CARMONY System of systems requirements and specifications

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1. Executive Summary

This deliverable describes the work in tasks 2.2 and 2.3 of CARMONY. It starts by presenting background materials on traffic orchestration followed by a literature review of the state of the art in traffic orchestration, including outlooks to other application domains. First versions of system of systems models of the CARMONY use cases are then given, followed by the results of task 2.3 on data exchange requirements and HMI specifications and requirements. The summary of the report also contains a first definition of the interlinked orchestrators in CARMONY.

The main results of the work are the understanding of the state of the art in orchestration, the data exchange requirements, the HMI specifications and the first versions of UC models.

The outputs will be used and further refined in future CARMONY work in WPs 3, 4, and 5. UC models will be further refined in T4.2.

Keywords: Traffic orchestration, data exchange, user interfaces, systems of systems;

2. Objectives

CARMONY task 2.2 had the objective to define the interlinked orchestrator, review the current state of the art in traffic orchestration, and provide system of systems models for the use cases. This contributes to establishing a common base in the project for how to discuss different actors and actor roles and how they interact and links directly to the overall objectives of the CARMONY project to improve traffic efficiency, safety and sustainability.

Task 2.3 had the objective to define the requirements for data exchange for the CARMONY interlinked orchestrator and for the use case demonstrations.

An important part of the work is to understand the meaning of the word orchestration and the different levels that the CARMONY interlinked orchestrator will work on. Importantly, orchestration is not necessarily the same as ordering. The traffic system is an emergent system where the effects are non-linear and cannot be easily analysed in advance. This means that simulations are required, and that the possibility that events do not proceed as planned must be taken account of. Table 1 shows definitions of orchestration in different domains. More details on orchestration are in chapters 3,4, 5, and 8 of this report.

Table 1. Definitions of orchestration in different domains.

Domain	Definition	Source
Music	Orchestration is the study or practice of writing music for an orchestra (or, more loosely, for any musical ensemble, such as a concert band) or of adapting music composed for another medium for an orchestra. Also called "instrumentation", orchestration is the assignment of different instruments to play the different parts (e.g., melody, bassline, etc.) of a musical work	Wikipedia[1]
Computing	In system administration, orchestration is the automated configuration, coordination deployment development, and management of computer systems and software.	Wikipedia[2]
Pervasive games	Gamemastering, sometimes referred to as Orchestration is used in pervasive games to guide players along a trajectory desired by the game author. To ensure proper gamemastering can take place, four components are needed: some kind of sensory system to the game allowing the game masters to know current events, providing dynamic game information; dynamic and static game information lets game masters make informed decisions; decisions need to be actuated into the game, either through the game system or through	Wikipedia[3]

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[1] https://en.wikipedia.org/wiki/Orchestration
[2] https://en.wikipedia.org/wiki/Orchestration_(computing))
[3] https://en.wikipedia.org/wiki/Gamemaster#In_pervasive_games

Domain	Definition	Source
	manual intervention; and finally a communication structure is needed for both diegetic or non-diegetic communication.	
Air traffic management	In this context, orchestration can be defined as the structured coordination of distributed human and machine agents so they can jointly perform a task as a coherent whole, under shared rules and negotiated authority.	Boy, The Orchestra: A Conceptual Model for Function Allocation and Scenario based Engineering in Multi-Agent Safety-Critical Systems, Proceedings of the European Conference on Cognitive Ergonomics, 2009
UAV swarns coordination	Consider the multi-UAV system in terms of a choir or an orchestra. In such a metaphor, DRONES map onto SINGERS, the DRONE OPERATOR becomes the CHOIR CONDUCTOR, the MISSION is equivalent to the SONG, and so on. Like team members, choir singers are highly skilled and have different responsibilities, but they are divided into subgroups singing different harmonies of the song. They must pay close attention to sing in sync with their subgroup as well as the rest of the choir. Naturally, they must know the parts of the song and their role in it. In this metaphor, the individual singer is less critical than in a team, but also less expendable than in a swarm, sitting somewhere in between. While the composer orchestrates the piece and its harmonies, the conductor guides the choir throughout their performance. The conductor sets the tempo for the entire choir and, using gaze, body language, and special signs, communicates with and instructs the entire choir, any of its harmonic subgroups, or even individual singers to pay closer attention or modulate their singing. In a multi-UAV system, the drones could keep a local copy of the mission (like sheet music) in case they lose data connection links with ground control (analogous to forgetting the lyrics).	Bjurling, O., Arvola, M., Ziemke, T., (2021), Swarms, teams, or choirs?: Metaphors in multi-UAV systems design, Advances in Human Factors in Robots, Unmanned Systems and Cybersecurity

3. Traffic orchestration

3.1 Traffic Orchestration through a System-of-Systems Approach

Modern mobility ecosystems are becoming increasingly complex, involving diverse actors, technologies, and infrastructures that must work together seamlessly. Traffic orchestration using a System-of-Systems (SoS) approach provides a framework for jointly coordinating these independent systems to achieve efficiency, safety, and sustainability. Rather than operating as isolated systems, vehicles, traffic management centres, infrastructure, and service providers interact dynamically, forming an interconnected network in which decisions and actions are distributed across multiple stakeholders.

A key aspect of orchestration is the ability to influence or direct behaviour within this SoS network. In emergency situations, traffic management authorities often have the legal mandate to issue binding instructions, such as clearing lanes for emergency vehicles or rerouting traffic during critical incidents. These actions rely on established governance structures and regulatory frameworks that grant public agencies decision-making authority.

However, during normal day-to-day operations, the situation is more nuanced. Traffic management typically cannot compel vehicles to follow specific routes or behaviours. Instead, it provides guidance and recommendations, supported by incentive structures and business models that encourage compliance. Examples include dynamic speed advisories, carpool lane reservations, and eco-routing suggestions. These measures depend on cooperation rather than enforcement, leveraging trust, transparency, and mutual benefits to align stakeholder interests.

The question of “who can give orders” in transport systems is therefore context dependent. In emergencies, public authorities and law enforcement hold clear mandates to instruct others. In routine operations, governance frameworks, contractual agreements, and market-based incentives shape interactions between actors such as fleet operators, mobility service providers, and individual drivers. This layered approach ensures flexibility while maintaining safety and resilience.

The CARMONY project illustrates this concept through six diverse use cases across urban and highway environments in Spain, Luxembourg, and cross-border regions. Each scenario, from emergency corridor activation to congestion prevention, demonstrates how orchestration can balance directive authority with collaborative engagement, creating a mobility ecosystem that is adaptive, efficient, and user-centric.

3.2 Traffic orchestration layers

Traffic systems orchestration is complex, and this complexity creates challenges in maintaining safety, efficiency, and sustainability. Local, short-term decisions such as rerouting vehicles can have unintended consequences if they are not aligned with broader traffic objectives. To avoid systemic inefficiencies, traffic orchestration must therefore operate across multiple time horizons, ensuring that real-time actions, short-term goals, mid-term strategies, and long-term governance reinforce each other.

As illustrated in Figure 1, CARMONY structures the orchestration into different complementary layers.

First, we have the preventive and reactive layers, which focuses on real-time, short-term decisions to ensure immediate actions prevent congestion and maintain flow. It also evolves operational guidelines through simulations, improving resilience and adaptability – this is the preventive layer part.

Secondly, we have the governance layer that operates at the strategic level and builds trust and compliance among stakeholders. It uses long-term simulations and incentive mechanisms to demonstrate collective benefits, ensuring that actors follow the orchestrator’s guidelines.

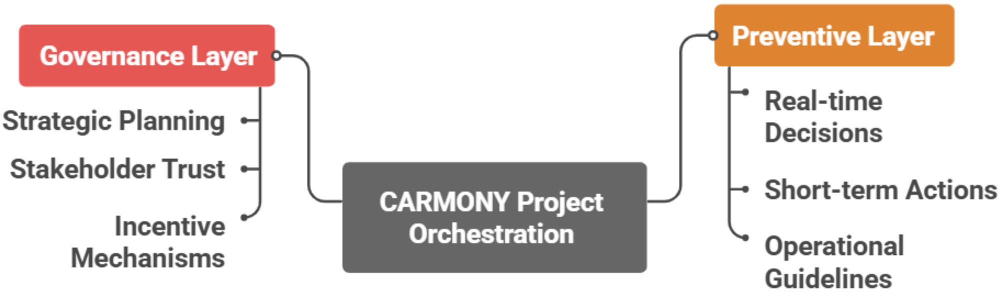

Figure 1. Overarching Orchestration Structure

3.3 Traffic Orchestration Time-Scales

We have identified that traffic orchestration in CARMONY spans four distinct time scales, each with specific objectives and methods. These are illustrated in Figure 2 and described in the following sub-sections.

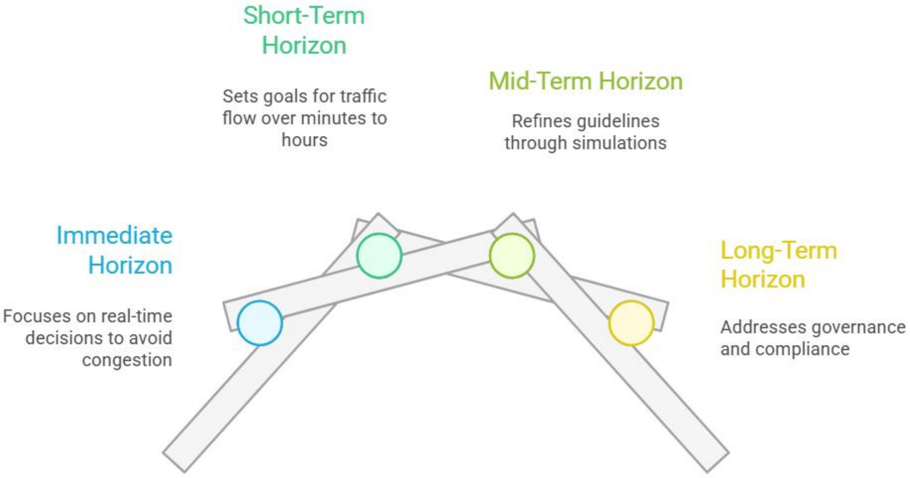

Figure 2. Four different Traffic Management Time Scales

3.3.1 Immediate Horizon

At the immediate horizon, which covers the *next fifteen minutes*, the system focuses on determining what vehicles should do to achieve their short-term objectives. This involves real-time decision-making based on current traffic conditions and predefined guidelines. For example, vehicles may be instructed to adjust their speed or change lanes to avoid congestion hotspots detected by sensors. These actions are part of the reactive layer, which ensures rapid and responsive interventions to maintain stability in the traffic system.

The immediate horizon focuses thus on rapid, real-time actions to maintain smooth traffic flow, which is illustrated in Figure 3. The cycle begins with monitoring traffic conditions through sensors that collect data on flow and congestion. This data is analysed to identify potential issues, enabling the system to make quick decisions on how to mitigate congestion. Once decisions are made, actions such as adjusting vehicle speed or changing lanes are implemented. Finally, the effectiveness of these actions is evaluated to ensure they have the desired impact on traffic performance. This continuous loop allows the system to respond dynamically to changing conditions within minutes.

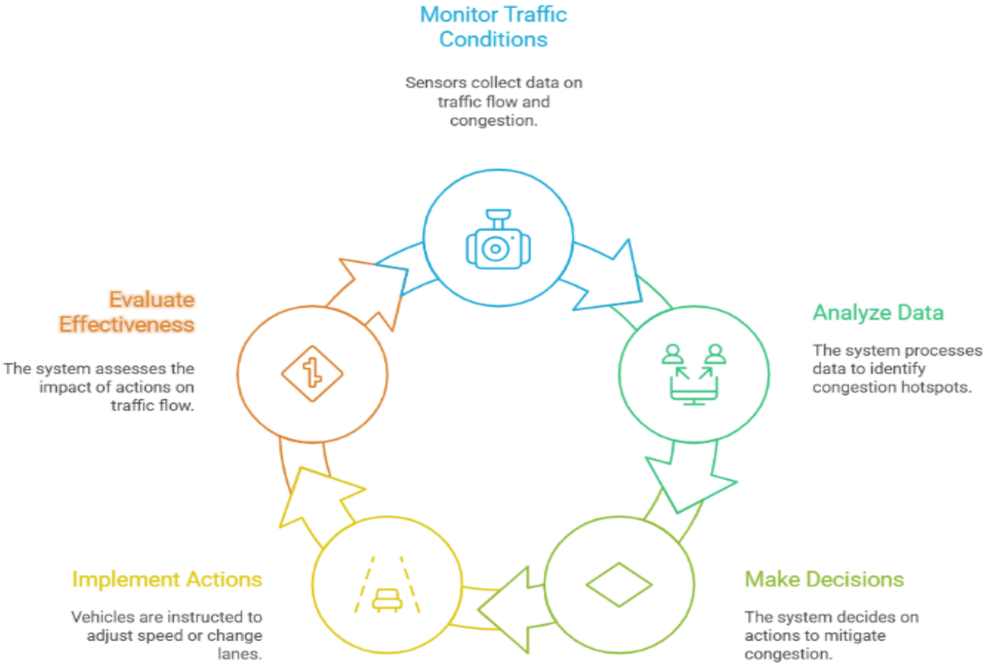

Figure 3. Immediate Traffic Management Cycle

3.3.2 Short-term Horizon

With a short-term horizon, the emphasis shifts from individual actions to setting collective goals for traffic over *several minutes to an hour*. Here, the orchestrator defines objectives such as maintaining a minimum average speed across a corridor during peak hours. Vehicles receive guidelines that prioritise overall throughput rather than individual travel time, ensuring that local decisions align with system-wide objectives. This level of orchestration belongs to the preventive layer, as it seeks to prevent congestion and inefficiencies before they occur.

As illustrated in Figure 4, the short-term orchestration of traffic flow starts by setting goals and guiding vehicle actions. The cycle begins with defining objectives for traffic, such as maintaining smooth flow or reducing congestion in specific areas. These goals are translated into clear guidelines that are communicated to vehicles, ensuring consistent behaviour across the system. Local decisions are then aligned with these objectives so that individual actions support overall traffic performance. Finally, proactive measures are taken to prevent congestion before it occurs, creating a dynamic and responsive system that balances immediate needs with short-term goals.

