may vary across time. Therefore, keeping track of the version of the digital representation of this infrastructure and the associated data observed is key. General-purpose Version Control Systems (VCS), optimized for textual data, often store complete, full copies of binary assets for each revision, resulting in an unfeasible storage footprint when dealing with spatial big data. Since they are designed to find differences at the text line-level, using diff algorithms, they are unable to detect modifications in binary files. A single change in a binary file implies significant bytes modifications, and the VCS interprets it as a completely new file. Therefore, it cannot generate change patches (or deltas) for binary files, so it saves the entire file with every modification.

Various approaches have been proposed to solve the storage problem inherent to versioning. For instance, Cserép & Giachetta, (2015) proposed an operation-based revision control model for managing geospatial datasets to avoid the loss of semantic information and improve the storage efficiency. In the same way, Jing et al. (2019) designed a version-based lightweight collaborative model that extracts only the related geospatial objects to generate a version, significantly reducing the storage size. Meanwhile, Sveen (2020) designed *GeomDiff*, an algorithm and binary storage format for differential geospatial vector data comparison. It was tailored to utilize the mathematical structure of vector geometries to express changes as minimal deltas.

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Nowadays, there are various tools with different approaches to managing map versioning. The most popular ones include Kart, ArcGIS, PostGIS and CARTO:

- *Kart* is an open-source plugin for QGIS that replicates the Git version control model (Commit, Branch, Merge) at the vector feature level.
- *ArcGIS Online* is a leading proprietary platform that offers version control at the geodatabase level, using traditional and branch versioning models, optimised for multi-user editing and advanced datasets (licence required).
- *PostGIS* is an open-source extension that provides spatial capabilities to PostgreSQL. Its versioning is not native but is achieved through the implementation of History Tables and Triggers (temporal data approach).
- CARTO is a Software as a Service (SaaS) that manages versioning at the dataset level through a history of changes and collaboration flows in the cloud (subscription required).

3.1.2 AVAILABILITY, QUALITY, DATA SHARING, ACCESSIBILITY AND INTEROPERABILITY

The availability of data has dramatically increased due to technological advances and the popularisation of various devices and platforms. The extensive use of mobile devices with GPS, geotagged social media posts, call logs, and other sources has enabled the collection of enormous amounts of mobility data. Despite the vast quantity of information generated, the availability and accessibility of this data is limited by privacy restrictions and policies implemented to protect sensitive user information. As a result, the data obtained is often sparse and gaping in attributes, as well as totally heterogeneous and lacking in semantic context. This entails data pre-processing, which represents a cost for companies or entities.

To address the access and management of these volumes of information, different alternatives have been proposed to facilitate access to this mobility data. For instance, Sánchez et al. (2023) designed a platform to facilitate the harmonisation and enrichment of heterogeneous data by leveraging linked data principles, semantics, and artificial intelligence (AI) technologies, increasing the data value. Chevallier et al. (2023) have been working on a cloud platform to facilitate access to mobility data openly, in an interoperable, transnational, and privacy-preserving way, using the FAIR principles. Wilkinson et al., (2016) and Santana et al., (2022) designed a Scala framework for scalable analysis of mobility datasets.

On the other hand, Generative Artificial Intelligence (GenAI) could be used for gap-filling, entity matching and data moderation and verification, solving critical challenges related to geospatial data. Its use impacts time savings and improved efficiency, bringing quantifiable benefits, but it is critically needed to maintain trust and traceability in AI decisions, advocating for multi-model consensus and action reversibility (Sheehan, 2023). In a different approach, Lettich et al. (2023) transform simple location routes into complex Multi-Aspect Trajectories (MATs) for semantic enrichment.

Several works propose the generation of synthetic urban mobility data to address data scarcity and ensure privacy. Kapp et al., (2024) use generative models to generate synthetic urban mobility data to mitigate serious privacy concerns associated with the sensitive personal information, whereas Uğurel et al. (2024) use physics-regularized gaussian processes for synthetic mobility data generation.

High data quality and reliable sharing mechanisms are essential for effective Multimodal Traffic Management (MTM). Data are the basis of all monitoring, modelling, and decision-making processes, and their accuracy, completeness, and consistency directly determine the performance of the systems that rely on them. Low-quality or incomplete data can lead to biased models, inaccurate forecasts, and suboptimal decisions, particularly in real-time traffic management applications. For example, if traffic datasets have missing or wrong values, models perform poorly. Even a few gaps in traffic flow records can significantly degrade forecast accuracy

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and introduce bias (Jiang et al., 2025). In practice, unreliable or incomplete data can lead to wrong predictions of congestion or travel times and thus suboptimal control actions.

Furthermore, interoperability and standardization are crucial so that data collected from different sources, i.e., vehicles, sensors, infrastructure, or users, can be combined meaningfully. Studies of MaaS systems note that integrating multiple providers' data needs strong cooperation and standardized interfaces because incompatibilities across regions and providers can be a challenge. At the same time, sharing data raises privacy and security issues. Data sharing is essential for creating value, but it "simultaneously exposes the ecosystem to new and evolving vulnerabilities" (Belen-Saglam et al., 2025). Therefore, data-sharing frameworks must include strong privacy protection, confidentiality and trust mechanisms. In other words, personal mobility data should be protected by design, ensuring data integrity and user privacy while still allowing authorized stakeholders to share and use the information. Some of the most widely used techniques to enable secure data sharing in MTM include federated data spaces, semantic interoperability frameworks, differential privacy, homomorphic encryption, federated learning, data anonymization, and standardized APIs.

3.1.3 DATA SPACES

Effective access to, pooling of, and sharing of data are foundational to modern traffic management solutions. However, although effective data sharing between different parties is progressing, a new paradigm has recently emerged that goes beyond previous data sharing models: the data space, which we further define in this section. Yet a unified understanding of data spaces, including their structure and technical implementations, as well as a multimodal traffic viewpoint, remains underdeveloped.

Recognizing the potential of shared and reusable data to drive innovation, the European Union has adopted several key legal instruments under its European Data Strategy. The Data Governance Act (European Parliament, 2022) establishes frameworks to enhance trust, enable data reuse, and increase data availability across sectors. The Data Act (European Parliament, 2023) builds on this by clarifying user rights, ensuring fair access to data and strengthening interoperability. Together, they support the establishment of common data spaces in domains such as mobility, energy and health.

In this context, the Communication on a European Strategy for Data (European Commission, 2020a) proposes the creation of a single market for data with focus on governance frameworks, infrastructure, interoperability, portability rights, and the creation of data spaces, while the Communication on the Creation of a Common European Mobility Data Space (EMDS) (European Commission, 2023b) outlines a framework to connect and integrate diverse and often fragmented transport data ecosystems. It addresses challenges related to data discoverability and accessibility, and sets out recommendations to enhance harmonization, interoperability, and governance. Rather than promoting centralized storage, it supports a federated approach that enables secure and controlled data exchange, with the goal of improving multimodal transport coordination, planning, and long-term sustainability.

The Data Space Support Centre (DSSC) adopts the definition of a data space as provided in the CEN Workshop Agreement on Trusted Data Transactions (ECS, 2024), which describes it as *an interoperable framework, based on common governance principles, standards, practices and enabling services, that enables trusted data transactions between participants*. Further definitions of data space concepts can be found in the glossary of the Data Space Support Centre and the International Data Spaces Association.

The concept of data spaces has rapidly evolved from abstract architectural principles into tangible implementations aimed at enabling secure, sovereign, and interoperable data sharing across organisations and sectors. This development is particularly relevant in the context of European mobility and transport ecosystems, where data is distributed among various actors, each with their own access policies, data models, and technical infrastructure. At the core of data space design is a shift from centralized data collection to federated infrastructures that preserve data ownership while enabling controlled access and use (Otto, 2022). The following review highlights recent contributions that frame data spaces as enablers of both technical interoperability and organisational collaboration in the European context.

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Data spaces can be contextualized as meta-organisations, emphasizing decentralization and mutual trust (Guggenberger et al., 2025). Proper functioning of a data space therefore has an inherent dependence on active participation and contribution of its members. Data ecosystems exist at a meta-level within data spaces, representing the sum of collaborative data-sharing activities in one or between multiple data spaces (Möller et al., 2024). Different data ecosystems can overlap by sharing the same data space.

Review of the interplay between data-driven organizations and data spaces gives insight into what they should provide, demand, and expect from one another (Gieß et al., 2024). Dimensions to be considered are architecture; services; data quality; interoperability; business; governance; design; trust; and actors. The key drivers of data space adoption mirror these dimensions and include controllable complexity, cost clarity, data sovereignty, ecosystem governance, ecosystem readiness, interoperability, mature technology, regulatory certainty, security, technology competence, transparency, and trust (Hutterer & Krumay, 2024).

There can be a multitude of reasons for commissioning data spaces and expected benefits are various. These include increasing the availability of crucial data; enabling technical, organisational, semantic and legal interoperability; optimising data-collection, and reducing administrative burden as listed by the European Commission with regards of the creation of a common European mobility data space (European Commission, 2023b). Business cases that emerge from the creation of data spaces include bartering and marketplaces (Ammann, 2025).

Various design decisions must be made when implementing a data space. These can be focused around the five foundational functions of data spaces: cataloguing, identity management, logging, certification, and vocabulary provision (Otto, 2022). These functions collectively enable discoverability, trust, and semantic alignment. This architecture enables data to remain at its source while granting access only, when necessary, thereby supporting data sovereignty – a cornerstone principle of data spaces. Implementations must focus on ensuring the data sovereignty of all agents, including individuals, organisations, and states (Ryan et al., 2024).

Reference architectures offer a conceptual framework for designing and implementing data spaces (IDSA, 2025b). Examples of reference architectures include IDSA, Gaia-X, FIWARE and DSBA (IDSA, 2025a).

Data space connectors provide gateways that connect existing systems and their data to a data space ecosystem (IDSA, Dataspace Connector Introduction, 2025). There are various architectures, including the FIWARE Data Space Connector, the Eclipse Dataspace Connector (EDC), Simpl, the True Connector, the IDS Connector and the MDS Connector (IDSA, 2025a; Simpl Programme, 2025). These differ in terms of design options along key dimensions, such as licence, deployment options, service level, portability, access control, communication protocol, transfer protocol, availability of a graphical user interface and supported data space specifications (Gieß et al., 2024).

Implementing a *mobility data space* raises additional domain-specific questions, such as those relating to data formats. Mobility-related data can be grouped into clusters and linked to domain-specific standards (Bellini et al., 2024). Additionally, these standards can be classified with regards to their temporal domain, mobility domain and subdomain, as well as their format. A minimum viable demonstrator for a mobility data space is presented in Drees et al. (2021). Central components of the data space are defined to include a data marketplace, identity provider, clearing house, vocabulary service, and a data app store. An effort in a similar direction is presented by (Mobidatalab, 2024). Metadata and services catalogues were made available using CKAN and GeoNetwork. While missing the governance dimensions, and therefore not considered a data space as defined by the DSSC, it offers valuable information on the technical implementation including the metadata and services catalogues, data enrichment, and anonymization mechanisms.

Technical innovations in AI have sparked interest in combining data spaces with emerging machine learning technologies, such as Large Language Models (LLMs). Using Retrieval-Augmented Generation (RAG) enables LLMs to retrieve reliable information, combatting issues such as hallucinations. RAG4DS presents a high-level architecture for RAG data space models, highlighting potential opportunities and possible challenges (AI-Qatf et al., 2025).

Despite the efforts of projects such as PrepDSpace4Mobility (PrepDSpace4Mobility, 2025), deployEMDS (deployEMDS, 2025), and Mobility Data Space (MDS, 2025), considerable effort is still required to join or create a mobility data space. This is because not all

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data spaces support every functionality on business cases, governance models, access control, and data space connectors supported, among others.

3.2 MODELING AND SIMULATION

3.2.1 INCIDENT DETECTION, PREDICTION AND FORECASTING

Non-recurrent disruptions, including traffic incidents, vehicle malfunctions, extreme weather conditions, infrastructure maintenance, and scheduled public events, are common occurrences across road networks. These events interfere with normal traffic operations and often result in unpredictable delays for road users (Lee et al., 2021). Effective mitigation of such disruptions requires a combination of strategic planning, real-time information exchange, adaptive traffic management mechanisms and, most importantly, timely detection of the abnormal pattern (Vlahogianni et al., 2014).

Advancements in computational capabilities have significantly enhanced the role of data-driven methodologies in transportation research during the last 20 years. Together with the integration of empirical traffic data with machine learning and deep learning techniques, the above aspects have enabled more robust analysis in transportation research (Tedjopurnomo et al., 2020; Yin et al., 2021; Fafoutellis & Vlahogianni, 2024). These approaches support the development of predictive models and optimization frameworks that improve traffic flow management, which, when combined with established theoretical models, they offer a comprehensive toolkit for addressing complex transportation challenges in dynamic environments (Fafoutellis & Vlahogianni, 2025).

In general, traffic flow is characterized by two states (Bramich et al., 2022): congested and uncongested (free flow). Free flow conditions are characterized by low density and elevated speeds. In contrast, the congested state emerges when both flow and speed are significantly diminished due to increased vehicular accumulation. As traffic volume intensifies, the effective capacity of the roadway deteriorates, resulting in a decline in throughput and the manifestation of severe congestion. Notably, the recovery from congestion back to free-flow conditions does not restore the original capacity instantaneously; instead, the discharge rate remains suppressed, indicating a hysteresis effect on the traffic flow response.