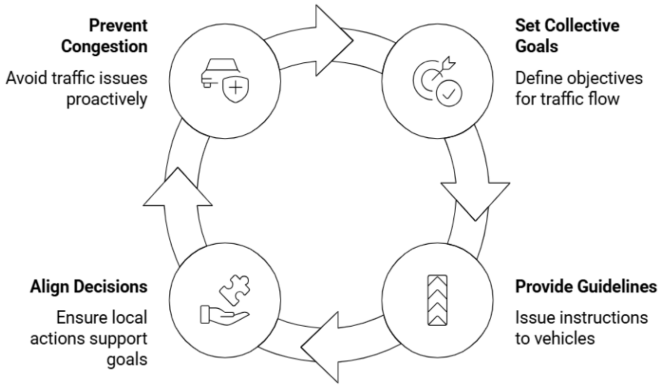

Figure 4. Short-Term Traffic Management Cycle

3.3.3 Mid-term Horizon

The mid-term horizon spans *hours or even days* and focuses on evolving the guidelines that govern immediate actions. This is achieved through simulations and scenario analyses that explore different strategies for recurring traffic challenges. For instance, simulations may be used to determine optimal lane-allocation strategies for mixed traffic comprising autonomous and human-driven vehicles during rush hour. By refining these guidelines, the system ensures that real-time decisions are informed by robust and tested approaches rather than ad hoc rules. This process strengthens the preventive layer by making it more adaptive and resilient.

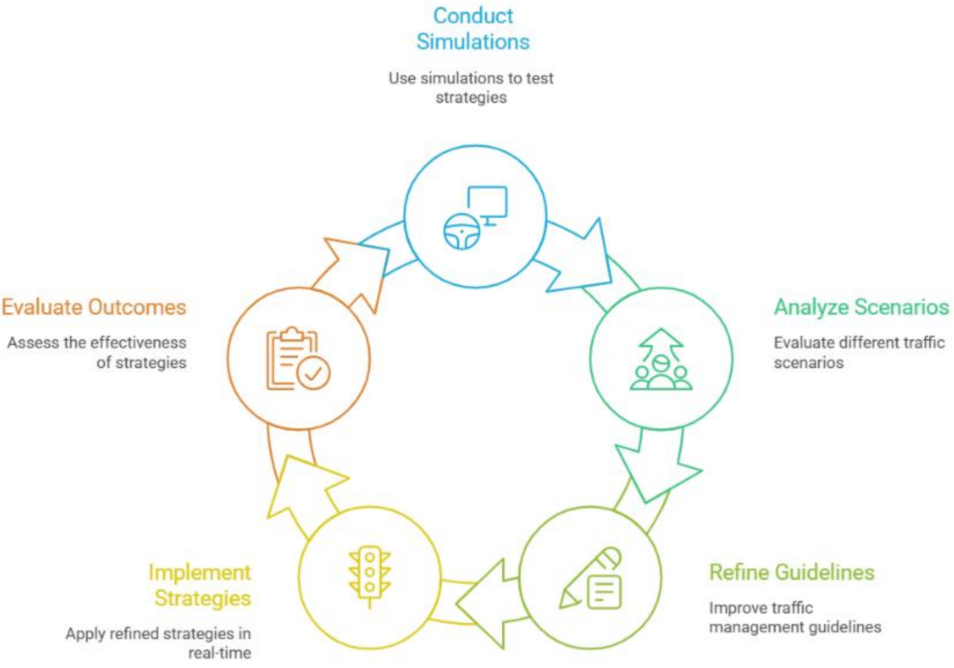

Figure 5. Mid-Term Traffic Management Cycle

Taken together, the mid-term horizon focuses on improving traffic management strategies through an iterative process of analysis and refinement, which is illustrated in Figure 5. It begins with conducting simulations to test different approaches under varying conditions. These simulations provide insights that allow the evaluation of multiple traffic scenarios, helping identify effective strategies. Based on these findings, guidelines are refined to improve decision-making in real-time operations. The updated strategies are then implemented in practice, and their effectiveness is assessed through outcome evaluations. This continuous cycle ensures that traffic management evolves based on evidence and experience, creating a system that is adaptive and resilient.

3.3.4 Long-term Horizon

The long-term horizon primarily addresses governance and compliance. At this scale, the orchestrator seeks to convince stakeholders to follow the guidelines by demonstrating the benefits of cooperation *over weeks or months*. Large-scale simulations are employed, e.g., showing that adherence to the orchestrator’s recommendations reduces congestion and emissions for all actors. This strategic perspective belongs to the governance layer, which emphasises trust-building, transparency, and the design of incentives that encourage compliance. By aligning technical orchestration with stakeholder interests, the governance layer ensures that the system remains sustainable and widely accepted.

The long-term horizon focuses thus on creating sustainable cooperation among stakeholders, and Figure 6 illustrates an example of such cooperation within the CARMONY project. The figure shows that the process begins by demonstrating the benefits of compliance through simulations that show positive outcomes, such as, reduced congestion and emissions. These results help build trust by establishing credibility and reliability. Once trust is in place, interests are aligned so that technical orchestration matches stakeholder needs. To strengthen cooperation further, incentives are designed to reward compliance. Together, these steps form a continuous cycle where evidence, trust, and incentives work hand in hand to ensure long-term acceptance of traffic orchestration.

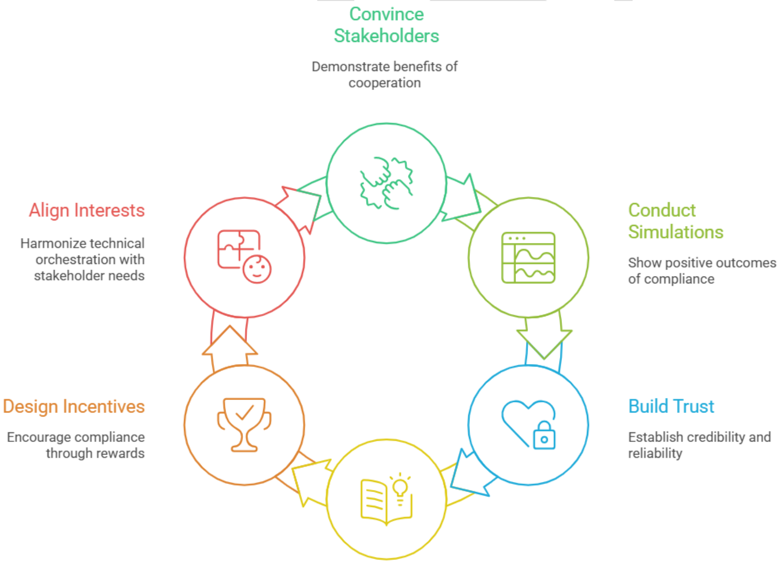

Figure 6. Cycle of Governance and Compliance

4. State of the art in Traffic Orchestration

4.1 The Literature Searching Process

In order to understand the state of the art and the practice of current traffic system orchestration, including identifying actors, roles, systems, and governance, we conducted a SotA literature review.

4.1.1 Goal and research questions (RQs)

Based on the CARMONY project scope, the study goal was to investigate the existing body of knowledge related to multi-actor traffic orchestration, with a special focus on conflict identification to ensure effective orchestration in complex traffic scenarios.

Based on our goal, we defined the following four main research questions (RQs):

- **RQ1**: What are the different levels of traffic orchestration, and what time-scales do they operate on?
- **RQ2**: How can integrated railway traffic management approaches enhance efficiency, reliability, and resilience in constrained rail networks?
- **RQ3**: What are the institutional and operational challenges of integrating upper and lower airspace governance in Europe?
- **RQ4**: What characterises orchestration in the military domain, and how does it relate to managing combined and joint forces?

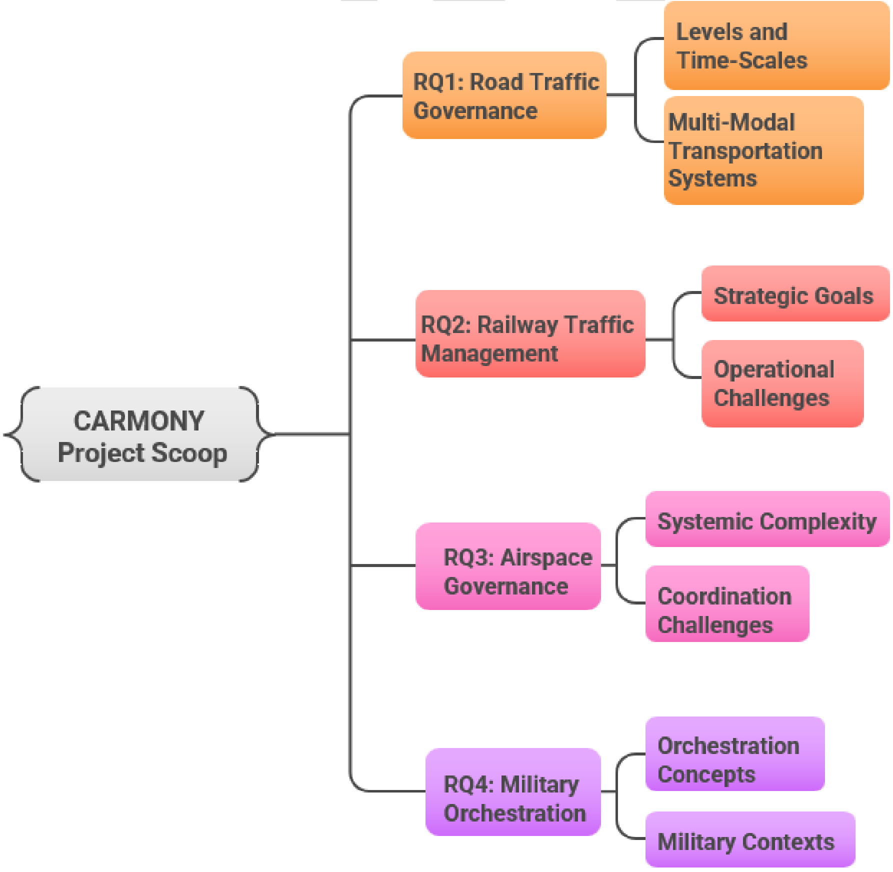

Figure 7. CARMONY Project Research Questions and Objectives

As illustrated in Figure 7, we have identified different objectives for each of the stated RQs.

The first research question examines how the investigated research papers address the evolution of European road traffic governance toward orchestrated coordination among institutions, regulations, and digital systems. Moreover, we also aimed to understand how traffic orchestration and management are carried out in different related multi-modal transportation systems, such as rail, airspace, and the military domain. In RQ2, we focus, e.g., on balancing strategic goals and operational challenges within the railway domain. In RQ3, we capture systemic complexity and coordination challenges within the European airspace domain, and in RQ4, we explain orchestration concepts in military contexts.

4.1.2 Search strategy

The search strategy outlines the key bibliographic sources and search terms, defines the inclusion and exclusion criteria, and describes the process used to select the studies that are included.

4.1.2.1 Search terms

As illustrated in Figure 8, the search strategy for our literature review was designed to find research related to orchestration and management in different transport domains. To make the search both broad and focused, we organised our keywords into two main groups: vertical categories and horizontal categories.

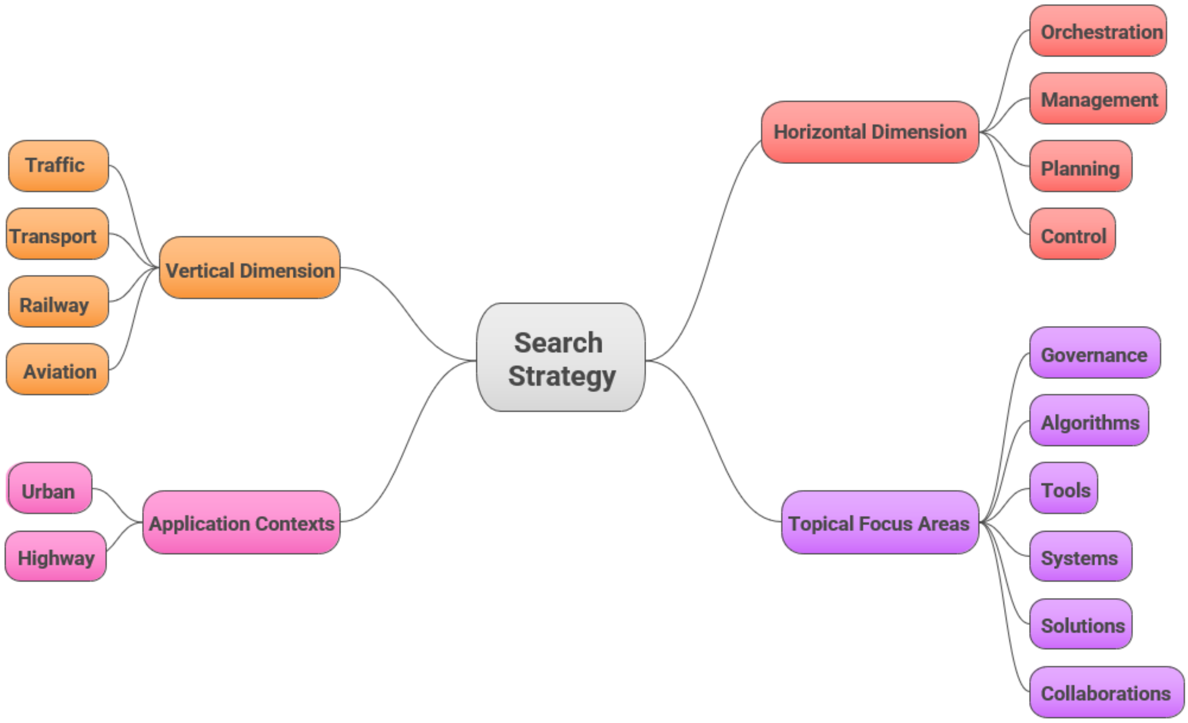

Figure 8. Search Strategy for Literature Review

The vertical categories represent the main transport areas we studied: *traffic*, *transport*, *railway*, and *aviation*. These four areas were chosen because they capture different parts of the transport system where orchestration and coordination are important. Including several domains also allowed us to compare how similar ideas are applied in different contexts.

The horizontal categories represent the main functions we focused on: *orchestration*, *management*, *planning*, and *control*. These terms cover both strategic and operational aspects of how complex transport systems are coordinated, both from long-term planning and governance to real-time traffic control perspective.

We also focused our search on two main contexts: *urban* and *highway* environments. These were selected because they represent two important but different types of transport settings where urban areas with multimodal and data-rich systems, and highways with large-scale, connected, and automated systems.

To make the search more precise, we added a set of supporting keywords, such as e.g. *governance*, *algorithms*, *tools*, *systems*, *solutions*, and *collaborations*. These helped us find studies that discuss both the technological and organisational sides of orchestration, including decision-making methods, digital tools, and coordination between actors.

4.1.2.2 Bibliographic sources

We selected the list of relevant bibliographic sources based on their relevance and coverage since these sources are recognised as the most representative in the CARMONY project scope domain and used in many publications. The list includes, e.g., ACM Digital Library, IEEEXplore, Science Direct, Scopus, Google Scholar, CiteSeer library, Inspec, Springer Link, etc. Moreover, we also performed a manual search in related EU (and horizon) projects.

4.1.3 Data extraction

We reviewed and extracted information from publications that were identified as relevant to our study. For each publication, we noted the main focus, application area, and key findings related to orchestration within the selected transport domains.

The collected material was then organised according to the structure of our Research Questions (RQs) to facilitate comparison of results and identification of common themes. This helped us see how different studies addressed similar challenges or perspectives across the domains of traffic, transport, railway, and aviation.

A summary of the extracted material and its connection to each research question is provided in the next section.

4.2 Results

The literature shows that, at the governance level, the road, rail, and aviation sectors share broadly aligned strategic objectives. Across all three domains, policies emphasise safety, interoperability, standardisation, and multi-stakeholder coordination under coherent European regulatory frameworks (Cordoș et al., 2025; Finger & Bert, 2022). These common goals reflect the maturity of European transport governance in promoting integration, sustainability, and technological harmonisation across modes.

At the traffic-management level, however, operational realities diverge. Both rail and aviation function within inherently limited-capacity networks, where safety-critical constraints demand continuous coordination, precision, and centralised control. Their management approaches rely on predictive planning, real-time supervision, and well-defined recovery strategies to maintain service regularity and restore planned operations after disturbances (Abril et al., 2008; Cacchiani et al., 2014).

In contrast, the road sector remains largely decentralised and reactive, dependent on individual driver behaviour rather than coordinated orchestration. As a result, roads act as passive infrastructure, unable to dynamically optimise throughput in response to fluctuating demand or disruptions. This limits the potential to implement professional, system-wide traffic management comparable to that of rail or aviation.

Recent research identifies emerging cooperative and automated technologies as a turning point for road transport. Cooperative Intelligent Transport Systems (C-ITS) and Connected, Cooperative and Automated Mobility (CCAM) enable real-time communication between vehicles, infrastructure, and control centres—creating the foundation for active, orchestrated road networks (C-Roads, 2023; ERTRAC, 2023; TM 2.0, Rehrl et al., 2020). Studies show that these systems improve traffic efficiency, safety, and environmental performance through data sharing and coordinated decision-making (C-ITS Platform, 2021; CCAM European Partnership, 2024).

This evolution marks a transition from individual, reactive driving toward a professional orchestration paradigm—where strategic, system-level decisions can be made dynamically to optimise safety and capacity utilisation in real time. In this context, the road domain could progressively approach the operational discipline and resilience long established in the rail and aviation sectors, realising a fully integrated, data-driven European mobility ecosystem.

- RQ1: What are the different levels of traffic orchestration, and what time-scales do they operate on?

Road traffic orchestration in Europe operates across two complementary levels: **European governance-level frameworks**, which define long-term strategic, regulatory, and institutional coordination across countries and stakeholders, and **road traffic management-level orchestration**, which functions on shorter operational time-scales to manage real-time traffic flows, system interactions, and data exchange among connected infrastructures and vehicles.

European governance-level frameworks

The governance of road traffic in Europe is evolving from traditional management toward orchestrated coordination among institutions, regulations, and digital systems. This transformation reflects the growing need to align public authorities, private service providers, and infrastructure operators within interoperable and data-driven frameworks.

Current literature highlights several key focus areas shaping the state of the art at governance level. First, institutional orchestration now combines multi-level governance and public–private cooperation through shared data standards and strategic EU frameworks (Cordoș et al., 2025). Second, data governance has become the cornerstone of mobility orchestration, supported by initiatives such as the European Mobility Data Space and National Access Points (Doulkeridis et al., 2024). Third, regulatory developments—notably the EU Data Act and Data Governance Act—are consolidating clear rules for interoperability and accountability in mobility data sharing (Andraško et al., 2021).

At operational level, the Traffic Management 2.0 paradigm promotes collaborative governance between public and private actors (Rehrl et al., 20216), while ongoing research points to persistent challenges in cross-border and multi-modal coordination (Al Sabouni et al., 2023). Additionally, emerging studies emphasise security-by-design approaches to ensure trust in cooperative ITS (Pavleska et al., 2025) and conceptual frameworks linking policy, data, and infrastructure into a cohesive governance model for smart mobility (Finger & Bert, 2022).

Overall, the European state of the art demonstrates a clear transition toward integrated, data-centric, and collaborative traffic governance, establishing the basis for future large-scale orchestration of connected and automated mobility systems.

Table 2. European governance areas

Focus area	State of the art	Reference
Governance = orchestration of institutions, rules, and data-sharing	Recent reviews frame European traffic/mobility governance as aligning multi-level public authorities with private actors via interoperable data and standards—beyond mere operations. This includes EU-level strategies (implemented nationally) and public–private coordination mechanisms.	Cordoș (2025)
Data governance is the linchpin	Mobility Data Spaces and National Access Points are identified as foundational governance instruments enabling lawful, trusted and interoperable data exchange across public and private actors. These frameworks underpin cross-actor orchestration through data stewardship, certification and sovereignty.	Doulkeridis et al (2024)
Legal and regulatory articulation is maturing	Analyses explore how mobility data sharing aligns with the EU Data Act and Data Governance Act. Governance is evolving toward clearly defined roles, compliance duties and interoperability obligations across Member States.	Andraško et al (2021)
From "management" to "collaborative governance" (TM 2.0 logic)	The TM 2.0 paradigm extends traffic management toward continuous collaboration between public authorities and private service providers, emphasising shared objectives, data exchange and co-decision frameworks rather than unilateral control.	Rehrl et al (2016)
Multi-modal and cross-border coordination remains a challenge	Studies highlight institutional fragmentation, heterogeneous standards and the absence of harmonised cross-border orchestration across transport modes, which limit integrated European mobility governance.	Al Sabouni et al (2023)
Security-by-design governance for cooperative systems	Cooperative ITS requires explicit architecture-based governance, defining roles, assurance and certification to guarantee trust and accountability in cross-organisational traffic orchestration.	Pavleska et al (2023)
Conceptual foundations of smart-transport governance	Theoretical work conceptualises governance as the institutional framework connecting digital infrastructure, policy and operations within smart mobility ecosystems, providing the foundation for orchestration at European scale.	Finger et al (2018)

Road traffic management-level orchestration

At the operational level, road traffic management orchestration refers to the dynamic coordination of systems, data, and actors to optimise network performance and ensure safe, efficient, and sustainable mobility. While governance frameworks provide the strategic and regulatory foundation, traffic management orchestration translates these principles into real-time, data-driven decision-making across infrastructures and vehicles. This level of orchestration operates on shorter time-scales—ranging from seconds to hours—and involves the continuous adaptation of control strategies in response to evolving traffic conditions.

Current research and demonstration projects highlight several key focus areas shaping the state of the art at the traffic management level. First, the evolution from traditional Traffic Management Systems (TMS) toward cooperative and predictive management architectures is evident. The Traffic Management 2.0 (TM 2.0) concept embodies this transition, promoting active collaboration between road authorities, service providers, and connected vehicles through data sharing and co-decision mechanisms (Rehrl et al., 2020).

Second, the integration of Cooperative Intelligent Transport Systems (C-ITS) and Vehicle-to-Everything (V2X) communication technologies enables a finer temporal and spatial resolution in traffic control. This real-time data exchange supports adaptive signal control, incident detection, and demand-responsive routing—key capabilities for orchestrated management of complex transport networks (Pavleska et al., 2025).

Third, the use of AI-based decision support systems is transforming operational orchestration. Predictive models leveraging floating car data, connected vehicle information, and historical traffic patterns are increasingly used to anticipate congestion, manage disruptions, and balance traffic loads (Doulkeridis et al., 2024). Such systems represent a shift from reactive management to proactive orchestration.

Despite these advances, the literature identifies persistent integration and interoperability challenges. Many national and regional systems remain fragmented, with limited harmonisation of data formats, performance indicators, and communication standards (Al Sabouni et al., 2023). This fragmentation hampers the emergence of a truly orchestrated European network capable of seamless, cross-border operations.

Finally, new frameworks emphasise the importance of human–machine collaboration and ethical governance within traffic orchestration, ensuring transparency, accountability, and public trust in automated decision-making (Finger & Bert, 2022).

Overall, the state of the art in road traffic management orchestration reveals a clear transition toward cooperative, intelligent, and predictive management of road networks. These developments bridge the gap between high-level governance frameworks and on-the-ground traffic operations, laying the foundation for a continuously adaptive and interoperable European transport ecosystem.

Table 3. Important themes in road traffic management and orchestration research.

Focus area	State of the art	Reference
From control to orchestration	Traditional Traffic Management Systems (TMS) are evolving toward integrated orchestration platforms that combine data-driven control, predictive modelling, and coordination between infrastructure operators and mobility service providers. The TM 2.0 concept exemplifies this paradigm shift toward shared responsibility and co-decision.	Rehrl et al (2016)
Integration of C-ITS and V2X	Cooperative Intelligent Transport Systems (C-ITS) and Vehicle-to-Everything (V2X) technologies enable real-time, bidirectional	Pavleska et al (2025)

Focus area	State of the art	Reference
communications	communication between vehicles, infrastructure, and control centres, supporting adaptive signal control, incident management, and multi-modal coordination.	
AI and predictive traffic orchestration	Artificial Intelligence and machine learning are increasingly applied for predictive traffic control, anomaly detection, and congestion forecasting. These approaches enhance the capacity for proactive, self-adaptive orchestration of urban and interurban networks.	Doulkeridis et al (2024)
Data integration and interoperability	Despite progress, fragmentation persists among national and regional TMS architectures. The lack of harmonised data formats, KPIs, and communication standards continues to hinder cross-border interoperability and coordinated network management.	Al Sabouni et al (2023)
Multi-modal and network-level orchestration	Research highlights the emergence of integrated management approaches spanning road, public transport, and logistics modes. Network-level orchestration frameworks seek to optimise flows across transport domains through shared situational awareness and cooperative control.	Cordoș et al (2025)
Human–machine collaboration and ethical orchestration	Advanced orchestration systems increasingly integrate human oversight, transparency, and accountability mechanisms. Ethical and explainable AI frameworks are explored to maintain trust and legitimacy in semi-automated traffic management.	Finger et al (2018)

4.3 Orchestration in the railroad domain

Railway infrastructure is inherently a limited-capacity system, constrained by physical layouts, signalling principles, and safety margins. Unlike road transport, where capacity can expand dynamically through routing or lane management, railway capacity is largely fixed and must therefore be optimised through intelligent traffic management. This makes the traffic management layer the operational core of railway orchestration—where strategic objectives are translated into concrete control actions that maximise infrastructure usage while maintaining safety and punctuality.

The strategic goals of railway traffic management include enhancing network efficiency, ensuring reliable service performance, and increasing resilience against operational disturbances. Achieving these goals requires not only robust planning but also the ability to adapt dynamically when deviations occur between planned timetables and real-time conditions. Through advanced tools such as timetable optimisation, real-time rescheduling, automated train operation (ATO), and digital signalling (ETCS and moving block), modern traffic management systems enable proactive decision-making and conflict resolution that preserve capacity and service quality even under disruption.

Recent research and practice emphasise that optimising a constrained rail infrastructure demands an integrated approach combining strategic capacity planning, predictive control, and adaptive traffic orchestration. This approach transforms railway operations from reactive control to data-driven, anticipatory management, ensuring that every available path, time slot, and signal block contributes to the sustainable and efficient use of Europe’s rail network.

The two-level layers involved or impacting railway orchestration in Europe:

European Railway Governance Layer — Actors and Roles

- European Commission (The Directorate-General for Mobility and Transport, DG MOVE):
    - Defines overarching EU transport policy.
    - Promotes market opening, interoperability, and the creation of the Single European Railway Area (SERA).
- European Union Agency for Railways (ERA):
    - Acts as the technical and safety authority for the EU rail system.
    - Empowered by the Fourth Railway Package to issue:
        - Vehicle authorisations.
        - Single safety certificates for railway undertakings.
    - Leads the harmonisation of interoperability standards, particularly ERTMS/ETCS deployment.
- National Safety Authorities (NSAs):
    - Supervise railway safety at national level : SCHIG in Austria, EBA in Germany, EPSF in France.
    - Ensure compliance with EU and domestic safety regulations.
- National Regulatory Bodies (NRBs):
    - Monitor market access, fair competition, and non-discriminatory use of infrastructure.
- Infrastructure Managers (IMs):
    - Responsible for network operation, maintenance, and capacity allocation.
    - Examples: SNCF Réseau (France), DB Netz (Germany), RFI (Italy).
- Railway Undertakings (RUs):
    - Operate passenger and freight train services using allocated infrastructure capacity.
- Cross-industry coordination bodies:
    - RailNetEurope (RNE): Coordinates international capacity allocation and traffic management.
- Sector associations:
    - CER (Community of European Railway and Infrastructure Companies) – represents incumbent operators and IMs.

    - ERFA (European Rail Freight Association) – represents independent freight operators.
    - UIC (International Union of Railways) – develops global technical standards and best practices.
- Research and innovation coordination:
    - Europe’s Rail Joint Undertaking (EU-Rail):
        - Funds and coordinates R&I projects, large-scale demonstrations, and the digital transformation of the European rail system.

Selection reference literature describing the governance areas are given in Table 4.