A fundamental distinction between congestion arising from excessive demand and that triggered by unforeseen incidents lies in state transitions. In the case of incident-induced congestion, transitions between traffic states tend to be discontinuous and abrupt, lacking the gradual progression typically observed under high-demand conditions (Persaud & Hall, 1989). Following the resolution of an incident, the roadway's capacity generally reverts to its original level, resulting in a discharge rate that exceeds the prior inflow. This asymmetry facilitates a more rapid clearance of accumulated vehicles compared to the rate at which congestion initially formed.

Non-recurrent traffic incident detection has remained a focal point of transportation research for more than five decades (Papadatou et al., 2025). Early contributions to the field predominantly fall into two methodological categories: statistical models and machine learning-based approaches (L. Li et al., 2022), both aiming to identify disruptions that deviate from typical traffic behavior. These events are often framed as outliers within the data, represented by anomalous patterns. However, such formulations often struggle when applied to high-dimensional, complex datasets, particularly due to the scarcity of labeled anomalous samples (Hsieh et al., 2019).

The spread of machine learning techniques in the early 2000s enabled the development of data-driven models that integrate time series analysis, nonlinear dynamics, neural networks, and Bayesian frameworks. These models seek to distinguish between congested and uncongested states by leveraging fundamental relationships among traffic variables such as speed, volume, and density (Anbaroglu et al., 2014; Nguyen et al., 2017; Saberi et al., 2020; Saeedmanesh & Geroliminis, 2017; Vlahogianni et al., 2008). More recently, the fusion of heterogeneous data sources, including social media and drone imagery, with unsupervised learning techniques has enhanced the accuracy and resilience of incident detection systems (Vlahogianni et al., 2021).

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Clustering methods have also been widely used, offering interpretable groupings of time-series traffic data (Neves et al., 2022; Serok et al., 2022). For example, Anbaroglu et al (2014) applied spatiotemporal clustering to isolate congestion patterns linked to non-recurrent events, while Tavassoli Hojati et al (2014) modeled the full lifecycle of incidents, incorporating both detection and recovery phases. Unsupervised algorithms such as K-Means and DBSCAN have proven effective in identifying anomalies without labeled data (Gupta & Tripathy, 2024; Jin et al., 2022). Graph-based approaches have further expanded the scope of analysis, enabling resilience assessments through network connectivity models (Gorji et al., 2022). Luan et al., (2021) advanced this direction by integrating traffic and social media data for enhanced anomaly detection.

Gao et al., (2025) introduced an adaptive Isolation Forest model tailored for urban traffic disruptions, offering scalability and minimal configuration for real-time deployment. Despite its strengths, the model's assumption of sparse, well-separated anomalies can lead to false positives in dense urban environments. This underscores a broader trade-off: while unsupervised models adapt well to evolving traffic baselines, they often lack interpretability, an essential feature for operational deployment in traffic management systems.

Thaika et al., (2018) proposed a PCA-based unsupervised method using GPS data, notable for its computational efficiency and ease of deployment. Although surpassed in accuracy by newer deep learning models, PCA remains relevant for large-scale applications requiring rapid anomaly detection with minimal overhead.

Collectively, these studies reflect the current state-of-the-art in unsupervised learning for traffic anomaly detection. Such methods excel in uncovering nonlinear patterns without labeled data, a critical advantage given the limited availability of comprehensive incident datasets. They offer superior adaptability to dynamic traffic conditions compared to classical statistical models, which often rely on rigid assumptions. However, these benefits come with trade-offs: increased computational demands, complex tuning, and reduced transparency. Balancing detection performance, scalability, and interpretability remains a central challenge, necessitating further research into efficient and explainable unsupervised frameworks.

Despite methodological advances, significant challenges persist. The high dimensionality of traffic data, its dynamic nature, and the rarity of anomalies complicate detection efforts (Fafoutellis & Vlahogianni, 2025; Kong et al., 2024). Moreover, many existing approaches are ill-suited for real-time applications, often requiring extended data sequences to capture the full incident lifecycle (Boukerche & Wang, 2020). Thus, the development of real-time-capable methods remains a critical research priority (Laña et al., 2021).

Moreover, the real-time identification of traffic disruptions has emerged as a prominent research challenge, particularly in distinguishing between recurrent and non-recurrent congestion. This difficulty stems from the high degree of similarity in traffic patterns exhibited by both types of events, despite their differing origins. Recurrent congestion typically manifests on urban roadways during certain periods, such as peak hours, when demand consistently exceeds network capacity. Although such conditions may result in substantial delays, they are considered part of the system's expected behavior. In contrast, non-recurrent congestion arises from unexpected disruptions, producing abrupt and severe degradation in traffic performance. The unpredictable nature and intensity of these events complicate their detection and classification in real-time systems.

3.2.2 TRAFFIC MODELING AND SIMULATION

Traffic simulations are used to model, analyze and optimize traffic flow and network performance under various conditions. The simulations are based on mathematical and computer-based formalizations and enable planners and engineers to evaluate the impact of infrastructure change, traffic control strategies, and different routing policies without the cost of real-world implementation. Common applications of traffic simulations include transportation planning and design, traffic operations and management, safety and incident management, evaluation of emerging technology, and traffic network analysis (Barceló, 2010; Kotusevski & Hawick, 2009).

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Different types of traffic simulations exist, depending on state type, space type, and time type (discrete vs. continuous), as well as the perspective of the model (macroscopic, mesoscopic, microscopic). Simulations can include and or combine Monte Carlo methods, cellular automata models, car-following models, gap acceptance models, lane-changing models, discrete event simulations, and continuous-time simulations. Furthermore, traffic simulations are not limited to road transportation systems, but also apply to warehouses, terminals, maritime and air transportation systems (Sokolowski & Banks, 2011).

In the context of land transportation systems, where these simulations are most commonly applied, microscopic simulations cover modelling of single vehicles and their interactions, mesoscopic simulations abstract traffic as aggregated flows on links of a graph together with queue representations, and macroscopic simulations regard even more abstracted fundamental states of the network (average flow, speed, and density) (Antoniou et al., 2014; Ejercito et al., 2017). Besides, traffic simulations usually cover three scopes, from moving parts (multi-modal vehicle population including pedestrians), fixed parts (the transport infrastructure, e.g. road network and intersections), to intangible parts (algorithms and behaviors that the moving parts and fixed parts follow, e.g. traffic light controller, route planning of cars, car following model). Various different software for traffic simulations emerged, each with different modelling approaches, file formats, and levels of transparency (open source vs. commercial) [5,6]. The most common softwares include PTV Vissim, PTV Visum, AnyLogic, Aimsun, CUBE, SUMO, INRO, SimTraffic, Paramics, FLOW, Polaris, and TransCAD.

Besides modelling traffic, several further aspects are often simulated jointly and combined with traffic simulations, including:

- Sensor, engine, and kinematic dynamics modelling of single vehicles to enable simulations of autonomous driving. Example: CARLA (Gutiérrez-Moreno et al., 2022).
- Agent-based modelling, to capture planning and decision making on daily activities, trips, routes, times and modes of transportation. Example: MATSim (Axhausen et al., 2016) and SimMobility Mid-term (Lu et al., 2015).
- Vehicle batteries, charging infrastructure, and energy market modelling to assess the impact traffic electrification and EVs. Example: CityMoS (Zehe et al., 2017).
- V2X, V2I, and V2V communication network modelling, to assess the impact of increasingly connected traffic and smart cities. Example: OMNeT++ (Varga, 2010).
- Emissions and noise pollution modelling of traffic, to assess the environmental impact of traffic. Example: PTV Visum.
- Land-use and longer-term mobility related individual and household decisions such as vehicle ownership, residential location or mobility subscriptions (planning applications). Example: SimMobility (Adnan et al., 2016) or Urbansim (Waddell, 2002).

Despite their extensive capabilities, current traffic simulations face several limitations, that include (Daamen et al., 2014):

- Data acquisition and evaluation challenges: Models often require extensive and high-quality empirical input data, which is costly and difficult to obtain in practice. There are limited standard evaluation criteria and performance indicators, complicating the interpretation and comparison of results.
- Data processing and enhancement techniques: focusing on preparing data for model usage by fusing multiple sources, extracting key features and patterns, and estimating essential inputs. In contrast, for on-line simulation applications, the goal is to generate consistent real-time estimates of the current traffic state to support short-term prediction, identify patterns for decision-making, and derive dynamic performance indicators. Such methods may influence significantly the results of simulations.
- Calibration issues: Simulations must be carefully calibrated with local empirical data; models calibrated for one location frequently do not transfer accurately to another, limiting their generalizability. Parameter calibration is sensitive—uncertainties, noise in data, and insufficient “goodness-of-fit” can strongly influence results.
- Reproducibility, transparency and legal challenges: Often, required data, instructions, and models to fully reproduce simulations are not published due to legal reasons such as copyright ownership or privacy concerns (Riehl et al., 2025b).
- Transferability issues: Besides, simulations cannot often be reproduced across different simulation software, as they differ in their assumptions and modelling. This sensitivity to assumptions often challenges the adequacy of simulations. Other

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challenges here are different file formats and modelling standards that impede simple transferability across software platforms.

- Computational expenses: Increased level of detail and more calibrated models often come at higher computational costs. Micro-level simulations of large networks are often far-away from real-time simulation with current computational facilities. Towards digital twin models that inform traffic operations and control centers in real time, accelerated simulation models must be found.

Within this project, we aim to develop three core-contributions:

- **Connected, Standardized, Simulation Platform:** To achieve better transferability and inclusion of various other simulation environments, we aim to develop a simulation platform. The simulation platform shall allow for the modular combination of various simulation aspects. The simulation platform shall be cloud native, including a persistence layer that serves as a data warehouse for real-time hot and cold storage of simulation results. At the core of the platform a central server coordination shall be used, that can easily relate to different modules and components via various Application Programming Interfaces (APIs), to allow for the integration of different models, programming languages, and software. Moreover, efforts into standardization of model parametrization and calibration, use of APIs, and incorporation of feedback loops between different simulators and artificial intelligence shall be part of the platform design. A vision for this platform can be found in Figure 1.

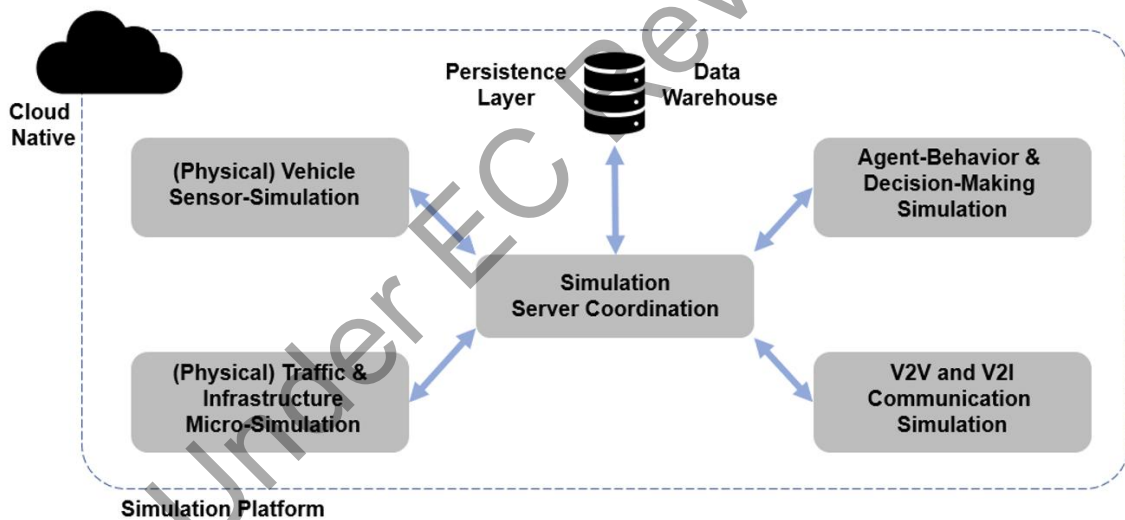


Figure 1: Server-Structured, Decentralized, Federated Communication Network for Simulation Coordination.

- AI tools for simulation: namely, self-supervised methods for non-recurrent event detection, reducing reliance on human-labeled data by automatically identifying patterns and handling large unstructured datasets (Fafoutellis & Vlahogianni, 2023); and advanced, application-agnostic AI algorithms to improve simulation exploration, and policy design in complex and stochastic simulations (Lempert et al., 2020).
- Reproducibility Guidelines: We aim to extend the preliminary findings in our previous works (Riehl et al., 2025b), and try to develop an understanding of the challenges when reproducing and implementing.