Table 4. Railroad developments

Focus area	State of the art	Reference
European Commission (DG MOVE)	Defines overarching EU transport policy and promotes the creation of the Single European Railway Area (SERA) through market opening, interoperability, and modal shift objectives. DG MOVE steers legislation such as the Fourth Railway Package to ensure fair competition and integration across Member States.	Lupu (2021 Witlox et al (2022)
European Union Agency for Railways (ERA)	Acts as the technical and safety authority for the EU rail system. Since the Fourth Railway Package, ERA is empowered to issue single vehicle authorisations and safety certificates, harmonising interoperability through TSIs and leading ERTMS/ETCS deployment across Member States.	European Union Agency for Railways (2024). Helak et al (2019)
National Safety Authorities (NSAs)	Supervise railway safety at national level and ensure compliance with EU and national regulations. Examples include SCHIG (Austria), EBA (Germany), and EPSF (France). Their activities are coordinated with ERA to maintain harmonised safety and interoperability standards.	Tomo et al (2024)
National Regulatory Bodies (NRBs)	Monitor market access, fair competition, and non-discriminatory use of infrastructure. They ensure transparent capacity allocation and access charging under the framework defined by EU directives and national legislation.	IRG-Rail (2024)
Infrastructure Managers (IMs)	Responsible for network operation, maintenance, and capacity allocation. IMs such as SNCF Réseau, DB Netz, or RFI manage infrastructure access under EU guidelines promoting transparency and interoperability.	Gašparík et al (2016)
Railway Undertakings (RUs)	Operate passenger and freight services under licences and safety certificates. They acquire infrastructure capacity from IMs and are	Březina et al (2007)

Focus area	State of the art	Reference
	regulated to ensure non-discriminatory access and fair competition.	
Cross-industry coordination bodies (RailNetEurope – RNE)	Coordinates international capacity allocation, traffic management, and harmonised procedures among Infrastructure Managers. RNE supports digital tools for cross-border capacity management and one-stop shops for path requests.	RailNetEurope (2024).
Sector associations (CER, ERFA, UIC)	Represent the interests of the rail sector at EU level. CER advocates for policy alignment and investment, ERFA for open-access freight operators, and UIC for global standardisation and best practices in operations and technology.	Institut Delors (2021)
Research and innovation coordination (Europe’s Rail Joint Undertaking)	Funds and coordinates R&I activities, large-scale demonstrations, and digital transformation projects to support the European Green Deal and SERA. Builds upon the former Shift2Rail initiative to integrate automation, data-driven traffic management, and sustainable operations.	Europe’s Rail Joint Undertaking (2023)

Rail traffic management orchestration

In national or state-level railway networks, traffic management is the responsibility of the Infrastructure Manager (IM), as established by European legislation—notably Directive (EU) 2012/34, which defines the framework for the Single European Railway Area. Operating companies acquire train paths or slots from the IM, which acts as the traffic manager. The allocation and scheduling of these slots are governed by principles of network optimisation, capacity efficiency, and operational safety, ensuring transparent and non-discriminatory access to railway infrastructure across the European Union.

At regional or local network level, a degree of vertical integration often exists: the operating company may also assume the traffic management function. This integrated model allows a more flexible and context-adapted orchestration of services for metros, tramways or regional lines out of the national or state network.

Regardless of the organisational structure, railway traffic orchestration is generally materialised through three main activity domains:

1. Planning activities (advance time): These cover the design and scheduling of services, capacity allocation, and conflict resolution before the operation phase.
2. Real-time control (control centre): A centralised or distributed system monitors and regulates traffic flow, responding to operational events, disruptions, or deviations from the planned timetable.
3. Deferred-time quality analysis: Post-operation evaluation ensures performance monitoring, safety assurance, and continuous improvement of planning and operational strategies.

Even in cases where a dedicated control centre is not present—such as on secondary or regional lines—the advance-time planning activities remain a fundamental component. These constitute the first step toward an orchestrated system, ensuring that operations follow a coordinated and safety-driven framework.

The following Table 5 summarises the state of the art in railway traffic orchestration (network capacity and traffic management research), highlighting key focus areas, their current understanding, and representative references. It provides an overview of how railway infrastructure is conceptualised as a limited-capacity system and how successive advances—from analytical modelling to digital and adaptive management—have progressively improved capacity assessment and utilisation.

Table 5. Railway traffic orchestration

Focus area	State of the art	Reference
Railway infrastructure as a limited-capacity system	The literature consistently defines railway infrastructure as a scarce and non-elastic resource constrained by signalling, headways, and timetabling. Capacity depends on infrastructure layout, operational rules, and service heterogeneity.	Abril et al (2008)
Quantifying infrastructure capacity	The UIC 406 methodology provides a practical approach to measuring capacity consumption through “timetable compression,” used by Infrastructure Managers to compare scenarios and detect bottlenecks.	Landex et al (2008)
Analytical foundations (blocking time theory)	Blocking-time and headway analysis formalise how safety margins and signalling determine the minimum train separation and thus network throughput.	Pachl (2014)
Comprehensive capacity analysis and modelling	Recent reviews integrate analytical, simulation, and optimisation approaches for determining and improving railway capacity at line and network level.	Sameni et al (2022)
Optimisation through timetable design	Timetable optimisation models allocate scarce track time efficiently under capacity and robustness constraints, often using integer programming or heuristics.	Lusby et al (2011)
Dynamic and real-time capacity optimisation	Advanced models for routing, rescheduling, and conflict resolution optimise infrastructure usage during disturbances and mixed traffic operations.	Cacchiani et al (2014)
Integration of automation and digital control	Deployment of ATO over ETCS and moving-block signalling (ETCS L3) increases capacity by reducing headways and improving driving regularity.	Wang et al (2022)
Capacity optimisation through predictive and	Real-time traffic management and predictive algorithms under digital signalling enhance infrastructure utilisation while maintaining stability and safety margins.	Versluis et al (2024)

Focus area	State of the art	Reference
adaptive management		
Energy- and demand-responsive operations	Optimisation of headways and timetables under variable demand improves both capacity utilisation and energy efficiency on constrained corridors.	Barrena et al (2014)

4.4 Orchestration in aviation

Distinguishing between upper and lower airspace governance is essential to understand the institutional and operational dynamics of the European aviation system. The two layers of airspace serve fundamentally different purposes and are subject to distinct governance structures, regulatory frameworks, and coordination mechanisms.

In the upper airspace, air traffic management is governed primarily at the European level, under the umbrella of the Single European Sky (SES) initiative. Here, supranational bodies such as EUROCONTROL, the European Union Aviation Safety Agency (EASA), and the European Commission (DG MOVE) coordinate the management of air traffic flows, capacity, and safety across national borders. This centralised governance is aimed at ensuring interoperability, efficiency, and network optimisation for high-altitude, cross-border operations.

Conversely, the lower airspace remains largely under national and regional jurisdiction, reflecting its proximity to local operations such as general aviation, regional flights, emerging unmanned aircraft systems (UAS) and urban air mobility (U-space) services. Governance in this layer involves a wider variety of actors — national air navigation service providers (ANSPs), civil aviation authorities, and, increasingly, local authorities and digital service providers.

Recognising this distinction is crucial for shaping coherent European policies, as the integration of upper and lower airspace governance will determine the continent's ability to manage increasing traffic complexity, new forms of air mobility, and the digital transformation of air traffic management. Understanding these different governance regimes also supports the development of regulatory frameworks that balance efficiency, safety, and innovation across all flight domains.

Table 6. Characteristics of coordination levels in upper and lower airspace.

Level	Upper airspace	Lower airspace
Governance	Supranational (EU, EUROCONTROL)	National / regional
Coordination	Integrated (Network Manager, SESAR, FABs)	Fragmented among national ANSPs
Main objective	Network optimisation and pan-European efficiency	Operational safety and local tactical management
Dominant regulation	*Single European Sky* regulations	National regulation + EASA harmonisation
Emerging actors	SESAR, EASA	U-space, USSPs, local authorities
Current trend	Increased automation and predictive management	Digital integration (U-space) and coexistence with manned aviation

European Aviation Governance Layer — Actors and Roles

- European Commission (Directorate-General for Mobility and Transport, DG MOVE):
    - Defines overarching EU aviation policy and legislation.
    - Oversees the implementation of the *Single European Sky (SES)* framework, promoting integration, efficiency, and interoperability across national air navigation systems.
    - Coordinates initiatives for sustainable air transport, digitalisation, and innovation through SESAR and the Green Deal.
- European Union Aviation Safety Agency (EASA):
    - Acts as the technical and safety authority for civil aviation in the EU.
    - Develops and enforces common safety and interoperability standards for aircraft, air traffic management (ATM), and air navigation services (ANS).
    - Plays a central role in U-space regulation for unmanned aircraft and in the harmonisation of CNS/ATM systems.
- EUROCONTROL (Network Manager):
    - Manages the European air traffic network under a mandate from the European Commission.
    - Optimises traffic flow, airspace design, and capacity balancing across Member States.
    - Provides coordination tools and procedures to ensure cross-border operational efficiency and safety in upper airspace.
- SESAR 3 Joint Undertaking:
    - Coordinates European R&I in air traffic management (ATM) and U-space, developing technologies for automation, trajectory-based operations, and integrated digital airspace management.
- National Civil Aviation Authorities (CAAs):
    - Supervise aviation safety and enforce compliance with both EU and national regulations.
    - License air navigation service providers (ANSPs) and oversee their operational performance.
- National Air Navigation Service Providers (ANSPs):
    - Manage national airspace operations, including en-route, approach, and tower services.
    - Examples include DSNA (France), DFS (Germany), and ENAIRE (Spain).
    - Coordinate with EUROCONTROL and EASA to ensure alignment with SES performance and safety objectives.
- Functional Airspace Blocks (FABs):

    - Regional cooperation frameworks that integrate airspace management across national borders, improving efficiency and interoperability.
    - Examples: FABEC (Central Europe), SW FAB (Spain–Portugal).
- Industry and coordination bodies:
    - CANSO (Civil Air Navigation Services Organisation): Represents ANSPs globally and promotes operational and technological harmonisation.
    - ACI Europe (Airports Council International): Represents airport operators in the European regulatory dialogue.
    - A4E (Airlines for Europe): Represents major airline groups advocating for a competitive and efficient European aviation market.
- Research and innovation coordination:
    - SESAR 3 Joint Undertaking: Successor of SESAR JU, co-funded by the EU and industry to lead large-scale demonstrations and digital transformation of European air traffic management.

Selection reference literature describing the governance areas are detailed in Table 7.

Table 7. State of the art references for ATM areas.

Focus area	State of the art	Reference
European Commission (DG MOVE)	Sets overarching EU aviation policy and steers Single European Sky (SES) reforms, performance schemes and compliance reviews in coordination with national authorities and the Network Manager.	FSR/EUI (2019)
European Union Aviation Safety Agency (EASA)	EU technical & safety authority for civil aviation; harmonises safety/interoperability rules for ATM/ANS and leads key files in U-space and human performance.	EASA (2024)
EUROCONTROL (Network Manager)	Operates the pan-European Network Manager to balance demand/capacity, optimise airspace design and flows, and coordinate cross-border operations under SES.	Bolić et al (2021) Markiewicz (2024)
National Civil Aviation Authorities (CAAs) / NSAs	Oversee safety and economic/performance supervision at national level; align plans and targets with EU frameworks and evolving SES reforms.	Franchina and Ingratoci (2024)
Air Navigation Service Providers (ANSPs)	Provide en-route, approach and tower services; interconnect with the Network Manager to deliver safe, orderly and efficient air traffic flows.	Bolić et al (2021) Andribet et al (2022)
Functional Airspace Blocks (FABs)	Cross-border cooperation frameworks to improve interoperability and performance; their role has evolved with recent SES reform proposals.	Motyka (2020) Franchina and Ingratoci (2024)

Focus area	State of the art	Reference
Industry & coordination bodies (CANSO, ACI Europe, A4E)	Represent operational and market stakeholders in EU policy/performance debates; contribute evidence on capacity, slots and market efficiency.	ACI Europe (2025) Finger et al (2019)
Research & innovation coordination (SESAR 3 Joint Undertaking)	EU public-private partnership funding R&I for the Digital European Sky (automation, TBO, virtual centres, U-space integration), with network-level demos and performance validation.	SESAR 3 JU (2025) SESAR JU (2024) Bolić et al (2021)
U-space & U-space Service Providers (USSPs)	EU framework for integrating drones and advanced air mobility into lower airspace, establishing mandatory/optional services and interfaces with ATM and common information services.	Regulation (EU) 2021/664 (official text) EASA (2024) EUROCONTROL (2023)

Air traffic management orchestration

At an operational level, the mission of Air Traffic Management (ATM) is to ensure the safe, orderly, and efficient use of a shared and dynamic airspace, while optimising the utilisation of capacity-limited infrastructures such as airports and future vertiports. As aviation evolves toward more complex, mixed operations—including conventional aircraft, drones, and urban air mobility vehicles—the strategic coordination of traffic management functions becomes increasingly critical to guarantee both safety and performance across the network.

1. Safety first — the core principle

Safety remains the fundamental objective of ATM. The system's primary role is to maintain safe separation between air vehicles, both horizontally and vertically, in all phases of flight. Because aircraft operate in a continuously changing three-dimensional environment, this requires constant surveillance, communication, and control. Airports—and, in the near future, vertiports—represent fixed, limited-capacity nodes within this fluid system. The precise management of runway or vertiport throughput, taxi flows, and arrival/departure sequences is therefore essential to preserving safety margins under increasing traffic density.

2. Orderly and efficient flow management

ATM's second key goal is to maintain order and efficiency in traffic flow across all airspace segments and ground interfaces. It seeks to reduce delays, fuel consumption, and environmental impact through the sequencing and spacing of aircraft, route optimisation, and real-time conflict resolution. Within Europe, EUROCONTROL, acting as the Network Manager, provides this coordination at a continental scale—balancing demand and capacity through Collaborative Decision-Making (CDM) processes that align the actions of airports, airlines, and air navigation service providers (ANSPs). This network-wide orchestration ensures that local capacity constraints are managed within a globally optimised operational framework.

3. Integration of diverse and emerging airspace users

Modern ATM increasingly operates within a multi-user environment, integrating commercial, general aviation, and military operations with new entrants such as unmanned aircraft systems (UAS) and urban air mobility (UAM) vehicles. The challenge is to achieve interoperability and equitable access—ensuring that all users can operate safely within shared airspace without compromising efficiency. This calls for digitalised coordination, automated traffic services, and a clear distribution of roles between strategic traffic managers (responsible for global airspace planning and flow control) and tactical air vehicle operators (responsible for immediate decision-making and compliance within assigned trajectories).

4. Environmental and performance objectives

Aligned with the goals of the Single European Sky (SES) and the SESAR programme, ATM also contributes to broader sustainability and performance policies. This includes reducing CO_2 emissions through trajectory-based operations, enhancing predictability and punctuality across borders, and digitalising airspace management to enable automation and real-time coordination. By treating both airports and vertiports as integral components of a coordinated network—each with measurable capacity and environmental impact—ATM supports a system-wide optimisation that advances safety, efficiency, and sustainability simultaneously.

Table 8. ATM state of the art.