3.3 NETWORK MANAGEMENT

3.3.1 SIGNAL OPTIMIZATION

Modern traffic management substantially differs from the well-established and widely used classical traffic flow optimisation approach. In the last century, the main focus in traffic management was to ease the flow of road users – or to be more precise – to reduce congestion of cars. Therefore the key role of real-time traffic signal control (TSC) technology was in managing congestion at road junctions, as described and analysed in (Tomar et al., 2022). Various approaches have been applied ranging from infrastructure adaption (e.g., building new roads) to traffic light optimisation. The state of the art in traffic light optimization involves advanced technologies and algorithms to improve traffic flow, reduce congestion, and enhance overall transportation efficiency. Key aspects of modern traffic light optimization can be summarized as:

- Real-time adaptive systems: These systems use sensors and connected vehicle data to adjust signal timing based on current traffic conditions (Tomar et al., 2022; Witeck et al., 2022). This approach allows for dynamic responses to changing traffic patterns, reducing delays and improving flow.
- Machine learning and AI: Reinforcement learning techniques are being applied to optimize traffic signal control, with some systems claiming to reduce commute times by up to 40% (Snap4City, 2023). These algorithms can learn and adapt to complex traffic patterns over time.
- Connected vehicle technology: GPS data from as little as 6% of vehicles on the road can be used to recalibrate traffic signals, resulting in a 20-30% decrease in stops at intersections (Wang et al., 2024). This approach offers a cost-effective alternative to traditional sensor-based systems and enables future applications, like Self-Synchronization of Connected Vehicles (Rodriguez & Fathy, 2019).
- Multi-objective optimization: Advanced algorithms like Particle Swarm Optimization and Genetic Algorithms are being used to balance multiple objectives, such as minimizing wait times, reducing emissions, and prioritizing public transportation (Snap4City, 2023; Witeck et al., 2022).
- Cloud-based systems: Large-scale, cloud-based traffic signal retiming systems are emerging, allowing for more efficient and cost-effective management of traffic signals across entire cities (Wang et al., 2024).
- Integration with Intelligent Transportation Systems (ITS): Modern traffic light optimization is increasingly part of broader smart city initiatives, incorporating various data sources and technologies to create more comprehensive traffic management solutions (Tomar et al., 2022).

These advancements in traffic light optimization are leading to significant improvements in urban mobility (Zavantis et al., 2024), with reduced congestion, lower emissions, and enhanced safety for all road users. In order to promote public transport, prioritisation systems have been implemented at neuralgic crossings, e.g. as fixed rules. More advanced systems even apply dynamic prioritisation rules which could alter traffic light signalling processes based on vehicle detection systems, e.g., via triggers integrated in the road or connected vehicle technology.

Such systems also exist for integrating crossing requests by passengers or even cyclists. However, even though these systems are “dynamic” in that sense that they change standard processes when triggers are pressed, they are only locally managed and do not consider systemic optimisation criteria. Within the FEDORA project, current traffic light management technologies will be used for integrating a systemic view into signal light management. In addition, traffic flow optimisation will be extended towards various types of road users (passenger cars, public transportation, pedestrians, cyclists, etc.).

The Social Optimum Model

The Social Optimum Model is based on a network graph as representation of the transport system and pre-defined route choices for users of different transport modes. Near real-time data will be integrated as an input for traffic management applications. The

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parameters to be optimized are time offsets and durations of signal phases at signalized intersections. The Social Optimum is defined as a system optimum with respect to an objective function that includes individual preferences of public transport users, car drivers, cyclists and pedestrians.

The objective function for the social optimum problem shall be a weighted sum of cost functions for each mode. Historically, such cost functions have first been defined for motorized road traffic and were based on easily measurable observations such as travel time and travel distance (Wardrop & Whitehead, 1952). Nowadays, in many cases additional components are used in cost functions [Manz et al. 2022], especially for non-car traffic, including e.g.:

- infrastructure conditions such as the type of pavement for bicycle routing (Weiß, 2022)
- the car traffic flows on the roads used for bicycle routing (Broach et al., 2012; Weiß, 2022)
- penalties or bonuses for certain means of transport, e.g. railways.

Some of these components represent a subjective assessment of “quality of travel”, i.e. they are not easily quantifiable, but must be derived from the observation of user behavior, e.g. using traffic surveys or passenger counts (Manz, 2022).

The choice of the components of the objective function and their respective weights is key to determining the social optimum and thus, the effects an optimized multimodal traffic management can achieve. Therefore, emphasis will be put on the design of the objective function and its calibration. This involves:

- defining quantifiable measures for each transport mode
- defining “quality of travel” measures for each mode and deriving quantifiable measures from them
- weighting the components of the objective function
- iteratively calibrating the model in a simulation setting

Depending on the exact definition of the objective function integer linear programming techniques or constraint programming techniques will be used to approximate the solutions of the underlying problem. As the results of the social optimum problem shall be used in near real-time traffic management applications, a metaheuristic based numerical approach will be developed in order to find close approximations within short computation times (some milliseconds up to a few seconds in the worst case). This approach will then be demonstrated and evaluated in a real-world pilot area and the results of the evaluations will be used to recalibrate the model iteratively.

Near real-time data sources currently in use in Vienna include traffic flow and speed measurements from stationary detectors (induction loops, infrared and radar sensors), speed measurements from FCD, and impacts on speeds and capacities from DATEX II traffic messages. These data sources cover motorized road traffic only. In the context of FEDORA, data derived from C-ITS messages (covering also public transport vehicles) and from AI-based camera tracking (including detection of pedestrians and cyclists) shall be made available to the traffic management system and the Social Optimum Model. Furthermore, the use of tracking data from navigating apps for cyclists shall be investigated.

3.3.2 PRICING AND INCENTIVIZATION

Traffic management is a mechanism that regulates spatio-temporal resource allocation (Waller et al., 2025). The capacity of transportation infrastructure (road, rail, water, air) is bounded. Therefore, at peak hours, when numerous users want to exploit shared resources simultaneously, conflicts arise, as demand exceeds supply. Road traffic congestion exemplifies this issue in almost all major cities worldwide. Congestion results in longer travel times, wasted fuel, air pollution, and economic loss. Standard supply-side measures, such as expanding road infrastructure, often fail in the long term due to induced demand—the “build more, get more traffic” paradox (induced demand) (Næss et al., 2012). Consequently, pricing and incentivization strategies have emerged as key demand-side approaches to reallocate traffic flows in space and time (Ecola & Light, 2009).

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Transportation policymakers are increasingly considering congestion pricing to influence travel behaviour a promising option for addressing urban traffic-congestion problems (De Palma & Lindsey, 2011). By attaching a monetary cost to the use of scarce road capacity, pricing schemes aim to: (1) reduce total consumption by discouraging discretionary trips or encouraging modal shifts to public transport, cycling, or remote work, (2) shift demand temporally by incentivizing travel during off-peak periods, and (3) prioritize high-value trips, allowing critical trips to access the network while pricing out less urgent uses.

Several approaches to pricing instruments can be distinguished (Cheng et al., 2017; Larson & Sasanuma, 2010):

- Cordon- or zone-based pricing (London, Stockholm, Singapore, Milan) charges entry to a defined area, sometimes dynamically.
- Distance- or duration-based pricing charges according to the amount of the infrastructure used.
- Dynamic or time-of-day pricing adjusts fees based on real-time demand, as pioneered in Singapore's ERP.
- High-Occupancy Toll (HOT) lanes (mostly in the U.S.) allow single-occupancy vehicles to use carpool lanes for a fee, balancing revenue with priority access.
- Parking pricing (Tokyo, Boston) reduces "cruising traffic" by aligning on-street and off-street parking costs.

Research and practice agree on the effectiveness of pricing and incentive mechanisms to substantially reduce congestion. Singapore achieved a 43% peak-hour traffic reduction in its central business district with its Area Licensing Scheme, later upgraded to ERP (Selmoune et al., 2020). London's congestion charges reduced zone traffic by ~30% and lowered crash rates by 35% in the first month. Milan's "EcoPass" and later "Area C" combined environmental and congestion goals, cutting NOx by 17% and increasing public transport use by 9%. Empirical studies also highlight road safety co-benefits, with zone-based schemes often reducing overall crashes, though initial mode shifts to cycling may temporarily increase cyclist exposure (Singichetti et al., 2021). To date, examples for cordon pricing can be found in many cities around the world (London, Stockholm, Singapore, Milan, Rome, Gothenburg, Oslo, Bergen, Trondheim, Kristiansand, New York City, Durham, Znojmo, Riga, Valletta), HOT lanes are common across major highways in the US, and parking pricing has become the norm in most cities.

Despite the mutual benefits of congestion pricing, the implementation of this effective traffic management tool is impeded by various social, ethical, and legal constraints (Riehl et al., 2025a). The largest issue is public and political resistance against congestion pricing, due to a lack of public trust, and clear communication of benefits. This leads to congestion pricing proposals being rejected at early stages. Since congestion pricing imposes a cost on something that was previously free—access to roadways during peak driving times—critics often suggest that it will harm those with lower incomes who will be forced to pay additional costs or be priced off the roads (Ecola & Light, 2009). Besides, issues with privacy due to automatic tracking of vehicles are another cause for acceptability issues (Gu et al., 2018). Research highlights, that acceptability can be improved through trial phases, transparent revenue use for reinvestments into public transport or equitable rebates, and low-complexity proposals that are easier to understand and reduce consequence uncertainty (Gu et al., 2018).

To overcome impediments and achieve a stronger real-world implementation, a growing branch of research studies (1) means to achieve greater acceptance for congestion pricing (Selmoune et al., 2020), (2) policy designs that can mitigate equity issues (Eliasson, 2016; Harper & Yang, 2023), and (3) alternatives to monetary pricing such as tradeable credit schemes or artificial currencies (Y. Li & Ramezani, 2022; Provoost et al., 2023; Riehl et al., 2024b, 2024a).

In contrast with congestion pricing (or price control), tradeable credit schemes (Chen et al., 2023; Goddard, 1997; R. Liu et al., 2024; Verhoef et al., 1997; Yang & Wang, 2011) are a form of quantity control characterized by the following features: (1) a fixed total number of tokens (mobility credits) or 'quota' is pre-specified by the regulator or transport authority, (2) an initial endowment allocates or distributes the tokens to a selected population (all individuals may not receive tokens), (3) individuals are allowed to buy and sell tokens in a market, (4) use of the road network requires tokens and can be differentiated by time of day, geography, vehicle type etc., and (5) enforcement is necessary to ensure valid trading/consumption of tokens. Tradable credit schemes have several potential advantages over pricing. First, they are revenue-neutral and hence, may not be faced with as much public opposition, more

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so if the tokens are handed out for free. Second, they are viewed as being less vertically inequitable than pricing (when toll revenues are not redistributed to users). Since the number of tokens each user receives may differ, any regressive effect (well documented for congestion pricing), which may trigger political opposition, can be addressed. In other words, lower income users who tend to travel less by car can obtain monetary gains by selling their excess credits. Third, they provide the ability to directly control quantity (maximum car usage), which may be beneficial in some situations, for example, when the price elasticity of demand in the short or medium term is low. Fourth, while the two instruments, pricing and tradeable credits, are identical in efficiency terms (congestion improvements) under perfect information of demand and supply, they perform differently when either demand or supply is uncertain (e.g., accidents, special events). In this case, tradeable credit schemes have been shown to be more efficient under strongly convex congestion effects (de Palma et al., 2018; Seshadri et al., 2022).

Although tradable credit schemes offer the possibility of addressing issues of equity compared to pricing, they still restrict usage of the scarce resource (road space) to those who monetarily value it the most. This may be contentious if structural improvements to the mobility system are not carried out in parallel so as not to restrict the mobility of those 'priced out' of using their cars. This leads to the third alternative, artificial currencies or Karma. Karma employs a currency different from money; it can only be gained by producing and only be lost by consuming a specific resource. It is a resource-inherent, non-monetary, non-tradeable, artificial currency for prosumer resources (produced and consumed by market participants alike) (Riehl et al., 2024b, 2024a).

Inside management strategies there are discussions on the objectives. In most existing works these objectives focus on efficiency. However, recent works highlight potential conflicts between efficiency measures (e.g. travel times) and users' perception (that includes fairness). Besides, there is an ongoing debate on the relationship between efficiency and equity. Some works argue there is a goal conflict, and thus a trade-off between efficiency and equity must be drawn, while others do not find that efficiency and fairness necessarily play a zero-sum-game. Discussing fairness is challenging, as there is no consensus on a clear definition, and defining fairness heavily depends on social and cultural contexts (Riehl et al., 2025a).

While there exists a substantial body of work on congestion pricing, artificial currencies, and tradable credits, the state of knowledge remains limited in several respects. Existing studies predominantly rely on stylized or equilibrium models, providing only coarse insights into system dynamics. There is little empirical evidence on how users and markets actually respond to such instruments, and almost no experimental data or real-world pilots to inform design and operation. Therefore, we will move the frontier forward by combining disaggregate, high-fidelity simulation models with experimental and pilot-based evidence, thereby filling a critical gap between theory and practice.

In the course of this project, we aim to (1) more systematically understand and explore the equity of congestion pricing, (2) explore the potential for artificial currencies namely Karma mechanisms, (3) explore human-centric experiments for behavioral acceptance and digital nudging, and (4) explore how a market for prioritization coupled with intelligent traffic light control (namely Urban Priority Pass) could shape urban traffic.

3.3.3 FREIGHT AND LOGISTICS OPTIMIZATION

Although logistics optimization has been researched for many years (Dantzig & Ramser, 1959), the combinatorial nature of logistics scheduling and vehicle routing, combined with the operational complexity of modern freight transport operations, means that even in the 21st century this field is active with many unsolved challenges to be addressed. Advancement in algorithms and optimisation strategies is not just of academic interest, significant cost savings, GHG reduction and lessening of congestion can be achieved with improved freight transport planning, scheduling and routing.

Several trends and developments in the industry offer both opportunities and new challenges in the field of logistics optimization:

- New Transport Technology such as cargo bikes, UAVs, autonomous trucks and Hyperloop are emerging. Cargo bikes are already providing solutions in cities and urban areas (Marincek et al., 2024), offering an attractive zero-emission option especially in narrow streets and controlled zones which are inaccessible to larger vehicles. UAVs are being considered in

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many R&I projects (including FEDORA, see also e.g. Dronamics; Drone Delivery; SAFIR-Ready). Similarly autonomous trucks are the subject of much active research (Olayode et al., 2023). Hyperloop is in an early stage of development but could offer ultra-fast low-emission transport in future logistics networks (Gkoumas, 2021). These new technologies offer very promising solutions, but from the logistics planner’s perspective add new options (increasing the search space) and new operational constraints (increasing the model complexity), that are outside the scope of conventional optimizers.

- New logistics paradigms such as the Physical Internet (Matusiewicz, 2024), synchronomodality (Giusti et al., 2019) and circular supply chains (Taddei et al., 2022) change the way freight transport operations are planned and managed, conferring increased flexibility, resilience and sustainability. However, they introduce new stringent requirements on logistics optimization algorithms: speed and integration. Dynamic replanning of shipments through a multimodal network requires algorithms to respond quickly to new events and data. Reverse logistics and circularity require an integrated approach over an extended network.
- Evolving societal and industry priorities mean that conventional cost minimization approaches may not be suitable. Increasingly shippers are concerned about environmental footprint (Rosano et al., 2022), although cost and service level remain high priorities. Recent trends such as shortages of logistics workers have driven a sharper focus on quality of life factors (ERSO, 2024).
- Increased prioritization of greener modes is supported by EU transport policy (European Commission, 2021) and is the subject of significant work in FEDORA and many other Horizon Europe projects. Increased use of intermodal services such as rail and inland waterway is desirable in terms of GHG and congestion reduction. From a logistics planning perspective this increases the complexity and size of the optimization problem to be solved, for similar reasons to those outlined for new transport technology above – each additional route/service is another choice to consider by the freight routing algorithm, and the impact grows polynomially or exponentially (or faster) as the number of options increases.
- Increased availability of real-time data from vehicle tracking systems or more sophisticated traffic monitoring technologies and data platforms such as those considered elsewhere in this document is a major facilitator for improved logistics planning. This is clearly an opportunity, but could also present a challenge in the context of information overload (Saxena & Lamest, 2018).

In FEDORA new synchronomodal logistics routing and scheduling solutions for freight will be developed. Previous work has made important advancements in this area. The SYNCHRO-NET and ePcenter projects developed successful synchronomodal logistics algorithms for large containerized freight networks, while ePcenter also developed initial models for new transport technology such as Hyperloop. AI-based techniques have been explored in many contents e.g. deep reinforcement learning for vehicle routing problems (Jiang et al., 2023) and ML-inspired methods for time dependent routing (Adamo et al., 2024). Hybrid ML/OR approaches have also been studied (Azevedo et al., 2024).

As mentioned above, a common problem for logistics optimization algorithms is execution speed. Search spaces typically grow exponentially or factorially, and industry operations typically have a large number of freight movements, vehicles/driver and other resources which mean that many algorithms are not suitable for operational logistics planning. Many algorithms use heuristics such as simulated annealing or tabu search, but often these become unmanageably slow for larger-scale problems.

Proposed solutions to the Inter-Terminal Truck Routing Problem for Delay Minimization (Ramadhan et al., 2023) use linear programming techniques and heuristics applied to small sets of vehicles and orders and relatively simple constraints. Another approach uses deep reinforcement learning (Adi et al., 2020) with a model which assumes that each vehicle acts as an agent with a small selection of possible actions at each stage of the process. Multi-objective inter-terminal truck routing has been addressed using a greedy heuristic approach and a simulated annealing approach to achieve a “Green-ITTRP” solution (Heilig et al., 2017).

Time-dependent vehicle routing subject to time delay perturbations has been contemplated for a multidrop VRP problem using a tabu search heuristic (Jabali et al., 2009). Relevant work on real-time conflict-free vehicle routing in warehouse settings (Adamo et al., 2024) uses a linear programming approach to recover feasible solutions in response to perturbations.

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Network tomography has been used to infer link delays, for example in software-defined networks using reinforcement learning (Tao et al., 2024) and in traffic monitoring in smart cities (Zhang et al., 2018). These techniques could be useful for inferring congestion problems in logistics networks, although other areas of the FEDORA project are developing relevant solutions in this space.

FEDORA will build on the successful solutions from previous Horizon projects such as SYNCHRO-NET and ePcenter to incorporate new capability to optimize door-to-door mobility of freight. A new multi-layered interoperable optimization architecture will be used to address larger-scale industry synchromodal and vehicle routing problems, including new algorithms with higher endurance capabilities with regards to the disruptions for freight movements.

The Synchromodal Conflict-Free Vehicle Routing Optimiser (SCF-VRO) will provide new synchromodal logistics routing and scheduling solutions for freight flows, enabling strategic simulation and dynamic multimodal rerouting in response to detected bottlenecks and delays in the traffic system. Risk-aware search and routing techniques will be used to reduce impact of congestion.

3.3.4 TRANSIT OPERATION AND SERVICES OPTIMIZATION

Urban transport sustainability planning was traditionally dominated by car-centric approaches, with the primary focus on minimizing individual travel times (Banister, 2005). However, as cities expanded and travel demand increased, it became evident that such a monolithic focus on automobiles was environmentally, socially, and economically unsustainable. In response, sustainable urban transport planning has shifted toward a paradigm in which mobility is regarded as a means to secure broader social benefits, rather than merely optimizing individual travel efficiency (Gössling et al., 2016). This new paradigm emphasizes a hierarchy that prioritizes walking, cycling, and public transit over private car use, enabling seamless integration between transport modes and fostering inclusive, efficient, and resilient urban systems (European Commission, 2011).

The new multimodal reality of large cities, however, introduces planning and operational challenges. From the traveler's perspective, selecting convenient mobility options requires processing large volumes of real-time information across different modes (Gallotti et al., 2016). From the perspective of operators and authorities, multimodal systems are more complex to manage, since they require the synchronization of multiple agencies, services, and schedules to ensure smooth interconnections (Barthelemy, 2019). These challenges have sparked the development of novel business models and digital platforms, ranging from proprietary applications to open public initiatives, aimed at improving multimodal journey planning and integration (Willing et al., 2017). Within this evolving ecosystem, innovative traffic management strategies have been introduced as congestion charging schemes (Crocì, 2016) perimeter control and ramp metering (N. Liu et al., 2016; Papageorgiou & Kotsialos, 2003) and dynamic route guidance. Commercial navigation services (Google Maps, Waze, TomTom, HERE) complement these strategies by providing turn-by-turn routing based on real-time traffic conditions (Belzowski & Ekstrom, 2014; Papageorgiou & Kotsialos, 2003).

Despite this progress, current approaches remain fragmented and fall short of addressing the complexity of modern urban mobility systems. Most optimization tools and decision-support frameworks operate in isolation, lacking structured integration protocols and failing to deliver a holistic "concept of operations" that reflects real-world practices (Çolak et al., 2016). Navigation platforms, although widely adopted, exacerbate selfish routing behaviors that destabilize network performance, producing congestion oscillations and diverting traffic through residential neighborhoods (Bagabaldo et al., 2024; Macfarlane, 2019). Moreover, the majority of traffic modeling and optimization methods rely on simplifying assumptions, such as traffic linearity, that are unable to capture the nonlinearities and uncertainties of urban mobility systems (Menelaou et al., 2023). Emerging transport modes further complicate the picture: current multimodal network management frameworks are not equipped to handle the rapid growth of micro-mobility services or their interactions with vulnerable road users, undermining progress toward EU active mobility targets (European Commission, 2011). Equally, shared and automated mobility services—including Mobility as a Service (MaaS), Logistics as a Service (LaaS), and Connected, Cooperative, and Automated Mobility (CCAM)—remain insufficiently integrated into current optimization and management solutions (Alessandretti et al., 2023; Barthelemy, 2019; Gallotti et al., 2016) while simulation models often lack validation with realistic datasets and overlook critical complexities such as multimodal freight flows and land–waterborne integration

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(Barthelemy, 2019; Gallotti et al., 2016). Consequently, the effectiveness of existing approaches remains limited, frequently resulting in suboptimal outcomes under unexpected or dynamic conditions.

The FEDORA project seeks to bridge these gaps by developing a unified and realistic framework for multimodal traffic management and urban mobility coordination. Unlike existing fragmented solutions, FEDORA integrates diverse data streams—such as National Access Points (NAPs), public transport datasets, and Data Space services—into a common platform for optimizing multimodal hubs and urban traffic flows. Advanced optimization and AI-assisted methods, including constrained deep reinforcement learning and dynamic programming, are employed to capture nonlinear dynamics and incorporate probabilistic constraints into trajectory planning, overcoming the limitations of traditional linear assumptions. The proposed framework will be validated through SUMO-based simulations and agent-based demand models, enabling the exploration of multimodal what-if scenarios and foresight analysis. Importantly, FEDORA extends beyond ground transport by incorporating UAV-based passenger services, which can both alleviate road congestion and serve as airborne monitoring platforms (A. P. Cohen et al., 2021; Exadaktylos et al., 2023; Shaheen et al., 2016). These UAVs provide “virtual measurements” in situations where direct data are unavailable, enhancing situational awareness and risk assessment (Alessandretti et al., 2023; Theocharides et al., 2024). By coordinating across modes, integrating simulation with real-world data, and leveraging novel mobility services, FEDORA delivers a socially optimal, sustainable, and resilient framework that advances the state of the art in multimodal urban mobility management.

3.3.5 DECISION MAKING, GOVERNANCE AND MENTAL MODELS IN TRAFFIC MANAGEMENT

Governance and decision-making models define how authority, accountability, and resources are distributed across institutions and actors. In public infrastructure, digital transformation, and mobility systems, such models determine how collective choices are structured, justified, and monitored across multiple levels of government (European Commission, 2023a; OECD, 2023).

This review provides a short overview of organizational aspects of traffic management, the regulatory framework, stakeholders, instruments, and policies. In the literature, traffic management is mostly discussed within the context of ITS and traffic management systems (TMS).

In the outlook, we focus on decision-making models that can be applied to traffic management processes.

Traffic Management – Regulatory Framework

How the road network is managed can vary greatly from area to area and is influenced by local, national and international legislation and policies (Urban ITS Expert Group, 2013). Relevant EU regulations include the ITS Action Plan (European Commission, 2008), the ITS Directive (European Parliament, 2010), and its Delegated Regulations for safety-relevant traffic information (SRTI) (European Commission, 2013) and real-time traffic information (RTTI) (European Commission, 2022).

Traffic Management – Stakeholders and stakeholder participation

The lists of potential stakeholders in traffic management are long and include the users of the transport system, residents along traffic arteries, national, regional and local government, traffic authorities, police and enforcement institutions, firefighters and rescue services, public transport operators, service and information providers, and industry, among others (Austroads, 2020; FGSV, 2002; Urban ITS Expert Group, 2013).

Effective multi-agency co-operation is seen as critical for the successful implementation of traffic management systems (Urban ITS Expert Group, 2013). Divergent interests and goals of different actors, differing assessments of potential impacts, and incompatibility between concurrent traffic management measures are seen, among others, as potential sources of conflicts and risks (FGSV, 2002).

As FGSV (2002) states: “Traffic management solutions are often not directly interchangeable between different urban areas or regions. It is, therefore, necessary that they are tailored to local requirements and should be reflective of local priorities and

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sensitivities”. It is recommended to seek the participation of all relevant organizations in the design, implementation, and evaluation of traffic management projects (FGSV, 2002; Urban ITS Expert Group, 2013).

In a bit more detail, the Reference Handbook for Harmonized ITS Core Service Deployment in Europe (EU-EIP, 2021) defines organizational requirements and advice for a wide range of traffic information and traffic management service use cases.

Organizational model

The Urban ITS Experts Group (Urban ITS Expert Group, 2013)[4] proposed an “ITS pyramid” as an organizational metamodel, consisting of:

- a strategy layer, describing the long-term and medium-term objectives of the service,
- a process layer, describing the actions of different actors,
- an information structure layer, dealing with the collection, distribution and presentation of information
- IT services and IT infrastructure layers

Accordingly, strategic objectives are mapped to a tactical layer providing a framework for traffic control and then to specific measures. Similar mappings can be found in (Austroads, 2020; FGSV, 2002) (for Australia), and (Kuciemba et al., 2023) (for the US).

Traffic management Implementations

For an extensive overview of ITS implementations in Europe, including organizational and administrative challenges, see (Cordoş et al., 2025). The Conference of European Directors of Roads (CEDR) records national TMS implementations across Europe (Olsen, 2015).