Focus area	State of the art	Reference
1. Air traffic planning	Strategic and pre-operational planning of air traffic flows (airspace design, slot forecasting, demand-capacity balancing) is well established; recent reviews highlight novel optimisation, big-data and machine-learning methods.	Chen et al (2024) Pinto Neto et al (2023)
2. Air traffic real-time management	Real-time monitoring, decision support and conflict-resolution systems are evolving rapidly; big-data analytics, AI techniques and enhanced surveillance/collaboration systems are increasingly part of the mix.	Kamdar et al (2025) Suárez et al (2024)
3. Airports & slot coordination (capacity-constrained nodes)	Airports function as limited-capacity infrastructure nodes in the air traffic system; research focuses on slot allocation optimisation, capacity modelling and integration of airport constraints with airspace flows.	Katsigiannis (2021) Melder et al (2024)
4. Low-level airspace traffic planning and management	With the rise of UAS and advanced air mobility, management of low-altitude and uncontrolled airspace is becoming critical; frameworks for UAS Traffic Management (UTM) and low-altitude airspace models are emerging.	Pongsakornsathien et al (2025) Lee et al (2023)
5. Principles of air urban mobility traffic management	Urban Air Mobility (UAM) introduces new dimensions of traffic management: vertiports, high density, mixed manned/unmanned operations, digital controllers; research explores frameworks for safe scalable operations in urban airspace.	Schuchardt et al (2022) Thipphavong, et al (2018)

4.5 Orchestration time-time scales in the military domain

The terms strategic and tactical are commonly used to denote orchestration and planning at different levels. They are however sometimes ambiguously used, or used for time-scales other than originally intended. In Table 9, we therefore provide definitions of military time-scales for orchestration and command and control along with an example of a possible CARMONY issue at that level.

Table 9. Different levels or command and control/orchestration.

Military level	Time-scale	Geographical scale	CARMONY level/questions
Grand-strategic political-strategic	Years to decades	National, European	"What should the effects of the traffic system be in the next decade?"
Military-strategic	Months to years	National, regional	"How do we want to change the effects of the traffic systems in the next years?"
Operational	Weeks to months	Regional	"How should we change the guidelines that the traffic management uses"
Tactical	Hours to days	Local area	"How should we direct traffic to avoid jams today?"
Technical-tactical	Seconds to minutes	Point location	"How should the vehicles drive the next minutes?"

5. System of system models for each use case

5.1 Systems of systems

A System of Systems (SoS) is a set of independent systems that interact to provide capabilities and effects that no individual system can deliver on its own. The defining characteristic of an SoS is that its constituent systems (CS) remain both operationally and managerially independent. A CS makes its own decisions, has its own objectives, and controls how its capabilities are offered and used. In mobility-oriented SoS, it is often analytically useful to treat individual vehicles rather than organizations as CS, since vehicles act independently, can participate in different collaborations over time, and directly execute transport-related capabilities. A CS may simultaneously contribute to multiple SoS or multiple collaborations within the same SoS.

An SoS is therefore not a centrally designed or fully controlled system. Instead, it is a socio-technical structure in which coordination emerges through interaction, shared rules, and incentives rather than through direct command. In many real-world cases, especially in transport and mobility, SoS take the form of collaborative and open systems, where participation is voluntary and where new systems can join under agreed conditions.

For an SoS to be viable over time, each participating actor must derive sufficient value from participation. This value may take different forms, such as direct revenue, access to markets or data, improved service quality, regulatory compliance, or indirect societal or strategic benefits. Because constituent systems are autonomous, participation is ultimately voluntary, and actors will adapt their behavior or withdraw if participation does not align with their objectives.

At the same time, actors in an SoS are often also competitors. An SoS therefore operates under co-opetition, defined as a situation where actors simultaneously collaborate to create shared value while competing over market position, resources, or control. This duality has important implications for SoS design and governance: mechanisms for coordination, incentive alignment, and conflict management must be designed to balance collective performance with individual actor interests, without assuming centralized control.

A constellation is a temporary configuration of one or more CS formed to address a specific problem instance. In transport systems, a problem instance is typically a journey request, while the constellation represents the set of systems jointly providing that journey.

Constellations are dynamic: they are created, adapted, and dissolved as conditions change. The same CS may participate in different constellations over time, and different constellations may coexist in parallel. Designing an SoS therefore largely concerns enabling formation, coordination, and evolution of constellations under changing conditions and constraints.

An SoS involves multiple roles, which must be clearly distinguished even when they are held by the same organization or actor. This distinction is important because different roles often imply different objectives, responsibilities, and decision rights.

Roles can be grouped into two broad categories:

Roles related to constituent systems:

- CS developer: designs and evolves the CS
- CS owner: owns the CS

- CS operator: operates the CS in practice.

Roles related to the SoS:

- SoS initiator: takes the initiative to establish the SoS.
- SoS designer: defines structure, interfaces, and operating principles.
- SoS operator: manages coordination, conflict resolution, and operational rules.
- SoS supporter: provides indirect support, such as funding or regulation, due to broader societal value.

Many other roles are possible, and what roles need to be included in an SoS model will differ from application to application.

Mediators are systems that support coordination and interaction between. Unlike CS, mediators do not primarily deliver end-user capabilities; instead, they enable the SoS to function by facilitating information exchange, coordination, and decision-making. Typical mediator functions include information aggregation and dissemination, booking and payment, route or resource allocation, and constellation formation. Multiple mediators may coexist within the same SoS, and CS may interact through different mediators depending on context.

An important first step when analysing a problem as an SoS is to make a list of concepts and entities that need to be modelled. This includes the actor roles and actors, CS, and also the goals and objectives of different stakeholders and actors. A preliminary list of such concepts that could be relevant for CARMONY follows:

- Simulations
  - Real-time simulation
  - Monthly simulation
  - Governance level simulations
- Decision support systems
  - Traffic management center – real-time traffic management.
  - Preventive layer traffic mgmt.
  - Governance level decision support
- Rules and instructions
  - Instructions to road users
  - Decision guidelines
  - Business models
  - Incentive mechanisms
  - Governance
- Agents in traffic (humans, autonomous cars)
  - Carmen, Patricia, and other actors mentioned in the use cases
  - VRU (non-connected)
  - VRU (connected)
  - Driver
  - Autonomous driving systems
- Vehicles
  - Car

  - Bus
  - Heavy duty vehicle
  - Light-duty vehicle
  - Bikes
  - Motorbikes
  - E-scooters
- Companies involved in traffic
  - Bus operator
  - Hauler
  - E-scooter operator
  - Mobility provider
- Data
  - Historical data
  - Real-time data
- Sensors
  - Road camera
  - Etc
- Goals for road users
  - Origin
  - Destination
  - Route
- Meta users
  - Municipality
  - Regional authority
  - National government
  - EU
  - Nature
- Goals for meta users
  - Congestion reduction
  - Emission reduction
  - Accessible transport for all
- Cost and benefits, values, effects
  - Travel time
  - Emissions
  - Waiting time (congestion)
  - Waiting time (transfers)
  - Accidents
  - Money
  - Congestion fee

This list will be further refined and updated in T4.2 and WP5.

5.2 Reference model for System-of-Systems Approach in Traffic Orchestration

The SoS approach serves as a conceptual reference model for managing complex transportation ecosystems within the CARMONY project. This model recognises that traffic orchestration involves multiple autonomous constituent systems that must collaborate to achieve shared objectives. Each CS retains its independence while contributing to higher-level goals through coordination, data exchange, and adaptive decision-making.

Figure 9. Principle of CARMONY Reference Model for SoS.

As illustrated in Figure 9, the reference model used in the CARMONY project is built on four foundational principles.

Interoperability: The model ensures that heterogeneous CSs such as vehicles, infrastructure, and mobility services can communicate and share data seamlessly. Standardised interfaces and protocols enable real-time coordination across diverse technologies and jurisdictions.

Scalability: The model supports expansion from local intersections to regional and cross-border networks. It accommodates increasing complexity without compromising performance, making it suitable for urban environments, highways, and international corridors.

Flexibility: The model balances directive authority with voluntary compliance. In emergency situations, traffic management authorities exercise clear decision mandates to issue binding instructions. In normal operations, the model relies on guidelines, recommendations, and incentive structures to influence behaviour without force.

Collaborative Governance: The model emphasises cooperation among actors/CSs through shared goals and transparent decision-making. Governance frameworks, business models, and incentive mechanisms align the interests of, e.g., public authorities, private operators, and end users, creating a resilient and adaptive SoS.

5.2.1 SoS Actors, roles, goals, objectives

Traffic orchestration in modern mobility environments is not about controlling a single integrated system. It is a challenge that involves multiple independent CSs that must cooperate to achieve shared objectives. This is the essence of the SoS concept. Each CS retains its autonomy while contributing to a higher-level purpose through coordination and information exchange. In the context of traffic management, this approach is particularly valuable because transportation networks are inherently distributed and involve diverse stakeholders with different priorities.

There is a wide range of actors that participate in traffic orchestration. These include public authorities responsible for traffic management and safety, infrastructure operators that manage physical assets such as roads and traffic signals, and mobility service providers that offer solutions for passenger and freight transport. Connected and automated vehicles represent another critical actor group, as they operate with a degree of autonomy while interacting with orchestration guidelines. End users, such as drivers, passengers, and vulnerable road users, also play an important role because their behaviour influences system performance. Finally, regulatory bodies define the legal and policy environment that governs interactions among all these actors.

Moreover, each actor assumes one or more specific role(s) within the SoS. Traffic management authorities act as orchestrators, setting strategic objectives and issuing directives during emergencies. Infrastructure CSs provide the backbone for data collection and enforcement, enabling real-time adjustments to, e.g., traffic signals and speed limits. Vehicles and mobility services execute tactical actions based on recommendations, balancing autonomy with cooperation. Regulatory bodies ensure compliance with laws and ethical standards, while end users contribute behavioural compliance through trust and incentives. These roles are interconnected, and their effectiveness depends on continuous communication and shared understanding of objectives.

The overarching goal of the SoS approach in traffic orchestration is to create a safe, efficient, and sustainable mobility ecosystem. Several specific objectives support this goal. Operational objectives include reducing congestion, optimising routing, and improving travel times. Safety objectives aim to minimise accidents and protect vulnerable road users. Environmental objectives focus on reducing emissions and supporting compliance with low-emission zones. Resilience objectives ensure rapid recovery from disruptions and maintain system stability under stress. Finally, user-centric objectives aim to enhance convenience and trust by providing transparent guidelines and fair incentive structures.

Creating a SoS model for each use case is important because it transforms complexity into clarity. These models illustrate relationships and dependencies among CSs across different SoS, showing how CSs and capabilities interact and how constraints potentially are generated. They also help uncover governance structures, management responsibilities, and incentive mechanisms that are often hidden in multi-organisational environments. By visualising both technical interconnections and organisational dynamics, the SoS model supports better planning, risk mitigation, and coordination. It becomes a shared reference point for stakeholders, enabling informed decisions and reducing misunderstandings.

In this section, we therefore introduce the six use cases developed within the CARMONY project. For each use case we begin with a concise use case description. This is followed by an SoS model for each use case that visualises the interconnected landscape of CSs, stakeholders, and their relationships, highlighting the dependencies that enable effective traffic orchestration. For more details on the use cases, we refer to D2.1 of CARMONY; D2.4 includes a comprehensive list of KPIs for each use case.

5.3 Use Case 1: Traffic Management Optimisation in Urban Environment Including Low Emission Zones (LEZ) in Murcia, Spain

This use case (see Figure 10 below) addresses the growing need for sustainable urban mobility in Murcia, where Low Emission Zones (LEZ) are being introduced to reduce pollution. The Interlinked Orchestrator leverages real-time data from connected vehicles, traffic sensors, and environmental monitors to optimise routing decisions. It considers LEZ restrictions, parking availability, and dynamic factors such as roadworks or special events. The orchestrator provides tailored solutions: for vehicles restricted from entering LEZ, it suggests transfer points and alternative transport options; for permitted vehicles, it offers optimised routes and parking guidance. By integrating historical traffic patterns with live data, the system ensures smoother traffic flow, reduces congestion, and promotes greener mobility choices. This approach not only improves travel efficiency but also supports public policy goals to reduce emissions and promote sustainable urban planning.

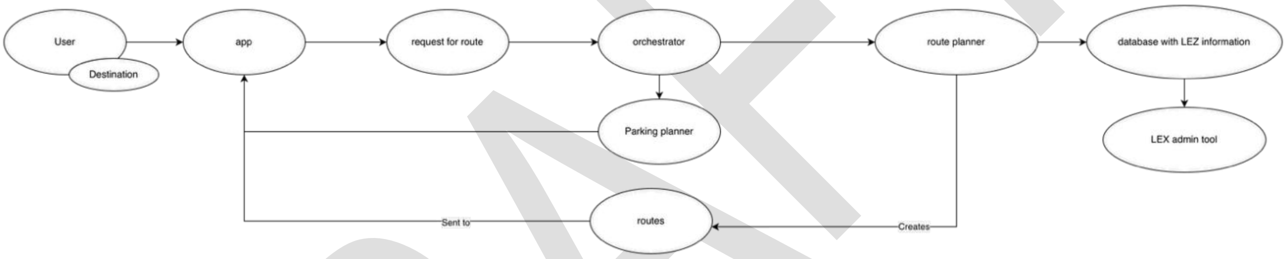

Figure 10. UC 1 model.

5.4 Use Case 2: Critical Road Blockage in Murcia, Spain

Urban traffic systems are highly vulnerable to sudden disruptions, such as a vehicle breakdown at a key intersection. In this scenario (see Figure 11 below), the orchestrator acts as a real-time crisis manager. When a connected vehicle (CV) reports a breakdown, the orchestrator immediately alerts nearby vehicles and reroutes them to minimise congestion. It also informs authorities and provides optimised access routes for technical assistance. Beyond traffic redirection, the system also considers passenger needs, offering alternative transport options for affected passengers. This holistic response reduces the length and duration of traffic jams, minimises fuel waste, and ensures safety for all road users. By integrating predictive algorithms and cooperative activities, the orchestrator transforms a potentially chaotic event into a controlled, efficient process, demonstrating its value in maintaining urban resilience.