OUTLOOK: Governance and DECISION-MAKING mental MODELS

Most of the traffic management literature focuses on technical solutions supporting strategic objectives and operational needs. Though stakeholder co-operation is often emphasized (Austroads, 2020; FGSV, 2002; Urban ITS Expert Group, 2013), little is to be found on the actual interactions between different participants in traffic management decision processes.

FEDORA aims to develop governance and decision-making mental models that bridge the gap between stakeholder expectations and conceptual understanding. This involves capitalising on familiar paradigms, augmenting cognitive processes, and contrasting rational with non-rational approaches to decision-making. The goal is to design governance arrangements that fit the transition to advanced network management.

In Decision Theory, Bounded Rationality (Simon, 2013) and Incrementalism (Lindblom, 1959) are core decision paradigms. The Garbage-Can Model (Cohen et al., 1972) explains how decisions emerge from dynamic problem-solution couplings. Prospect Theory (Kahneman & Tversky, 2013) introduced behavioural deviations from rationality. Multi-Criteria Decision Analysis (Raiffa & Keeney, 1975; Saaty, 2008) formalized quantitative comparison.

Recent works include Noise (Kahneman et al., 2021) on decision hygiene and Cynefin Framework (Snowden & Boone, 2007) for complexity. ISO 31000(ISO, 2018)and Stage-Gate (Cooper, 1990) ensure risk-aware decision checkpoints. New Multi-Criteria Decision analysis studies (Bousquet et al., 2023; Demir et al., 2023; Więckowski et al., 2023) extend decision science to sustainability, infrastructure, and open data contexts.

Modern governance and decision systems combine clarity, participation, evidence, and learning:

- Classify the problem context (Snowden & Boone, 2007)
- Assign decision rights (ISO/IEC, 2024).

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- Engage stakeholders via co-creation (Ansell & Torfing, 2021).
- Apply structured analysis (Bousquet et al., 2023; Demir et al., 2023; Więckowski et al., 2023).
- Integrate risk and evidence loops (European Commission, 2023a; ISO, 2018).
- Review and adapt decisions (Cooper, 1990).

These models are particularly relevant for MTM governance, where uncertainty, complexity, and multiple stakeholders make purely rational approaches insufficient. Non-rational models capture the adaptive, negotiated, and sometimes emergent nature of decisions in traffic and network management.

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4 IMPLEMENTATION AND BEST PRACTICES

In recent years, EU research and innovation projects have addressed multimodal traffic management challenges through pilots and demonstrations. The multimodal traffic management cluster of EU projects has outlined a vision for transforming transportation systems into multimodal, sustainable, and resilient systems that align with EU climate-neutrality and resilience policy goals. This vision is based on a combination of technologies and services, data and policy frameworks to encourage collaboration of public authorities, infrastructure managers, information service providers and transport service providers, including freight transport companies. In this section, MTM EU-projects are presented with a focus on:

- Measurable impact and results related to management and policy innovations,
- Acceptance limitations and future steps for real -world deployment, and
- Standardization, legal or regulatory aspects and governance models

DIT4Tram Project (ID 953783): The DIT4Tram project (Distributed Intelligence and Technology for Traffic and Mobility Management) develops and validates a Distributed Network and Traffic Management (DNTM) framework enabling decentralized, multimodal, and cooperative traffic management in urban and interurban conditions. Its aim is to develop multi-actor cooperation models and data interoperability solutions to enable real-time, AI-supported decision-making in dynamic mobility systems. The project integrates multi-agent reinforcement learning, Cooperative Intelligent Transport Systems (C-ITS), and tradable mobility credits in simulation-based and real-world pilots to demonstrate scalability, robustness, and sustainability. In total six pilots were carried out across Europe (Fafoutelis et al., 2025). In Glyfada, Greece an on-demand shuttle bus service was tested, reaching an average waiting time of 9.5 minutes and travel time of 10.6 minutes, with the potential to reduce private car use by about 60%. In Athens, Greece a reinforcement learning perimeter control system reduced vehicle-hours travelled by up to 23.4% compared to baseline methods. In Bordeaux, France an auction-based traffic light control system improved travel times for cyclists and reduced their waiting time by around 5 seconds. The Utrecht, Netherlands pilot used Floating Car Data to replace radar sensors for queue estimation and tested bike priority at an intersection, showing that data-based methods are possible but still need improvements. In Amsterdam, Netherlands, a Tradable Mobility Credits (TMCs) system balanced road space use and promoted multimodal trips, while on the Mediterranean Corridor (Spain-France) pilot, simulations showed that the TMC approach, that was used in this case to optimize traffic distribution, could lower travel times and delays and increase average speed and fuel efficiency. The project involved stakeholders and users from the first stages of the evaluation process to ensure the acceptance of its solutions. The impact assessment also highlighted the need for real-life testing and with more realistic data, without assumptions to ensure the findings are reliable (Katzilieris et al., 2022). In addition, the framework considered the regulatory, and policy aspects, recognizing that standardized data procedures and clearly defined governance structures are needed to make the large-scale deployment of decentralized traffic management systems possible (Havlin & Blumenfeld Lieberthal, 2022).

TANGENT Project (ID 955273): The TANGENT project (Enhanced Data Processing Techniques for Dynamic Management of Multimodal Traffic) develops data-driven, real-time traffic management tools for cities and regions. Its purpose is to promote coordination between transport authorities, operators, and users through data harmonization, forecasting, and multimodal decision support systems. Simulation and real-life data from four pilot locations (Renne, Lisbon, Greater Manchester, and Athens) are used to validate methodologies, such as cooperative management concepts, C-ITS integration and dynamic congestion pricing. In Rennes, France the pilot tested cooperative corridor management through V2X exchange of data between road infrastructure and vehicles. While overall vehicle delay increased in some cases, the pilot improved the cooperation between transport operators and local authorities and between passenger and freight transport (Tristant et al., 2024). In Lisbon, Portugal, a real-time multimodal monitoring and decision-support dashboard was tested, that was user-friendly and intuitive and provided relevant information in a clear way (Cunha et al., 2024). In Greater Manchester, United Kingdom, Dynamic Congestion Pricing (DCP) during special events

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reduced congestion by 64% inside the changing zone and 7% outside, also reducing emissions by 56% (Tune et al., 2024). In Athens, Greece a DCP scheme was also tested for managing urban congestion, which resulted in a reduction of 23.6% inside the charging zone and a reduction of 6% of system-wide emissions (Chalkiadakis et al., 2024). Stakeholder cooperation and acceptance was evident through the pilots. The project emphasized common data formats and legal compliance with Data Governance Act and GDPR to support safe and transparent data handling (Comerio et al., 2022). It also prioritized the need for governance frameworks and formalised collaboration platforms governed by a central coordinating authority to support data sharing, distribute responsibilities, and enable the large-scale deployment of multimodal traffic management systems (Comerio et al., 2022).

ORCHESTRA Project (ID 101016167): The ORCHESTRA Project (Coordinating and synchronizing multimodal transport improving road, rail, water and air transport through increased automation and user involvement) aims to enhance the coordination between road, rail, water and air transport through the development of tools and MTM strategies. Its goal is to help authorities, operators, and users coordinate different transport modes and respond more effectively to disruptions. ORCHESTRA created a Multimodal Traffic Management Ecosystem (MTME) that promotes communication and synchronization across transport networks and supports the integration of connected and automated vehicles (CAVs) and vessels (Tedeschi et al., 2022). The testing and evaluation took place through two pilots. In Herøya Industrial Park, Norway, a real and simulated pilot merged data from roads, rail and shipping activities in order to optimise freight logistics within the industrial area. Important performance indicators such as truck waiting time, gate delay, and CO₂ emissions were monitored, and one CAV trial was successfully completed, demonstrating the feasibility of multimodal data sharing even in a complex industrial setting (Ronke et al., 2024). At Malpensa Airport, Italy, data were used to test a decision-support tool for managing disruptions in road, rail and airport connections. The system proved to be effective in producing alternative multimodal travel routes and reducing passenger delays. Stakeholders identified benefits for safety, robustness, and congestion management, and the pilot showcased the collaboration between airport and transport operations (Ronke et al., 2024; Sharpanskykh et al., 2024). The project also focused on standardization and regulatory harmonization, defining a reference architecture and roadmap to guide the legal deployment of multimodal traffic management under automation. Finally, ORCHESTRA created new governance and organization models to aid coordination across transport modes, providing deployment toolkits that included business, market, and administrative frameworks for adoption on a large scale in the future (Søråsen et al., 2024).

CONDUCTOR Project (ID 101077049): The CONDUCTOR Project (Fleet and traffic management systems for conducting future cooperative mobility) aims to create, integrate, and test novel traffic and fleet management systems for both passengers and freight. The project focuses on creating a common open platform enabling seamless multimodality and interoperability between transport networks. The project develops dynamic balancing and priority-based management tools, using data fusion, machine learning, and cooperative vehicle technologies, to support public authorities and operators in the management of mixed traffic environments with automated vehicles. The project tested these techniques in five pilots (Katzilieris et al., 2025). In Athens, Greece, dynamic bus lane allocation and transit signal priority reduced passenger travel time by 11%, vehicle travel time by 19% and emissions by more than 11%, improving public transport efficiency and lowering operational costs. In Madrid, Spain, experiments with CAV management and penetration rates, and showed that the best performance was achieved with a 45% CAV penetration rate, reducing queues by up to 15% and travel time by 2%. In Almelo, Netherlands, real-world testing of freight signal priority achieved smoother freight flows and reduced idling. A Slovenia-Italy-Croatia-Austria cross-border pilot tested a DRT system that reduced fuel consumption by 8.7% and improved planning efficiency. Finally, a second Madrid pilot demonstrated that last-mile parcel delivery combined with DRT-CCAM services increased fleet utilisation and reduced idle trips by 9.1%. 58 European organizations participated in stakeholder analysis in CONDUCTOR to ensure that the proposed CCAM solutions address real mobility needs and support social acceptance of automation (Brambati et al., 2023). The project's work also complemented EU policy guidelines for CCAM, calling for interoperability and policy coherence. Finally, CONDUCTOR highlighted that governance structures should evolve in parallel with the technological progress, as “fast-paced advancements in CCAM technology often move ahead of existing governance and policy frameworks” (Chau et al., 2024).

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SYNCHROMODE Project (ID 101104171): The SYNCHROMODE Project (Advanced Traffic Management Solutions for Synchronized and Resilient Multimodal Transport Services) develops AI-based tools and cooperative models to synchronize passenger and freight mobility across different transport modes (Mitsakis & Tzanis, 2024). Its aim is to advance data harmonization, multimodal coordination, and real-time traffic management by aggregating information from public transport, shared mobility, logistics, and connected vehicles. The project formulates a SYNCHROMODE toolbox, a set of models and algorithms designed to facilitate dynamic, network-level management and help authorities manage disruptions, bottlenecks or changes in travel demand. Three pilot case studies were designed to test these solutions. First, in Madrid, Spain, the project focuses on the integration of urban parcel delivery, public transport and on-demand mobility to reduce traffic generated by deliveries during off-peak hours and promote sustainable last-mile logistics. The pilot activities are not yet finished, but the expected outcomes include reductions of up to 40% in emissions, 20% in delivery distances, and 10% in shipping costs. In the Province of South Holland, Netherlands, the Dutch pilot explores how cooperative and data-driven strategies can reduce congestion and accidents and enhance the predictability of the transport network and the efficiency of public transport. Finally, in Thessaloniki, Greece, connected vehicle and data-based models are tested to deploy multimodal coordination and resilience strategies at large scale, aiming for reduced travel times, enhanced network capacity, and lower emissions.

DELPHI Project (ID 101104263): The DELPHI project (Federated Network of Platforms for Passenger and Freight Intermobility) aims to create a network of interconnected platforms that support seamless cooperation between passenger and freight transport systems. Its goal is to promote data sharing, interoperability, and governance harmonization across Europe's multimodal mobility ecosystem. DELPHI develops a Platform Federation Reference Architecture and an AI- and machine learning-powered optimization framework to improve traffic and logistics management, reduce emissions, and lower delivery times and costs. The project also focuses on developing neutral governance structures and regulatory recommendations that ensure compatibility with EU standards and encourage cross-sector collaboration. Four pilot use cases are under development. In Madrid, Spain, the project integrates sustainable last-mile delivery solutions supported by blockchain technologies for the e-commerce sector. In Attica, Greece and Mykonos, Greece, DELPHI tests integrated passenger and freight data-sharing frameworks to enhance coordination between transport modes in both urban and rural contexts. The Cluj-Napoca, Romania pilot focuses on a data-sharing governance framework for passenger transport, validating new cooperation models between regional authorities and mobility providers. While results are not yet reported, these pilots will contribute to the validation of DELPHI's federated platform concept and demonstrate how digital interoperability can improve efficiency and sustainability across European transport networks.

ACUMEN Project (ID 101103808): The ACUMEN project (AI-aided Decision Tool for Seamless Multimodal Network and Traffic Management) develops an AI-based framework to support real-time, data-driven decisions for multimodal transport management. The project focuses on creating a safe, decentralised, and privacy-preserving data-sharing environment that allows different mobility providers and operators to coordinate traffic and passenger flows more efficiently. Through hybrid intelligence, explainable AI, and digital-twin technologies, ACUMEN aims to improve short-term traffic prediction, multimodal simulation, and network-level performance assessment, helping authorities design adaptive and sustainable transport strategies. Four pilot sites are under development (Viti et al., 2024). In Athens, Greece an integrated mobility platform is designed to provide traffic information, short-term multimodal forecasts, and decision-support tools for transport authorities. In Helsinki, Finland, the pilot promotes sustainable travel behaviour through personalised incentives encouraging walking, cycling, e-scooters, and public transport. In Amsterdam, Netherlands, the project demonstrates joint multimodal management to increase flexibility and resilience during network disruptions. Finally, in Luxembourg, the pilot explores door-to-door mass transit and automated vehicle integration, aiming to provide seamless, on-demand travel. Results are not yet reported, but ACUMEN is expected to deliver new AI-based monitoring and forecasting tools, standardised data frameworks, and a predictive mobility management orchestrator, supporting future cooperation among European mobility stakeholders.

IN2CCAM Project (ID 101076791): The IN2CCAM Project (Enhancing Integration and Interoperability of CCAM eco-system) demonstrated the feasibility and effectiveness of integrating CCAM solutions into European environments through real-world and

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simulated pilots (Ruffin et al., 2023). For instance, simulated route planning in Bari proved that adaptive routing based on real-time traffic data may decrease last-mile delivery emissions and foster inclusive mobility for various social groups. Real-life pilots in Trikala and Tampere, including autonomous minivans and DRT, increased traffic light efficiency, and enhanced safety for vulnerable road users, with successful remote operation and monitoring frameworks. In Turin, dynamic traffic management based on integrated use of automated vehicles, parking data, and UVARs improved flow, reduced travel time, and decreased emissions. In Vigo, the deployed strategies for V2I, such as platoon support or emergency vehicle management, reduced stop-and-go traffic, and improved intersection safety. Moreover, simulation activities in Guimarães assessed the systemic impacts of CCAM deployment on congestion, travel times, and air quality, thus providing strong decision support for urban planning. User and stakeholder acceptance was generally high, especially in cases where CCAM services were aligned with public transportation networks.

deployEMDS Project: The deployEMDS project (deploy European Mobility Data Space) works towards the creation of a common European Data Space for data in the mobility domain (Federl et al., 2024). This data space will allow different parties to enable data access and sharing while ensuring data sovereignty. To achieve this a decentralised methodology is used, that reuses previous developments in this field, including the prep4DSpace project, the Data Space Support Centre results and the Simpl program. As part of the project specific use cases for different types of mobility data were investigated and are currently being implemented in various cities and regions in Europe. More specifically, pilots are being implemented in cities and regions such as Barcelona, Budapest, Flanders, Île-de-France, Lisbon, Milan, Sofia, Stockholm and Tampere, focusing on applications such as demand-responsive transport management, traffic forecasting, journey planning, accessibility support for people with limited mobility, and MaaS integration. Although most pilots are still ongoing, expected outcomes include improved traffic efficiency, enhanced accessibility, better multimodal travel experiences, and more sustainable commuting through data-driven decision support systems.

NAPCORE Project: The NAPCORE project (National Access Point Coordination Organisation for Europe) aims to harmonise mobility data platforms across Europe. According to the ITS Directive 2010/40/EU each European Member State is required to establish a National Access Point (NAP), which is to provide mobility related data. Since then, it has become apparent that major differences between the setup data access, data formats and standards used exist. This hinders consumers, that prefer uniformity in these regards. This project's objective is to provide coordination, improve interoperability, harmonisation and alignment between the NAPs of different European Member States. Working towards these goals cooperation between partners from 27 countries is currently ongoing.

Table 5 summarises the findings from all the above pilot projects and can be found in the APPENDIX.

The reviewed pilots and demonstrators across European research projects (DIT4TraM, TANGENT, ORCHESTRA, CONDUCTOR, SYNCHROMODE, DELPHI, ACUMEN, IN2CCAM, and deployEMDS) collectively showcase a strong evolution toward integrated, data-driven, and cooperative traffic and mobility management. Early-stage deployments in simulation environment, such as those in DIT4TraM and TANGENT, demonstrated tangible performance gains in traffic efficiency, travel time reduction, and emission savings through dynamic control, reinforcement learning, and tradable mobility credit mechanisms. Real-world implementations in cities like Glyfada, Utrecht, Bordeaux, and Amsterdam validated the technical feasibility of on-demand services, auction-based control, and multi-agent traffic optimization, with measurable impacts on waiting times, system efficiency, and sustainability. These findings underline the potential of AI-based decentralized management, connected infrastructure, and mobility credit systems to improve operational performance while promoting multimodal and sustainable choices.

Subsequent and ongoing pilots—particularly under IN2CCAM and deployEMDS—extend these advances into real-world CCAM environments, emphasizing fleet integration, remote operation, data governance, and multimodal coordination. Cities such as Trikala, Tampere, Turin, and Vigo demonstrated that connected automated shuttles and V2X-enabled corridors can operate safely and efficiently, with improvements in intersection crossing times, situational awareness, and user acceptance. Meanwhile, large-scale initiatives, such as those developed in deployEMDS and ACUMEN are operationalizing mobility data spaces and decision-support systems, focusing on interoperability, inclusiveness, and accessibility across Europe's transport ecosystems. Although many pilots are still ongoing, early evidence confirms that integrated data sharing and real-time coordination substantially enhance

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resilience, service efficiency, and environmental performance, paving the way for scalable, cooperative, and human-centric CCAM network management.

The above-mentioned pilots that were conducted across diverse urban and regional locations in Europe tested a range of MTM solutions in real and simulated environments. The pilots across the projects show that the use of artificial intelligence, prediction tools and decision-support platforms have the ability to improve traffic management. Most pilots reported reducing congestion, emissions and travel times, validating the benefits of dynamic, multimodal, and data-driven strategies. Moreover, the willingness to adopt these solutions by stakeholders, i.e. municipalities, transport operators, and infrastructure managers, was also positive, especially when the tools were easy to use and collaborative. However, several challenges were observed. For example, scalability of solutions was an issue, as some solutions that worked well in small-scale or controlled environments showed uncertainty when applied to larger or more complex networks. In other cases, pilots faced issues with limited availability of real-time data, which affected the performance of decision-making tools. Despite these challenges, findings indicate that with proper data management and clear governance frameworks, MTM could be ready to support more efficient, sustainable, and resilient mobility across Europe in the near future.

A cross-comparison of the projects reviewed reveals a set of gaps that remain insufficiently addressed despite considerable progress. In the area of data, most projects highlight issues of fragmented data governance, heterogeneous formats, limited semantic interoperability, and a lack of scalable mechanisms for cross-sectoral sharing, which constrains consistent real-time multimodal coordination. Pilots have demonstrated a number of promising services related to dynamic pricing, prioritization, C-ITS cooperation, and multimodal routing, but these mostly remain mode-specific, with little attention given to the integration of aspects of social fairness, cross-modal optimisation, or incentivised demand management. In simulation and modelling, few approaches can offer more than corridor or intersection-level analysis, let alone network-wide multi-modal simulation, Sim2Real transfer, or high-fidelity digital twins which can incorporate behaviors and heterogeneous agents. These are issues across projects that directly inform FEDORA's innovation focus and its developments towards federated data spaces, socially-aware optimisation services and modular multi-scale simulation frameworks.

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5 FEDORA VISION

FEDORA's vision for network and traffic management is built around a future mobility ecosystem that is inclusive, self-organising, anticipatory, and human centric. In this ecosystem, digital collective intelligence and governance enable seamless coordination across all transport domains, i.e. ground, air, and maritime, and at all scales. The goal is to move from federated multimodal integration toward distributed cognition, in which infrastructure, vehicles, and mobility services dynamically negotiate priorities, share intent, and balance efficiency with societal and environmental goals. In this future paradigm, traffic management will no longer be a centralized or decentralised control system, but rather a living digital organism capable of perceiving, reasoning, and adapting autonomously in real time, guided by shared ethics, sustainability, and inclusiveness.

This vision is informed by the insights gained from the EU-funded projects reviewed in the previous section. These projects show clear progress in areas such as data-driven coordination, C-ITS cooperation, and AI-based optimisation. However, they also reveal important limitations, including weak interoperability, fragmented governance, inconsistent semantics, limited cross-modal coordination, and the absence of large-scale multimodal simulation tools. FEDORA builds on these lessons by focusing directly on the gaps that appeared across many projects: fragmented data ecosystems, optimisation services that cannot scale, and simulation frameworks that remain isolated or incomplete. By addressing these issues, FEDORA aims to create an architecture that extends and strengthens what previous initiatives have already achieved.

This next generation of network management will leverage digital twins, edge-intelligent infrastructure, and trusted AI agents to ensure resilience, transparency, and fairness in decision-making at a strategic, tactical and operational level. Continuous co-learning among human operators, automated agents, and policy frameworks will enable mobility systems that self-improve over time, aligning transport performance with climate neutrality, safety, and accessibility objectives. The integration of terrestrial and aerial mobility, safe communications, and decentralized data economies will underpin a pan-European cognitive mobility fabric that senses, predicts, and acts collectively.

To support its vision, FEDORA will introduce the following innovation aspects:

- Flexible data model and semantic enrichment to enhance data integration, interpretation, and interoperability through adaptable interfaces and query models.
- Cross-sectoral data sharing platform enabling automated data extraction, AI-based dataset evaluation, and transparent sharing via smart contracts.
- Socially fair optimization promoting inclusive, multimodal mobility through layered network control at intersection and corridor levels.
- Karma artificial currency for dynamic congestion pricing, with blockchain-based transparency supporting multimodal demand management.
- Synchromodal Conflict-Free Vehicle Routing Optimiser using resilient algorithms and the Subito method to improve multimodal freight routing and reduce congestion.
- Scenario-based, multi-heuristic routing with genetic algorithms and behavioral nudging to support socially and environmentally conscious travel choices.
- Advanced VTOL and UAV management framework using deep reinforcement learning for safe urban air mobility and optimal vertiport placement.
- Integrated UAV-based monitoring system combining air and ground data to enhance situational awareness and handle data uncertainty.
- Multimodal simulation and Sim2Real techniques for reliable traffic control across simulated and real network environments.

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- Self-supervised and generative learning to detect and simulate non-recurrent traffic events from unstructured data.
- Enhanced modeling and simulation tools capturing new mobility technologies, user behavior, and environmental impacts.
- Active Learning and Bayesian Optimization methods to calibrate simulations, support policy design, and explore complex transport scenarios efficiently.

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6 CONCLUSION

This deliverable provides the conceptual and methodological foundation for the FEDORA project. It establishes an understanding of the current challenges and opportunities in traffic management, through a review of the scientific literature, state-of-the-art implementations and EU projects in the domains of data, modelling and simulation and network management for MTM. The analysis identified the challenges, opportunities and research gaps that are going to be addressed by the FEDORA project, especially those that focus on interoperability, data availability and governance, the integration of heterogeneous transport modes, and the scalability of advanced optimization and simulation frameworks.

This review of data sources and architectures underlined the importance of federated data spaces and particularly the European Mobility Data Space which enables trustworthy, secure, and interoperable data exchange. It also identified the need for semantic harmonization, AI-based data enrichment, and privacy-preserving mechanisms as enablers for unlocking the full potential of multimodal data in traffic management. In the field of modelling and simulation, the deliverable reviewed recent advances in predictive analytics, incident detection, and multi-scale traffic modelling, outlining how AI and digital twin technologies are enabling a change in real-time and forecasting capabilities for traffic management. Similarly, the review of management strategies showed that while innovative tools such as dynamic pricing, perimeter control, and cooperative signal optimization have measurable impacts on a small scale, their fragmented deployment limits network-wide coordination and efficiency. The analysis of EU-funded projects highlights the measurable benefits of AI-driven, data-informed, and interoperable MTM approaches in reducing emissions, improving travel times, and enhancing safety. Importantly, stakeholder acceptance and governance readiness were consistently found to be key enablers for the transition from pilot to real-world deployment.

Building upon these insights, the deliverable defined the research and innovation directions that will guide FEDORA's technical activities. It stated a vision of an integrated, AI-enabled, and federated platform that combines data spaces, simulation environments, and management tools into a unified operational framework. FEDORA's developments, that include self-supervised learning for incident detection, simulation-to-reality transfer, socially fair optimization, and federated data governance, will advance the state of the art toward more adaptive, sustainable, and resilient mobility systems.

In summary, this deliverable contributes to the overall project objectives by:

- Establishing a common conceptual baseline for all partners and work packages
- Identifying the technological and governance gaps that shape the developments of FEDORA
- Providing best practices that derive from EU-funded research and pilot deployments
- Facilitating the development and validation framework of FEDORA's federated platform

These outputs ensure that subsequent technical, methodological, and validation activities within the project are aligned with European priorities and are capable of scalable advancements in MTM.