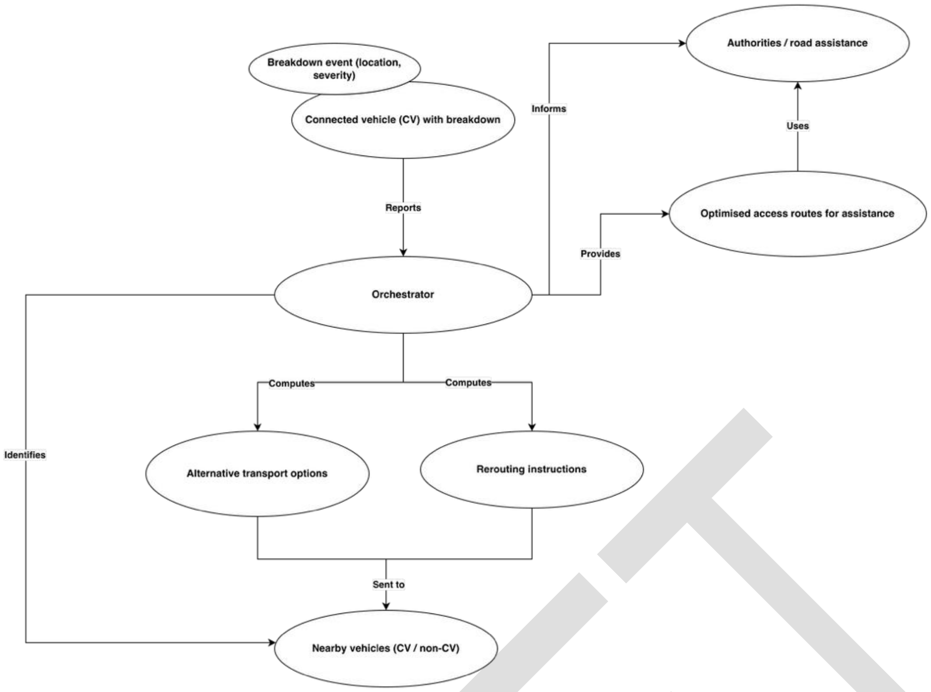

Figure 11. UC 2 model.

5.5 Use Case 3: Traffic Orchestration During a Disruptive Event – Emergency Corridor Activation in Murcia, Spain

Traffic jams and poor coordination often delay emergency response in congested urban areas. This use case introduces a proactive solution: the orchestrator creates emergency corridors. When an ambulance or other emergency vehicle receives an incident alert, it receives the available corridors from the orchestrator and choses one of them. The orchestrator then clears the path by notifying connected vehicles and adjusting traffic signals to prioritise the emergency vehicle. Connected Vulnerable Road Users (VRUs) are also protected through mobile app alerts that help them avoid hazardous zones. Once the emergency vehicle reaches its destination, normal traffic flow is restored seamlessly. This orchestration significantly reduces response times, improves safety, and demonstrates how technology can save lives while minimising disruption for other road users (graphical illustration see Figure 12).

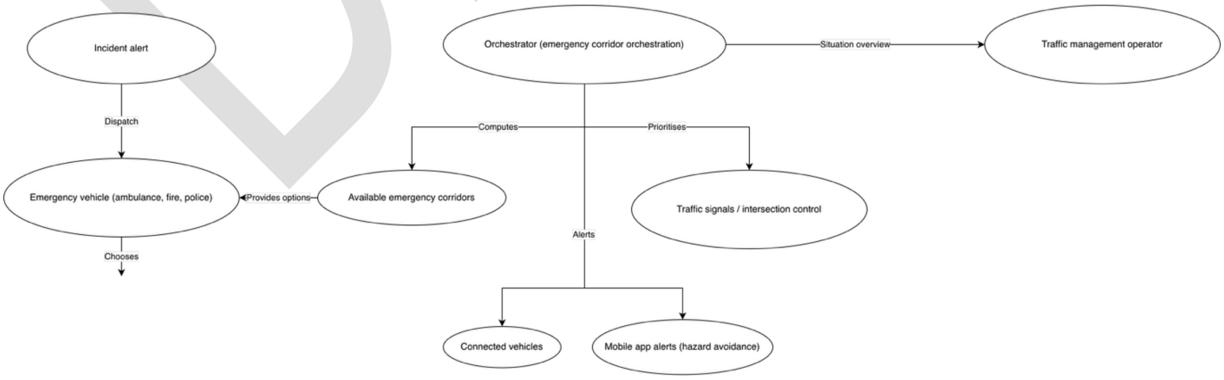

Figure 12. UC 3 model.

5.6 Use Case 4: Carpool Lane Optimisation and Innovative Mobility Services at Highway A3, Luxembourg

Highway congestion is a persistent challenge, even on roads equipped with carpool lanes. Often, these lanes remain underutilised while regular lanes are overcrowded. This use case focuses on optimising carpool lane capacity on Luxembourg's A3 highway. The orchestrator dynamically manages lane access, allowing non-carpool vehicles to reserve time slots when the lane is underused. It communicates availability to drivers and CCAM vehicles in real time, ensuring efficient lane utilisation. Two scenarios are tested: daily cross-border commuting and freight transport optimisation. By reducing congestion and improving lane capacity, this approach enhances travel efficiency, lowers fuel consumption, and supports sustainable mobility practices. It exemplifies how orchestration can balance fairness, efficiency, and environmental goals in high-demand corridors (graphical illustration see Figure 13).

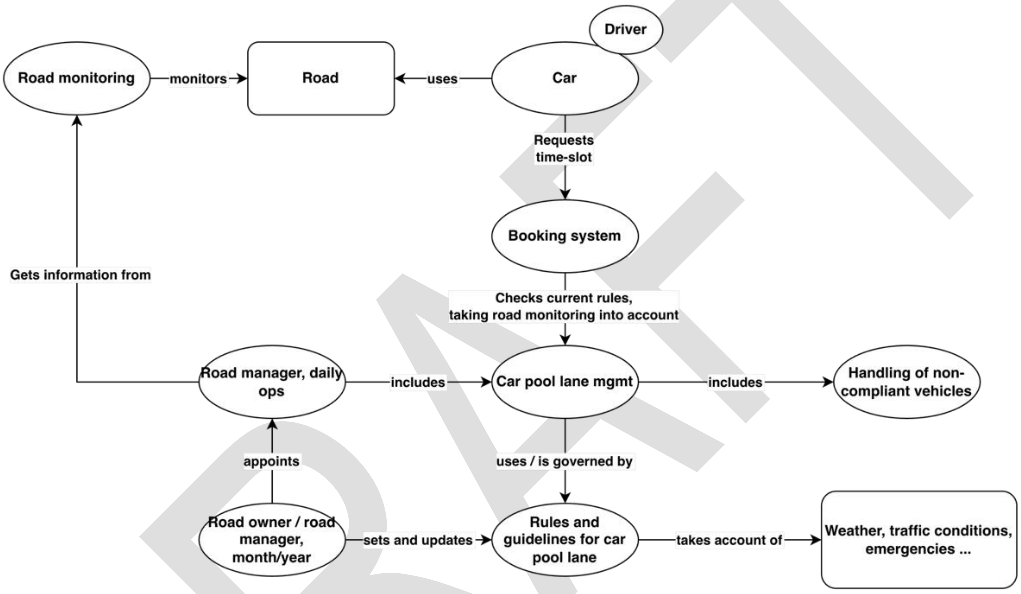

Figure 13. UC 4 model.

5.7 Use Case 5: Cross-Border Highway Traffic Optimisation in Case of Interruption at Highway A13 Schengen–Luxembourg/Germany border.

Cross-border highways are critical for both commuters and freight transport, yet they face unique challenges, including regulatory differences and unpredictable disruptions. This use case targets the A13 corridor between Luxembourg and Germany, a vital route for thousands of vehicles daily. The orchestrator uses real-time traffic data, historical patterns, and regulatory constraints to provide personalised routing for commuters and optimised paths for freight operators. It considers factors like rest periods, border crossing times, and truck-specific restrictions. By harmonising traffic flows across borders, the system reduces delays, fuel consumption, and emissions, while ensuring compliance with EU regulations. This use case demonstrates the orchestrator's ability to manage complex, multinational traffic ecosystems effectively (graphical illustration see Figure 14).

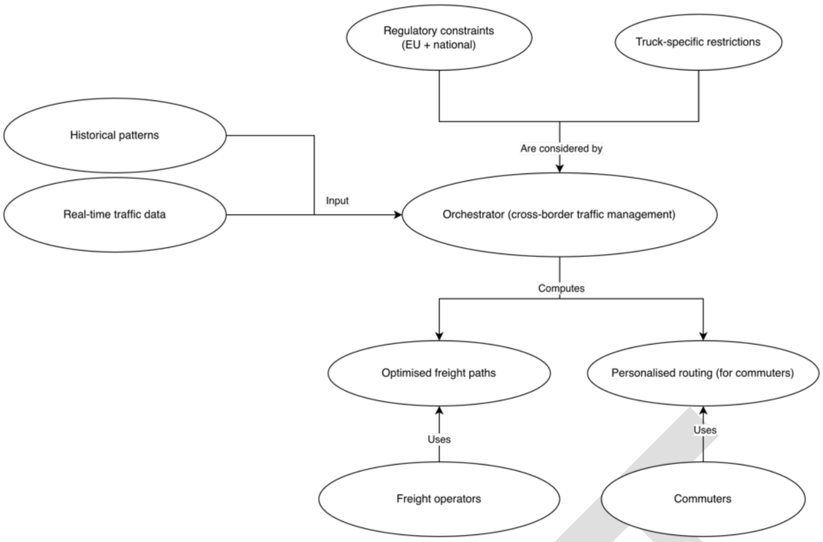

Figure 14. UC 5 model.

5.8 Use Case 6: Speed Reduction for Daily Traffic Jam Avoidance at Highway A3, Luxembourg

Traffic jams often result from sudden speed variations and a lack of coordination among drivers. This use case explores proactive congestion prevention on Luxembourg's A3 highway. The orchestrator analyses historical and monitors real-time traffic conditions and predicts when jams are likely to occur. It then applies two strategies: direct communication with connected vehicles and drivers via apps, instructing them to reduce speed, and dynamic adjustment of speed limits displayed on roadside signs. These measures harmonise traffic flow, reduce stop-and-go patterns, and prevent bottlenecks before they form. The system also evaluates the penetration rate of connected vehicles needed for a significant impact. By improving safety, reducing fuel consumption, and minimising delays, this use case illustrates how predictive orchestration can transform highway traffic management (graphical illustration see Figure 15).

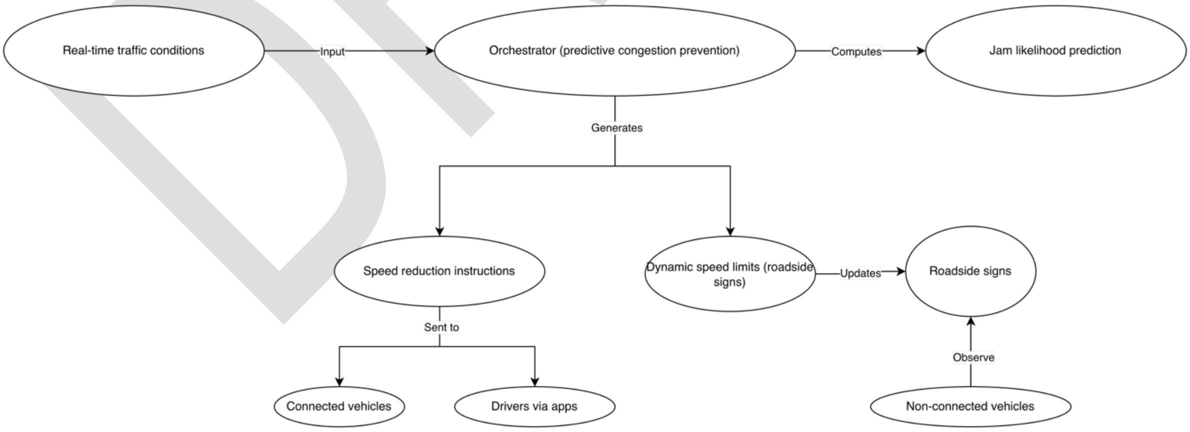

Figure 15. UC 6 model.

6. Data Exchange Requirements

Effective mobility flow orchestration within a CCAM framework relies fundamentally on high-quality, real-time, and interoperable data exchange between connected vehicles, roadside infrastructure, traffic management systems, and mobility service operators. Mobility flow optimization is likely to prioritize collective situational awareness, traffic efficiency, multimodal coordination, and congestion reduction, all of which require consistent data sharing using standardized C-ITS messages and interfaces. Effective traffic orchestration within CARMONY depends fundamentally on the availability, quality, and timely exchange of mobility data across all actors in the connected mobility ecosystem. As CARMONY views the problem as from System-of-Systems perspective, data must flow seamlessly between vehicles, infrastructure, traffic management centres, service providers, and regional authorities, each of which contributes partial and complementary information. The resulting data fabric enables the orchestrator not only to understand the current state of traffic flow, but also to anticipate disruptions, evaluate response strategies, and communicate personalised or collective guidance in real time. For this reason, data requirements in CARMONY encompass both microscopic elements (individual vehicle status, location, intentions) and macroscopic elements (network state, aggregated flow, predicted congestion), ensuring a consistent multiscale view of the mobility system. This chapter describes the data sharing framework needed for CARMONY.

6.1 Standards of Data Sharing Frameworks for CCAMs

A cornerstone of mobility flow management is the periodic broadcast of Cooperative Awareness Messages (CAM), through which connected vehicles communicate their position, speed, acceleration, heading, and basic dynamic state. This continuous flow of vehicle status information enables traffic management centres to monitor real-time traffic conditions, estimate traffic densities, detect the onset of queue formation, and derive travel-time forecasts. CAMs therefore form the baseline upon which macroscopic traffic state estimation and dynamic traffic control strategies are built.

In parallel, Decentralized Environmental Notification Messages (DENM) are used to transmit event-driven information regarding incidents and disruptions that may impede mobility. These include reports of congestion, accidents, unexpected obstacles, stationary vehicles, adverse road surface conditions, or weather-induced hazards. The timely distribution of DENM messages helps operators identify abnormal situations early, initiate appropriate mitigation measures, and dynamically adjust traffic signalling or routing recommendations to maintain efficient flow across the network.

6.1.1 Real-Time Vehicle Data

Connected and automated vehicles must share the following data at high frequency:

- Position, speed, acceleration, heading (CAM/BSM equivalent)
- Intent and manoeuvre information (e.g., turn indicators, braking events)
- Perception outputs, such as detected objects and VRUs (CPM)
- Operational status, including system health, automation mode, and failure states

6.1.2 Event and Incident Data

Event-driven data shall be broadcast using standardized message sets:

- Hazards, incidents, accidents (DENM)
- Traffic congestion and abnormal traffic flow
- Roadworks and temporary speed limits
- Obstructions, degraded road conditions, or weather-related risks

6.1.3 Interoperability and Standardization Requirements

Interoperability across vehicle manufacturers, infrastructure suppliers, and national or regional deployments is guaranteed through adherence to established ETSI C-ITS standards, including CAM (EN 302 637-2), DENM (EN 302 637-3), MAPEM and SPATEM (TS 103 301), IVIM and VAM (TS 103 300), and CPM (TS 103 324), as well as the supporting security and congestion control protocols. Harmonized semantics, standardized geographic reference frames, and synchronized time sources ensure coherent interpretation of mobility data across all connected elements. Integration with traffic management systems is further facilitated through compatibility with contemporary urban data formats such as DATEX II, NGSI-LD, and digital twin frameworks.