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APPENDIX

Table 5: Reference solutions from previous projects

Solution name	Short description	Project/ Lead Research Team	Area/ Size/ Real or Simulated	Measurable Impact and results	Other findings (e.g., acceptance, feasibility)
Optimizing on-demand services	Enhance the existing transit system with a novel on-demand service with dynamic routing	DIT4TraM/ NTUA	Glyfada, Greece/ City level (701 trips)/ Real	Average waiting time 9.5 min, travel time 10.6 min, reduced compared to existing transit alternatives	Potential to reduce private vehicle usage by ~60% according to stated preference survey
Integrated distributed management for urban mobility	Multi-agent and centralized Reinforcement Learning for perimeter control	DIT4TraM/ NTUA	Athens, Greece/ Network-wide/ Simulated	Reduced vehicle hours travelled by up to 23.4%, with an additional 7.3% improvement over the multivariable PI controller	High potential for AI-based control, inclusion of public transport data is needed
Real-time auctioning for prioritizing movements at intersections	Prioritization of cyclists and high occupancy vehicles at intersections using auction-based control	DIT4TraM/ University Gustave Eiffel	Bordeaux, France/ Intersection-level (~20 cyclists)/ Real + Simulated	Auction-based control outperformed fixed-time in all scenarios, message delay <1s, reduced travel times for cyclists (waiting time reduced ~5s, speed increased ~1-2km/h)	Strengthened cooperation between public/private stakeholders
Decentralized regional multi-class network traffic control and guidance	Integrated Network Management and Floating Car Data for queue estimation and bicycle priority optimization	DIT4TraM/ TU Delft	Utrecht, Netherlands/ Corridor-level/ Real	Floating Car Data can substitute radar at low-cost sites, no major changes in speed or flow after bike waiting time adjustment	External factors affected traffic flow more than parameter changes, feasibility proven but radar still needed for critical sites
Resilient mobility management through cooperation and sharing	Implementation of Tradable Mobility Credits to manage urban traffic demand, balancing road space usage and promoting sustainable transport modes	DIT4TraM/ TU Delft	Amsterdam, Netherlands/ City-wide/ Simulated	Regulations reduced e-moped-only trips and promoted multimodal use, travel times remained stable	Concerns about profits from private operators, potential for public transport complementarity
Demand management for interurban mobility (Mediterranean Highway pilot)	Tradable Mobility Credits to reduce congestion on the AP-7 highway and improve traffic distribution between the main highway and secondary roads	DIT4TraM/ University Gustave Eiffel	Mediterranean corridor (France-Spain)/ Corridor-level/ Simulated	The best Level of Service (LoS) occurs at a 70% credit allocation rate, optimal tuning range between 0.7-0.8, at 70% allocation the network-wide density decreases, and average speeds are higher than in the baseline	Demonstrated scalability of distributed management for long-distance corridors

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<p>Fostering intermodal cooperation of passenger and freight transport in urban areas</p>	<p>Implement and test a cooperative corridor management concept based on V2X data exchange between vehicles and infrastructure in mixed traffic environments</p>	<p>TANGENT/ Rennes Metropole - ID4Mobility</p>	<p>Rennes, France/ Corridor-level/ Simulated</p>	<p>Average delay all vehicles: +5–6%; bus delay: +1–14%; slight improvement only at 30% carpooling scenario</p>	<p>Importance of the availability and reliability of data sources, Testing fostered collaboration among Rennes Métropole, DIRO, and transport operators, establishing a long-term cooperative framework.</p>
<p>Integrated urban and interurban transport management with C-ITS</p>	<p>Experimentation of real-time monitoring and decision-support tools to manage congestion, disruptions, and improve public transport services</p>	<p>TANGENT/ CARRIS</p>	<p>Lisbon, Portugal/ Corridor-level/ Simulated</p>	<p>The dashboard is user-friendly, intuitive and provides relevant information in a clear way</p>	<p>The access to multimodal real-time information is of interest to operation management and benefits all users</p>
<p>Optimization of transport flows both in urban and in rural/semi-rural region</p>	<p>Testing framework designed to assess the effectiveness of toll adjustment and dynamic congestion pricing in managing traffic flow during special events</p>	<p>TANGENT/ Transport for Greater Manchester</p>	<p>Manchester, United Kingdom/ Network-wide/ Simulated</p>	<p>Within the pricing zone, congestion was reduced by 64%, Congestion outside the pricing zone also saw a 7% improvement, system-wide emissions were reduced by 56%</p>	<p>That system can generate profit</p>
<p>Future transport management with CAVs</p>	<p>Test Dynamic Congestion Pricing (DCP) to manage urban congestion on major arterials and evaluate shockwave reduction in dense urban traffic</p>	<p>TANGENT/ NTUA</p>	<p>Athens, Greece/ Network-wide/ Simulated</p>	<p>Congestion reduced by 23.60% inside pricing zone, congestion outside zone improved by 22.69%, system-wide emissions reduced by 6%</p>	<p>Dynamic congestion pricing reduced shockwave patterns by lowering delay time and improving traffic speed</p>
<p>Herøya Industry Park</p>	<p>Integration and testing of a multimodal traffic management framework in an industrial park environment, combining real-life CAV trials with data simulations.</p>	<p>ORCHESTRA/ Herøya Industrial Park</p>	<p>Herøya, Norway/ Industrial area level (road-rail- maritime terminal operations)/ Real + Simulated</p>	<p>Average truck waiting and gate times monitored; KPIs included truck waiting time, gate waiting time, and idling CO₂ emissions. The CAV completed one full pilot run during the trial period.</p>	<p>Real-life deployment proved challenging, Demonstrated feasibility of multimodal data sharing for industrial traffic management</p>
<p>Malpensa Airport</p>	<p>Simulation of multimodal traffic management for disruptions along the connection of Milan city and Malpensa Airport. the pilot applied a decision-support environment using synthetic and historical data to test coordination between public transport, rail, and airport operators.</p>	<p>ORCHESTRA/ Milan Airport</p>	<p>Milan, Italy/ Network-wide/ Real + Simulated</p>	<p>Simulation results confirmed the MTME tool's effectiveness in managing major disruptions and generating alternative multimodal travel plans. KPIs included macro travel time delay, queue length, waiting/transfer ratios, and missed flights.</p>	<p>Integration proved technically feasible but limited by the lack of real-time data, stakeholders highlighted benefits for safety, resilience, and congestion reduction and supported continued data-sharing collaboration</p>
<p>Urban Traffic Management in Athens</p>	<p>Use of transit signal priority and the dynamic utilisation of bus lanes to enhance service efficiency, reduce congestion, and optimise the overall performance of the urban mobility network</p>	<p>CONDUCTOR/ NTUA</p>	<p>Athens, Greece/ Network-wide/ Simulated</p>	<p>11% reduction on passenger travel times and 19% reduction on vehicle travel times, ETA accuracy improved by 12.35%, >11% reduction in emissions, 11% reduction in fuel consumption</p>	<p>Reduced operational costs associated with public transport operations</p>

<p>Urban Traffic Management in Madrid</p>	<p>Management of planned and unplanned events to support the recovery of optimal transport network operations, with a particular emphasis on the integration of Connected and Automated Vehicles</p>	<p>CONDUCTOR/ Aimsun</p>	<p>Madrid, Spain/ Network-wide/ Simulated</p>	<p>45% CAV penetration is suggested as the optimal threshold for balanced performance improvements for both planned and unplanned scenarios, Mean queues are reduced by 9%–15%, 2% reduction in travel times</p>	<p>Confirmed the potential of CV-based rerouting strategies to enhance network resilience and accelerate recovery under mixed-traffic conditions</p>
<p>Freight Signal Priority for Sustainable Logistics</p>	<p>Assess the impact of freight signal priority through intelligent traffic light controllers equipped with CCAM functionalities</p>	<p>CONDUCTOR/ UT</p>	<p>Almelo, Netherlands/ Corridor-wide/ Real</p>	<p>Smoother freight flows with fewer stops and reduced idling</p>	<p>Improved freight traffic efficiency without compromising other users' service</p>
<p>Cross-border Shuttle Optimization (Slovenia, Italy, Croatia, Austria)</p>	<p>A Demand Responsive Transport System spanning across Slovenia, Croatia, Italy and Austria aiming to improve underserved links between urban centers and major airports</p>	<p>CONDUCTOR/ GoOpti</p>	<p>Slovenia, Italy, Croatia, Austria/ Network-wide/ Real + Simulated</p>	<p>Optimization is creating plans with less kilometers, 8,7 % decrease of average fuel consumption</p>	<p>The DRP achieved a substantial reduction in manual planning effort, improved operational efficiency confirming its technical maturity and suitability for real-time automated operation.</p>
<p>Urban Logistics in Madrid</p>	<p>Coordination and integration strategies for urban last mile delivery of parcels and DRT-CCAM services, leveraging the periods of lower demand of DRT-CCAM services for urban parcel delivery</p>	<p>CONDUCTOR/ NOMMON</p>	<p>Madrid, Spain/ Network-wide/ Simulated</p>	<p>Increase in the DRT-CCAM fleet utilization rate, 9.1% reduction in the idle trips, reduces the travelled times in both demand scenarios (by 4% and 2% resp.</p>	<p>Enhanced fleet utilization</p>
<p>Madrid Case Study</p>	<p>Integrating urban last-mile parcel delivery with public transport services to reduce delivery-related traffic during off-peak hours as well as designing alternative transportation services, such as Shared Mobility or Demand Responsive Transport services, to complement public transport in areas and time periods where they are suitable, both for passenger and parcel transportation</p>	<p>SYNCHROMODE / NOMMON</p>	<p>Madrid, Spain/ Network-wide/ Simulated</p>	<p>No Reported Results Yet, KPIs include Reduction of average travel times of over 10% for those using DRT services. Reduction of average waiting times of over 30% for those using DRT services, Reduction in distance travelled by logistic delivery agents of over 20%, Reduction of last-mile logistic operators' shipping costs by 10%, Reduction of emissions coming from last-mile delivery vehicles by 40%</p>	<p>No Reported Results Yet</p>
<p>Dutch Case Study</p>	<p>Enhance regional mobility by optimizing the availability of existing infrastructure, stimulating sustainable mobility behavior, bringing together programming, traffic and mobility management, embracing innovation and data-driven solutions, fostering closer regional</p>	<p>SYNCHROMODE / MAPTM</p>	<p>Province of South Holland, Netherlands/ Network-wide/ Real + Simulated</p>	<p>No Reported Results Yet, KPIs include: Reduction of traffic congestion, Reduction of accidents, Improve predictability of the network, Increase level of service of public transportation</p>	<p>No Reported Results Yet</p>

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Thessaloniki Case Study	<p>cooperation, and forging ties with neighboring regions and countries</p> <p>City-scale simulation of multimodal and MaaS coordination, using FCD and MFD frameworks to improve resilience and environmental performance</p>	SYNCHROMODE / CERTH-HIT	Thessaloniki, Greece/ Network-wide/ Simulated	No Reported Results Yet , KPIs include: Travel time reduction, Capacity increase, Emission reduction	No Reported Results Yet
Madrid Use Case	Multimodal transport for a Sustainable Last Mile Delivery (LMD) supported by blockchain for sharing economy in the e-commerce Channel	DELPHI/ DHL	Madrid, Spain/ Network-wide/ Real	No Reported Results Yet	No Reported Results Yet
Attica Use Case	Integrated freight and passengers' models and data sharing framework in the Attica region	DELPHI/ ATD	Attica, Greece/ Network-wide/ Real	No Reported Results Yet	No Reported Results Yet
Mykonos Use Case	Integrated freight and passengers' models and data sharing framework at the island of Mykonos	DELPHI/ ICCS	Mykonos, Greece/ Network-wide/ Real	No Reported Results Yet	No Reported Results Yet
Cluj-Napoca Use Case	Integrated passengers' models and data sharing governance framework in the Cluj-Napoca Metropolitan Area	DELPHI/ MCN	Cluj-Napoca, Romania/ Network-wide/ Simulated	No Reported Results Yet	No Reported Results Yet
Athens Pilot	Design, implement, and test an innovative holistic mobility platform with the capability to provide transport/traffic analytics, make multimodal short-term traffic predictions (private car and public transport), and provide a simulation/decision making tool for the transport authorities	ACUMEN/ DAEM	Athens, Greece/ Network-wide/ Simulated	No Reported Results Yet	No Reported Results Yet
Helsinki Pilot	Offering incentives and nudges for adopting sustainable modes of transportation, including walking, cycling, e-scooter, and utilizing public transport and other sustainable demand-responsive transport services	ACUMEN	Helsinki, Finland/ Network-wide/ Simulated	No Reported Results Yet	No Reported Results Yet
Amsterdam Pilot	Joint multimodal management to improve flexibility and resilience	ACUMEN/ AMS	Amsterdam, Netherlands/	No Reported Results Yet	No Reported Results Yet