Table 10. Standard ITS Messages.

Message	Standard	Type	Purpose
CAM	EN 302 637-2	Periodic	Presence + basic status
DENM	EN 302 637-3	Event-based	Hazard / event notification
SPATEM	TS 103 301	Periodic	Traffic light phases
MAPEM	TS 103 301	Static/semi-static	Intersection map/lanes
SREM	TS 103 300	Event-based	Priority request
SSEM	TS 103 300	Event-based	Signal response
CPM	TS 103 324	Frequent	Sensor-detected object sharing
VAM	TS 103 300-4	Periodic	VRU awareness
IVIM	TS 103 301	Event	Road authority info

6.1.3.1 ETSI C-ITS Standards

Traffic orchestration must comply with:

- ETSI EN 302 637-2 (CAM)
- ETSI EN 302 637-3 (DENM)
- ETSI TS 103 324 (CPM)
- ETSI TS 103 300 (SREM/SSEM/VAM)
- ETSI TS 103 301 (MAPEM/SPATEM)
- ETSI EN 302 895 (Cross-layer DCC)

This ensures interoperability between vehicles from different OEMs, infrastructure and transport operators data formats all data must follow:

- ASN.1-encoded V2X messages
- ISO 18750, Datex II, NGSI-LD for traffic center integration
- Consistent geospatial references (WGS84/ECEF)
- Time synchronization via GNSS or network time protocols

6.2 Data Exchange Requirements and Specification Orchestration (System of Systems)

The orchestration of connected mobility requires a coordinated data-exchange ecosystem in which each actor, i.e. connected vehicles, automated vehicles, mobility users, and the interlinked orchestrator plays a distinct role. Connected vehicles must continuously provide accurate, anonymised status data and receive real-time guidance that shapes overall traffic flow. Automated vehicles extend these requirements with higher-integrity sensing, routing adaptability, and strict operational constraints to ensure safe and authorised automated operation. Mobility users interact through applications that provide personalised routing, warnings, and transparency about orchestration decisions, while ensuring consent, privacy, and safety. At the core, the interlinked orchestrator aggregates heterogeneous data (traffic, sensors, weather, infrastructure), conducts real-time and non-real-time simulations, predicts congestion, generates governance-compatible policies, and issues optimised recommendations for all actors. Together these requirements enable interoperable, ethically compliant, simulation-supported, and traffic-efficient cooperative mobility management.

6.2.1 Connected Vehicles

Connected Vehicles participate in the traffic ecosystem by continuously sharing standardized, anonymized data such as position, speed, origin as well as destination, vehicle profile, and status updates with the orchestrator. They must be able to receive routing recommendations, LEZ information, emergency warnings, and lane-reservation guidance in real time. Their onboard or app-based interface must allow drivers to provide essential inputs, e.g., permissions, destinations, or emergency updates, while presenting orchestrator messages clearly and safely.

6.2.2 Automated Vehicles

Automated vehicles extend the capabilities of connected vehicles with autonomous driving functions that integrate orchestrator messages directly into their AD stack. They must support automated routing, status reporting, speed instructions, and V2X communication with traffic lights and emergency vehicle notifications. Operational constraints (weather, safety drivers, emergency stops, authorized areas) govern their deployment in pilots, while ensuring real-time responsiveness and safe fallback behaviour.

6.2.3 Mobility Users

Mobility Users rely on mobile apps and interfaces that provide personalized, accessible, and transparent guidance reflecting traffic conditions, LEZ rules, obstacles, and multimodal travel options. Users contribute data (location, permissions, preferences) while retaining strong control over privacy, consent, and security. The system ensures inclusivity, ethical treatment, and protected data-handling throughout pilot participation.

6.2.4 Interlinked Orchestrator

The Interlinked Orchestrator acts as the central intelligence layer that fuses real-time sensor data, historical datasets, simulation outputs, mobility trends, and user requirements. It generates governance rules, speed advisories, routing recommendations, conflict resolution strategies, emergency corridors, lane reservations, and multimodal suggestions. It must interoperate with TMS, traffic signals, dashboards, simulations, and external interfaces while ensuring reliability, traceability, and fairness for all actors.

Table 11. Data Requirements of Mobility Actors and Interlinked Orchestrator.

Requirement Category	Connected Vehicles	Automated Vehicle	Mobility User	Interlinked Orchestrator
Data Exchange & Communication	Send anonymized data (position, speed, O/D, profile); receive routes, warnings; real-time comms (MQTT/AMQP); HTTPS for non-real-time; report breakdowns	Receive orchestrator messages; report AV mode status; send position/status; support V2X traffic light info	App sends location, permissions (LEZ), destination; receives warnings and guidance	Define communication rules; manage real-time data ingestion; ensure >99.5% availability; maintain secure logs
Localization & Mapping	Provide accurate position; support standard message interfaces	Provide 50 cm accuracy; use HD maps; interpret routing	View own position in app	Use maps (e.g., OSM); integrate HD map data; detect incidents & lane closures
Routing & Recommendations	Receive and follow recommended route; update based on obstacles; support LEZ constraints	Accept rerouting requests; follow speed advisories and routes automatically	Receive personalized multi-modal suggestions	Calculate optimal routes; provide speed instructions; simulate and update guidance in real time
Emergency & Safety	Receive emergency vehicle warnings; clear corridor; report road obstacles	React to emergency vehicle info; provide safety fallback (operator, weather limits)	Receive VRU warnings, road hazard notifications	Manage CEV corridors; compute emergency warnings; perform collision risk estimation (CRE)
Simulation Requirements	Act as simulated agents sending/receiving messages	Provide low-fidelity AV behavior; integrate with orchestrator	Not directly simulated (app interactions abstracted)	Support real-time and non-real-time simulations; model CAV penetration; run long-term governance simulations

Requirement Category	Connected Vehicles	Automated Vehicle	Mobility User	Interlinked Orchestrator
Ethics, Data Protection & User Rights	Provide anonymized data only; comply with GDPR	Same GDPR constraints as CVs	Consent, data rights (access/rectify/ delete), vulnerability protection	Ensure privacy-preserving orchestration; run ethics assessment; enforce data-minimization
Operational Constraints		Weather restrictions; operator within 70 m; authorized zones; speed up to 30 km/h	App tailored to user needs; accessible interface	Must run governance logic fairly; adapt rules if actors disadvantaged
Interoperability & Standards	Use standard interfaces; compatible with orchestrator protocols	AD stack must interpret standard orchestrator messages	App uses standard web/mobile protocols	Integrate tools, dashboards, TMS; implement machine-readable policies; use open standards
Dashboards & Monitoring				Display real-time & simulated KPIs; user-role views; environmental data; visual/spatial/temporal exploration
Lane Management / Traffic Control	Request lane reservations; follow lane-change instructions	Receive speed control and lane instructions	Receive congestion and multimodal suggestions	Compute lane reservations; update VSLs; predict jams; adapt strategies

6.3 Data Exchange Requirements for sending information and guidelines to the vehicles and users

The system shall define a unified data-exchange mechanism for transmitting guidance from the Interlinked Orchestrator to vehicles and mobility users, despite the absence of an existing standard. This mechanism must support the delivery of (i) route recommendations, (ii) parking-space suggestions, and (iii) multimodal travel options when a mode change is required (e.g., when a private vehicle cannot enter a Low Emission Zone). Each message issued by the orchestrator shall include a clear explanation of the rationale behind the recommendation, such as congestion mitigation, LEZ restriction, obstacle avoidance, or emergency-related interventions. The communication protocol shall explicitly indicate whether a message constitutes a mandatory instruction or a voluntary advisory: mandatory in safety-critical or emergency scenarios, and advisory in all routine traffic-management situations where the orchestrator cannot impose compliance. Here we define a practical, custom message definition for use in CARMONY to send orchestrator guidance to vehicles and users.

Messages must be explicit about intent (order vs advisory), rationale (why it was issued), scope (which vehicle(s) / area / time), and actionable content (route, parking, multimodal suggestion). All messages must include provenance, timestamps, message versioning, and cryptographic signature metadata fields (PKI) so recipients can validate source and purpose. Messages need to be kept compact for real-time channels but allow optional rich payloads for when bandwidth permits.

Table 12. Common Message Header.

Field	Type	Required	Description
messageId	string (UUID)	Yes	Unique message identifier
version	string	Yes	Schema version (e.g., "CARMONY-v1")
issuedBy	string	Yes	Orchestrator ID (entity issuing message)
issuedAt	ISO8601 timestamp	Yes	UTC issuance time
validFrom	ISO8601 timestamp	cond.	When message becomes active
validUntil	ISO8601 timestamp	cond.	Expiration time
priority	enum {low, normal, high, emergency}	Yes	Delivery/processing priority
scope	object	yes	Target selection (single vehicle id, group, area polygon, broadcast)
intent	enum {order, advisory, info}	yes	Whether compliance is mandatory
rationale	array of objects	yes	One or more reasons (code + free text + confidence)
correlationId	string	no	Links to related messages or events
signature	object	yes	Signature metadata (alg, certId, signature)
language	string (BCP47)	no	Preferred natural language for messages

Table 13. Actionable Payloads.

Payload Field	Type	Req.	Used by
route	object	conditional	Route suggestion payload (polyline, waypoints, ETA, restrictions)
parkingSuggestion	object	conditional	Candidate parking lot id, coords, availEstimate, walkTime, price
multimodalOptions	array	conditional	Suggested onward transport (PT, bike-share, taxi) with cost/time/travelSteps
explanation	string / structured	yes	Human- and machine-readable explanation of rationale
mandatoryUntil	ISO8601	cond.	If intent==order, when requirement ends
confidence	0..1 float	no	Orchestrator confidence in recommendation
legalReference	string	cond.	For orders: legal basis or authority id
uiHints	object	no	HMI instructions (text, urgency tone, icons)
rollbackPlan	object	no	Optional; what to do if non-compliance or comms fail
metricsRequested	array	no	Which telemetry/ACKs orchestrator requests back

6.4 Data Security and Privacy Requirements

Interlinked CCAM orchestrators operate in a highly distributed, multi-stakeholder ecosystem where vehicles, infrastructure, urban platforms, and mobility service providers exchange sensitive operational data. Ensuring trustworthy collaboration requires stringent security and privacy controls across all communication layers. The system must guarantee that only authorized entities can trigger traffic-management actions, that data is not tampered with in transit, and that information about drivers and vehicle behaviour is processed in accordance with European privacy regulations. The following sections detail the requirements for authentication, integrity, and privacy within the CCAM data-exchange framework.

6.4.1 Authorization and Authentication

Secure identification of all entities participating in data exchange is essential to avoid spoofing, unauthorized command injection, or false information entering the orchestration loop. Infrastructure actors such as traffic control centers, municipal orchestrators, and fleet operators must authenticate themselves using standardized public key infrastructures for cooperative systems, consistent with ETSI ITS-S and C-ITS PKI principles. Vehicles must authenticate incoming instructions to verify that they originate from legitimate orchestrators and not from rogue or spoofed sources. Authorization mechanisms must reflect role-based responsibilities: only designated actors are permitted to issue traffic-management decisions or operational instructions. For example, emergency authorities may send mandatory rerouting orders, while general traffic management systems are limited to advisory guidance. Mutual authentication between all communicating endpoints ensures accountability and traceability, while encrypted sessions prevent credential leakage or impersonation.

6.4.2 Data Integrity

Data integrity guarantees that the information exchanged between orchestrators, vehicles, and user interfaces is complete, unaltered, and reliable. In the context of traffic orchestration, corrupted data such as modified route suggestions or forged parking availability—could degrade mobility efficiency or threaten safety. Integrity must be ensured at multiple stages: message generation, transmission, storage, and aggregation. Digital signatures and cryptographic hashing should be applied to all orchestrator-to-vehicle instructions, including routing recommendations, compliance levels, or multimodal travel suggestions. Communication protocols must include replay protection to prevent delayed or duplicated messages from influencing vehicle behaviour. Additionally, integrity checks must extend to internal system logs and decision-support outputs, ensuring that recorded evidence cannot be manipulated and that audit trails remain trustworthy for operational evaluation and legal compliance.

6.4.3 Privacy Protection

Protecting user and vehicle privacy is essential when orchestrators access sensitive data, such as vehicle identifiers, trip histories, or mobility preferences. Privacy requirements must comply with GDPR and relevant mobility data-governance frameworks, ensuring that only the minimum necessary data is shared and that personal information is pseudonymized whenever possible. The system must enforce purpose limitation, ensuring that data collected for traffic optimization is not repurposed for unrelated activities such as commercial profiling or law enforcement without appropriate legal grounds. Data minimization principles require orchestrators to use aggregate or anonymized mobility flow data whenever vehicle-level granularity is not strictly necessary. Consent and transparency mechanisms must be in place for user-facing services particularly when providing personalized route recommendations or last-mile multimodal suggestions.

6.5 Data Space, Logging and Storage

A CCAM orchestration ecosystem relies on an interoperable and secure data infrastructure that enables the exchange, traceability, and controlled retention of mobility information. The architecture must support distributed data spaces that allow organizations to maintain control over their own data while enabling cross-domain collaboration. Proper logging and storage mechanisms ensure operational accountability, system debugging, and compliance with regulatory requirements.

6.5.1 Data Spaces

The orchestration relies on a mobility-oriented Data Space where different actors can publish, discover, and access data under well-defined governance rules. Each participant retains control over its data while allowing selective sharing through standardized interfaces. The Data Space must support multiple types of information: real-time traffic data, orchestrator recommendations, digital twins, simulation results, LEZ restrictions, public-transport availability, and parking facility status. Semantic consistency ensures that data from different cities, operators, or devices can be integrated seamlessly. Access policies define the roles of vehicles, users, infrastructure systems, and orchestration services, ensuring compliance with legal mandates and cross-border conditions.