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	when facing network disruptions		Network-wide/ Simulated		
Luxembourg Pilot	Demonstrate the impact of improving the seamless door-to-door travel by mass transit service	ACUMEN/ UniLu	Contern and Esch-sur-Alzette, Luxembourg/ Network-wide/ Real + Simulated	No Reported Results Yet	No Reported Results Yet
Developing and simulating of a Route Planner	A route planner simulation to facilitate CCAV usage by users from different social groups, enhancing inclusiveness. The plans will showcase alternatives based on real-time traffic information suitable to the user's preferences.	IN2CCAM/ Comune Di Bari, POLIBA	Bari, Italy/ Subnetwork level/ Simulated	Reduction in last-mile delivery costs and emissions. Supports greener logistics and better traffic fluidity in dense urban areas, Enhances competitiveness for businesses through faster deliveries..	Anticipated user acceptance based on workshops; feasibility supported by detailed AI simulation tools and adaptive routing for diverse passenger needs, including disabilities
Innovative urban freight transport and logistics	Simulate and perform a digital twin for new urban freight transport and last-mile logistics to reduce vehicle circulation in urban areas	IN2CCAM/ Comune Di Bari, POLIBA	Bari, Italy/ Subnetwork level/ Simulated	Reduced delivery completion times, fewer empty miles, optimized routing, and reduced vehicle circulation in urban areas. Data includes km driven, parcels/day, robot speed, and route efficiency	Feasibility evaluated using Digital Twin simulations. User acceptance and effectiveness to be assessed through planned surveys.
Integration of traffic and CCAM fleet (last mile mobility of people)	Integrate CCAM services with existing public transport using AV shuttles and Remote Operation Centre, enhancing last-mile connectivity and operational traffic efficiency	IN2CCAM/ VTT, Business Tampere	Tampere, Finland/ Network-wide (2000 drivers, 6300 kilometers with AVs transporting 2000 passengers)/ Real	Smoother last-mile transport, increased frequency of uninterrupted traffic light crossings (via GLOSA), reduced intersection crossing times, improved ROC-driven AV responses to hazards, and data sharing via ETSI-compliant messages	Early acceptance being evaluated via safety driver and stakeholder app usage
Remote monitoring and supervision of AVs fleet for safe and efficient operations, and real-time communication between vehicles and infrastructure	Showcase the operation of an automated shuttles fleet of Demand-Responsive Transport (DRT) service to connect a suburban area with the city centre, facilitating the mobility of workers who live in this peripheral area and other vulnerable groups	IN2CCAM/ e-Trikala, ICCS	Trikala, Greece/ Network-wide (2 automated minivans, SAE level 4)/ Real	Travel time reductions, increased uninterrupted traffic light crossings, improved AV speed adaptation, enhanced VRU safety	Demonstrates feasibility of multimodal, integrated AV deployment in a mid-sized city. Stakeholder support (municipality, PTOs, university, telecom) strong. Scenarios confirm scalability potential with larger fleets and integration into MaaS. VRU protection and user acceptability prioritized. Regulatory alignment ensured.
Dynamic traffic management	Implementation and simulation of dynamic re-routing strategies in urban traffic, integrating connected and automated vehicles (CAVs), real-time traffic data, parking availability, and Urban Vehicle Access Restrictions	IN2CCAM/ 5T, ITS Italia, LINKS	Turin, Italy/ Network-wide (1 automated minivan of SAE level 3 for at least 10 people)/ Real + Simulated	Improved traffic flow, reduced travel times and emissions with dynamic re-routing; green-light crossing frequency increased with traffic light priority. Benefits grew with more CAV fleets	High potential for real-world implementation, C-ITS standards (ETSI, DATEXII) support interoperability, feasibility dependent on CAV fleet size and communication infrastructure

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<p>Mutual awareness between CCAM fleet, infrastructure, and other users</p>	<p>(UVARs). Uses SUMO-based traffic simulation and real shuttle with RSUs and C-ITS messages.</p> <p>A data interchange framework enabling real-time bidirectional communication between CCAM vehicles (SAE L3-4), emergency vehicles (ITS-G5), human-driven cars (via Vigo Driving App), and the city's traffic infrastructure, using ETSI-compliant C-ITS services to increase mutual awareness and traffic efficiency.</p>	<p>IN2CCAM/ 5T, ITS Italia, LINKS</p>	<p>Vigo, Spain/ Single lane (2 CAV of SAE level 3-4)/ Real + Simulated</p>	<p>Successful real-time data exchange between vehicles and infrastructure using ETSI-standard messages, improved situational awareness and proactive event detection,</p>	<p>High system interoperability via ETSI standards, strong feasibility due to mature infrastructure (C-ITS, fiber network, cameras, RSUs)</p>
<p>Management strategy adapted to CCAM based on V2I interaction</p>	<p>Implementation of traffic light priority and adaptive control strategies in defined CCAM corridors to improve the flow and safety of automated vehicle fleets. Includes simulation and real-world testing of green phase extension, platooning management, emergency vehicle interaction, and dynamic rerouting based on traffic loads.</p>	<p>IN2CCAM/ 5T, ITS Italia, LINKS</p>	<p>Vigo, Spain/ Single lane (2 CAV of SAE level 3-4)/ Real + Simulated</p>	<p>Reduced stop-and-go events and improved average speed, better platoon integrity via green light extension, improved safety at complex intersections through proactive interaction with emergency vehicles, decreased travel time and balanced traffic loads through dynamic rerouting</p>	<p>Technically feasible due to mature ITS infrastructure and full interoperability using ETSI standards</p>
<p>Simulation of CCAM impact on traffic flow and potential congestion in urban and peri-urban areas</p>	<p>Simulations that analyse the environmental and demographic impact of traffic flow and congestion. The data gathered include information about historical travel itineraries samples for simulation, road infrastructure data, public transport and schedules for multimodal integration</p>	<p>IN2CCAM/ ubiwhere, Quadrilátero</p>	<p>Guimarães, Portugal/ Network-wide/ Simulated</p>	<p>Impacts measured across travel times, congestion, LoS, emission reductions, service design efficiency, integration of CCAM and public transport options analysed for deployment optimization</p>	<p>Simulation platform demonstrated capability for multi-scenario urban planning, strong potential for city-level mobility decision support, public acceptance and flexibility assessed via surveys</p>
<p>Multi-operator data governance ecosystem for bus fleets and demand-responsive transport</p>	<p>Enhance the Multi-Fleet Operation and Information System (SAEi) system, a next-generation multi-fleet management and passenger information system for regional public transportation.</p>	<p>deployEMDS / i2CAT Foundation</p>	<p>Barcelona / metropolitan area and surrounding counties / Real</p>	<p>No Reported Results Yet. Expected Results: Improved transportation planning and passenger experience while reducing costs.</p>	<p>No Reported Results Yet</p>
<p>Forecasting system to optimise traffic based on vehicle flow and air quality</p>	<p>Enhance usage of sensor data, both in the city of Barcelona and along the ring road.</p>	<p>deployEMDS / Eurecat</p>	<p>Barcelona / City and the surrounding primary road system / Real</p>	<p>No Reported Results Yet. Expected Results: Improved traffic management and higher transportation efficiency</p>	<p>No Reported Results Yet</p>

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<p>Multimodal connectivity and route planning integration with BudapestGO</p>	<p>Develop a flexible, multimodal route planning system integrated with the BudapestGO platform.</p>	<p>deployEMDS / Urban Institute Hungary</p>	<p>Budapest / City and its suburban agglomeration / Real</p>	<p>No Reported Results Yet. Expected Results: Robust multimodal route planning system</p>	<p>No Reported Results Yet</p>
<p>MaaRLiM – Mobility as a Right for people with Limited Mobility</p>	<p>Develop a service integrating personal mobility data and accessibility features with the goal to support multimodal mobility services for individuals with limited mobility.</p>	<p>deployEMDS / Urban Institute Hungary</p>	<p>Budapest / City and its surrounding suburban agglomeration / Real</p>	<p>No Reported Results Yet. Expected Results: Enhanced mobility options for people with limited mobility</p>	<p>No Reported Results Yet</p>
<p>Optimising the (re-)use of traffic measurements</p>	<p>Enhance traffic data usability and integration across regions</p>	<p>deployEMDS / imec, Digital Vlaanderen</p>	<p>Flanders / Region of Flanders / Real</p>	<p>No Reported Results Yet. Expected Results: easily accessible and utilizable traffic data for Flemish data consumers through user-friendly interfaces. Additionally answers to the generalization of Sustainable Urban Mobility Indicators and simulation are expected to be found.</p>	<p>No Reported Results Yet</p>
<p>MaaS for companies – A MaaS platform that facilitates the attribution of mobility credit for employees.</p>	<p>Develop a MaaS platform that helps companies manage and optimise mobility packages for employees, providing tools for trip planning, payment as well as carbon footprint tracking.</p>	<p>deployEMDS / Instant System</p>	<p>Île-de-France / Île-de-France region / Real</p>	<p>No Reported Results Yet. Expected Results: Improved management of mobility benefits, encouragement of sustainable travelling, and overall employee satisfaction</p>	<p>No Reported Results Yet</p>
<p>Journey planner optimisation – Sharing MaaS usage data and improve the itinerary planner with AI models exploiting user’s travel’s preferences</p>	<p>Improve journey planning by using data and AI to offer better travel options and making sure this data is easy to use across different platforms.</p>	<p>deployEMDS / Instant System</p>	<p>Île-de-France / Île-de-France region / Real</p>	<p>No Reported Results Yet. Expected Results: more accurate and user-friendly travel planning by improving recommendations and ensuring that data is consistently useful while prioritising user privacy.</p>	<p>No Reported Results Yet</p>
<p>Enhancing seamless route planning</p>	<p>Utilise existing as well as newly generated data to improve door-to-door navigation for People with Reduced Mobility (PRM) and provide detailed information for decision-makers</p>	<p>deployEMDS / Lisbon’s Municipal Company for Mobility and Parking</p>	<p>Lisbon / City / Real</p>	<p>No Reported Results Yet. Expected Results: streamlined access to meaningful information for the city’s decision-makers and fostered innovation by third parties, enabling them to enhance and develop applications and solutions tailored to PRM needs.</p>	<p>No Reported Results Yet</p>

<p>Increasing the attractiveness of alternative mobility solutions – Corporate MaaS</p>	<p>Reduce car dependency in work commuting and business travel. Alternative mobility solutions are become more attractive by making transport service and infrastructure data interoperable and usable for multimodal digital mobility service providers and corporate mobility management providers.</p>	<p>deployEMDS / Lisbon's Municipal Company for Mobility and Parking</p>	<p>Lisbon / City / Real</p>	<p>No Reported Results Yet. Expected Results: reduced car dependency</p>	<p>No Reported Results Yet</p>
<p>Increasing schedule reliability and/or commercial speed of buses</p>	<p>Increase the schedule reliability and commercial speed of buses by identifying and resolving transportation conflicts that slow down bus travel.</p>	<p>deployEMDS / Transportes Metropolitanos de Lisboa</p>	<p>Lisbon Metropolitan Area / 18 municipalities of the Lisbon Metropolitan Area / Real</p>	<p>No Reported Results Yet. Expected Results: improved communication of bus schedules and estimated times of arrival (ETA) to passengers</p>	<p>No Reported Results Yet</p>
<p>Decision support system for local public transport services planning</p>	<p>Optimise Milan's local public transport (LPT) network and services through a Decision Support System (DSS). Through the establishment of a local data space, multiple data sources will be shared and integrated to build algorithms and analysis models.</p>	<p>deployEMDS / AGENCY FOR THE LPT OF THE MILAN METROPOLITAN CITY, MONZA AND BRIANZA, LODI AND PAVIA BASIN</p>	<p>Metropolitan City of Milan and the provinces of Monza and Brianza, Lodi and Pavia / Real</p>	<p>No Reported Results Yet. Expected Results: streamlined LPT planning in Milan, improved efficiency and sustainability while meeting the city's mobility demands</p>	<p>No Reported Results Yet</p>
<p>MaaS-based mobility scenarios</p>	<p>Model future zero-emission mobility scenarios in Milan to support the transition to sustainable transportation through Mobility as a Service (MaaS) systems, facilitated by the development of EMDS.</p>	<p>deployEMDS / AGENCY MOBILITY ENVIRONMENT AND TERRITORY</p>	<p>Milan / City / Real and Simulated</p>	<p>No Reported Results Yet. Expected Results: Refinement of future zero-emission mobility scenarios, citizen support for the transition to sustainable transportation</p>	<p>No Reported Results Yet</p>
<p>Connected Green & Shared Mobility Journeys (GreenMob)</p>	<p>Develop a multimodal journey planner for Sofia, integrating various transportation modes into a seamless user experience while optimising for carbon footprint and providing a single payment method.</p>	<p>deployEMDS / GATE Institute</p>	<p>Sofia / City / Real</p>	<p>No Reported Results Yet. Expected Results: Efficient planning and booking of multimodal trips, reduce reliance on private cars and improving traffic and air quality issues</p>	<p>No Reported Results Yet</p>
<p>Implementing and monitoring zero emission zones and reduction of car traffic</p>	<p>Enhance evaluation of Stockholm's zero-emission zone by integrating and sharing high-quality data through the Stockholm Mobility Data Space (SMDS).</p>	<p>deployEMDS / RISE Research Institutes of Sweden AB</p>	<p>Stockholm / zero-emission zone in the centre of the City of Stockholm / Real</p>	<p>No Reported Results Yet. Expected Results: better environmental policymaking and improved data accessibility</p>	<p>No Reported Results Yet</p>
<p>Collection of data, mandated by</p>	<p>Provide harmonised data to the National Access Point (NAP) and EMDS,</p>	<p>deployEMDS / VTT Technical</p>	<p>Tampere / City / Real</p>	<p>No Reported Results Yet. Expected Results: smooth travel experiences and</p>	<p>No Reported Results Yet</p>

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<p>the ITS directive, and interface to the NAP</p>	<p>ensuring stakeholders can access and use Finnish transport data to develop services that meet end users' needs.</p>	<p>Research Centre of Finland Ltd</p>		<p>service expansion across Finland and Europe</p>	
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