6.5.2 Data Logging

All exchanges especially those influencing traffic behavior must be logged in a secure, tamper-evident, and auditable format. Logging encompasses message timestamps, orchestrator decisions, vehicle compliance reports, user interactions, and critical system events such as emergency corridor activation or LEZ access decisions. Logs support accountability, facilitate post-incident analysis, and help refine simulation models used in the governance layer. They also serve as evidence for auditing system performance, ensuring fairness, transparency, and alignment with regulatory requirements. To minimize privacy risks, logs must be pseudonymized and retain only the information strictly required for traceability.

6.5.3 Data Storage

Data storage requirements ensure that mobility data, orchestration outputs, system logs, and analytics resources remain accessible, secure, and tamper-proof throughout their lifecycle. Storage solutions must support redundancy and fault tolerance to ensure that no critical information is lost in the event of failures. Sensitive data must be stored using encryption at rest, and key management must follow best practices for multi-actor ecosystems.Storage systems must comply with data-sovereignty constraints defined by the data-space governance model. This includes ensuring that data remains within approved jurisdictions and that its retention duration aligns with legal, contractual, and operational constraints. Long-term storage may rely on tiered architectures where high-frequency operational data is placed on high-performance storage while historical or aggregated datasets are archived using more cost-efficient backends.

7. High level HMI principles and requirements

The Human–Machine Interface (HMI) plays a critical role in enabling safe, efficient, and intuitive communication between the orchestrator and the end users. Across desktop, mobile, and web platforms, the HMI serves as the primary channel to convey information, instructions, and warnings to the users, and collect feedback or data in return. A well-designed HMI ensures that information is presented clearly, consistently, and in a timely manner, supporting informed decision-making. Adherence to specifications and established standards is essential to guarantee interoperability, reliability, and safety across systems. In addition, alignment with agreed specifications is particularly important to enable harmonisation, scalability, and future integration, while ensuring that communication remains unambiguous, predictable, and fit for operational deployment.

In CARMONY, three types of devices are planned to be developed and used for communication with the end user, namely a web dashboard, an in-vehicle dashboard and a mobile app. The following table presents the devices to be used per pilot site and per user type. The potential user types are listed below:

- TMC or orchestrator operator
- Mobility manager
- Driver of CCAM vehicle
- Driver of non-CCAM vehicle
- VRU (pedestrian, cyclist, escooter rider…)
- Elderly
- Disabled (mobility disability)

There are some commonalities, as well as differences among the two sites in relation to the use of the devices by potential user categories.

Table 14. Devices to be used in Murcia pilot.

HMI TYPE	Users						
	TMC/ Orchestrator manager	**Mobility manager**	**Driver of CCAM vehicle**	**Driver of non-CCAM vehicle**	**VRU**	**Elderly**	**Disabled**
Web Dashboard	X	X					
In-vehicle dashboard			X				
Mobile app				X	X	X	X

Table 15. Devices to be used in Luxembourg pilot.

HMI TYPE	Users						
	TMC/ Orchestrator manager	**Mobility manager**	**Driver of CCAM vehicle**	**Driver of non-CCAM vehicle**	**VRU**	**Elderly**	**Disabled**
Web Dashboard	X	X					

HMI TYPE	Users						
	TMC/ Orchestrator manager	**Mobility manager**	**Driver of CCAM vehicle**	**Driver of non-CCAM vehicle**	**VRU**	**Elderly**	**Disabled**
In-vehicle dashboard			X	X			
Mobile app			X	X	X	X	X

Summarising the tables above, the devices are to be used per user type as follows:

- Web dashboard: TMC/orchestrator manager and mobility manager.
- In-vehicle dashboard: Driver of CCAM vehicle and non-CCAM vehicle (for Luxembourg only).
- Mobile app: Driver of CCAM vehicle (for Luxembourg only), driver of non-CCAM vehicle, VRU, elderly, disabled.

HMI requirements, tailored to the needs of the project follow below, for efficient user interface with the orchestrator.

7.1 Web dashboard

There are no special HMI principles in terms of colours that need to be applied for the specific type of device, apart from the generic ones that apply to all the PC/smart devices screens. A primary list of such requirements follows below, along with the relevant standards:

Table 16. Visual and Usability Requirements for Web-Based Dashboards.

ID	Requirement	Description	Applies to	Relevant Usability / Accessibility Standards
R1	Clear visual hierarchy	Primary information shall be visually dominant through size, position, and contrast	PC, Smart devices	ISO 9241-110 (Dialogue principles – suitability for perception), Nielsen heuristic: Visibility of system status
R2	Grid-based layout	Layout shall follow a consistent grid to ensure alignment and visual coherence	PC, Smart devices	ISO 9241-112 (Presentation of information), Material Design / Fluent UI guidelines
R3	Responsive design	Dashboard shall adapt layout and content to different screen sizes and orientations	PC, Smart devices	ISO 9241-210 (Human-centred design), WCAG 2.2 – Reflow (1.4.10)
R4	Minimum text size	Body text shall be ≥14 px (desktop) and ≥15 px (mobile); headings proportionally larger	PC, Smart devices	WCAG 2.2 – Text Resize (1.4.4), ISO 9241-303
R5	Readable typography	Fonts shall be sans-serif, with line spacing 1.4–1.6× font size	PC, Smart devices	ISO 9241-303 (Electronic visual displays), Nielsen heuristic: Readability
R6	High color contrast	Text and icons shall meet minimum contrast ratios	PC, Smart devices	WCAG 2.2 – Contrast (1.4.3, 1.4.11)
R7	Functional use of color	Color shall not be the sole means of conveying information	PC, Smart devices	WCAG 2.2 – Use of Color (1.4.1), ISO 9241-110

ID	Requirement	Description	Applies to	Relevant Usability / Accessibility Standards
R8	Consistent iconography	Icons shall use a consistent style and metaphor set	PC, Smart devices	ISO 9241-112, Nielsen heuristic: Consistency and standards
R9	Icon size and touch targets	Interactive elements shall be ≥44×44 px on touch devices	Smart devices	WCAG 2.2 – Target Size (2.5.8), ISO 9241-9
R10	Moderate information density	Information shall be grouped and spaced to avoid overload	PC, Smart devices	ISO 9241-110 (Suitability for the task), Cognitive Load Theory
R11	Progressive disclosure	Detailed information shall be hidden by default and revealed on demand	PC, Smart devices	ISO 9241-110, Nielsen heuristic: Aesthetic and minimalist design
R12	Card-based modularity	Dashboard elements shall be modular and independently rearrangeable	PC, Smart devices	ISO 9241-112, Responsive UI best practices
R13	Immediate visual feedback	User actions shall result in visible feedback within 200 ms	PC, Smart devices	ISO 9241-110 (Feedback), Nielsen heuristic: Visibility of system status
R14	Visible system state	Current system status shall always be clearly indicated	PC, Smart devices	ISO 9241-110, Nielsen heuristic: Visibility of system status
R15	Error visibility	Errors shall be clearly highlighted with guidance for resolution	PC, Smart devices	ISO 9241-110 (Error tolerance), WCAG 3.3 (Input assistance)
R16	Keyboard accessibility	All functionality shall be accessible via keyboard	PC	WCAG 2.2 – Keyboard Accessible (2.1.1), ISO 9241-171
R17	Focus indicators	Keyboard focus shall be clearly visible	PC, Smart devices	WCAG 2.2 – Focus Visible (2.4.7)
R18	Scalable UI	Dashboard shall remain usable up to 200% zoom	PC, Smart devices	WCAG 2.2 – Resize text (1.4.4), Reflow (1.4.10)
R19	Visual stability	Layout shifts during loading or updates shall be minimized	PC, Smart devices	ISO 9241-110 (Predictability), Web Vitals (CLS)
R20	Performance perception	Core content shall be visible within 2 seconds	PC, Smart devices	ISO 9241-210, Nielsen heuristic: Efficiency of use
R21	Touch-friendly spacing	Controls shall be spaced to avoid accidental activation	Smart devices	ISO 9241-9, WCAG 2.2 – Target Size
R22	Orientation support	Dashboard shall support portrait and landscape orientations	Smart devices	ISO 9241-210, Mobile usability guidelines
R23	Accessibility for diverse users	Design shall support users with reduced vision, motor, or cognitive abilities	PC, Smart devices	WCAG 2.2 (overall), ISO 9241-20
R24	Professional and consistent appearance	Visual design shall be consistent, minimal, and brand-aligned	PC, Smart devices	ISO 9241-110 (Consistency), Nielsen heuristic

ID	Requirement	Description	Applies to	Relevant Usability / Accessibility Standards
R25	Transparency and explainability	Complex data or AI-driven outputs shall be clearly labeled and explained	PC, Smart devices	ISO 9241-210, Trustworthy AI / Explainable AI guidelines

When it comes to CCAM related dashboards (e.g. traffic management centres, fleet supervision, remote operation support, incident monitoring), there are specific requirements that can be tracked in literature, extending standard usability requirements with AI transparency, safety, resilience, and accountability, aligned with CCAM, Trustworthy AI, and the EU AI Act. These are applicable only for PCs. In addition, a three level-warning is foreseen depending on the criticality of the event that is considered in the requirements below.

Table 17. Requirements for CCAM back-office dashboards.

ID	Requirement	Description (Safety-Critical / AI-Driven Context)	Applies to	Standards / Guidance	Alert Level
SR1	Safety-first visual hierarchy	Safety-critical info always visually dominant	PC	ISO 9241-110; ISO 9241-210	Informational: Moderate prominence; Warning: Highlighted visually; Emergency: Maximum prominence, top of layout
SR2	Priority-based layout zoning	Screen divided into critical/warning/informational zones	PC	ISO 9241-112; Endsley SA model	Informational: Peripheral zone; Warning: Center-left; Emergency: Center-top
SR3	Real-time responsiveness	Updates visually reflected within latency limits	PC	ISO 25010; ISO 9241-210	Informational: ≤2s; Warning: ≤1s; Emergency: <0.2s
SR4	Robust visual contrast	Enhanced contrast for safety alerts	PC	WCAG 2.2; ISO 9241-303	Informational: normal contrast; Warning: ≥7:1; Emergency: ≥10:1
SR5	Redundant visual encoding	Critical states use color + shape + text	PC	WCAG 2.2 (1.4.1)	Informational: color + icon; Warning: color + icon + optional text; Emergency: color + shape + text, flashing optional
SR6	Consistent safety iconography	Standardized and unambiguous symbols	PC	ISO 7010; ISO 9241-112	Icon prominence scales with alert level
SR7	Alert prioritisation rules	Concurrent alerts ranked by safety relevance	PC	IEC 62366; HF safety engineering	Levels prioritized: Informational < Warning < Emergency

ID	Requirement	Description (Safety-Critical / AI-Driven Context)	Applies to	Standards / Guidance	Alert Level
SR8	Controlled information density	High-risk situations trigger decluttering	PC	ISO 9241-110	Informational: standard layout; Warning: collapse non-critical cards; Emergency: show only critical info
SR9	Progressive escalation	Alerts escalate if unresolved	PC	CCAM HMI best practices	Informational → Warning → Emergency automatically
SR10	Persistent system state visibility	Automation mode & limits always visible	PC	UNECE CCAM guidance	Display adapts to alert level: highlighted for higher levels
SR11	AI decision transparency	AI outputs include human-readable explanation/confidence	PC	EU AI Act; Trustworthy AI	Informational: optional details; Warning: confidence shown; Emergency: full explanation + rationale
SR12	Confidence & uncertainty display	AI uncertainty visually distinguishable	PC	XAI guidelines	Informational: small icon; Warning: highlighted; Emergency: bold + flashing
SR13	Explainable drill-down	Operators can inspect AI reasoning & data sources	PC	IEEE 7001; ISO 9241-210	Informational: optional; Warning: recommended; Emergency: mandatory
SR14	Bias-aware visualisation	Avoid bias in AI interpretation	PC	EU AI Act (non-discrimination)	Apply at all levels; Emergency alerts require validation check
SR15	Operator action feedback	Actions produce immediate visual confirmation	PC	ISO 9241-110	Informational: subtle highlight; Warning: more prominent; Emergency: high-contrast confirmation
SR16	Error tolerance & recovery	Errors clearly indicated, safe recovery path	PC	WCAG 3.3	Informational: inline warning; Warning: highlighted; Emergency: modal + persistent until resolved
SR17	Role-based views	UI adapts to operator role	PC	ISO 9241-210	Same for all alerts, but emergency info always visible for all roles

ID	Requirement	Description (Safety-Critical / AI-Driven Context)	Applies to	Standards / Guidance	Alert Level
SR18	Auditability & traceability	AI outputs & operator actions logged	PC	EU AI Act; ISO 27001	Logging at all levels; Emergency logs include timestamp + operator override
SR19	Fail-safe visual modes	Degraded/fallback states simplified	PC	IEC 61508	Informational: no change; Warning: simplified layout; Emergency: only critical info visible
SR20	Visual consistency across systems	Harmonised visual language	PC	ISO 9241-110	Applies to all alert levels
SR21	Accessibility under stress	UI usable under high workload	PC	Human reliability engineering	Informational: standard; Warning: reduced info clutter; Emergency: only essential info visible
SR22	Scalable and zoom-safe UI	Usable at ≥200% zoom	PC	WCAG 2.2	Applies to all alert levels
SR23	Secure visual feedback	Security-relevant events clearly indicated	PC	ISO 27001	Highlight severity depending on alert level
SR24	Trust-supporting design	Visual design supports calibrated trust	PC	Trustworthy AI	All alert levels; emergency alerts designed for instant recognizability
SR25	Regulatory compliance visibility	Compliance states clearly identifiable	PC	EU AI Act; CCAM regulations	Applies to all alert levels; highlighted during warning/emergency

7.2 In-vehicle dashboard

The in-vehicle dashboard should be designed in order to allow a three-level warning. Key HMI elements characteristics are provided below from literature and chatgpt tool, for visual and acoustic messages.

Visual messages: both text and icons are needed

In general, larger icons and text size are used in CCAM vehicles than in conventional vehicles. The recommended characteristics are shown in Table 18.

Table 18. Visual messages requirements for in-vehicle dashboard.

Message type	Angular size	Physical size	Pixel size
Informational (situational awareness, no immediate action)	18-25 arcmin	6-9 mm	36-54 px
Warning (e.g. upcoming handover)	25-35 arcmin	9-12 mm	54-72 px

Emergency (e.g. system failure, imminent risk)	40-60 arcmin	14-20+ mm	84-120+ px

Acoustic messages: both voice and sound messages

The characteristics in Table 19 are recommended.

Table 19. Acoustic messages requirements for in-vehicle dashboard.

Aspect	Informational	Warning	Emergency
Urgency	Low	Medium	High
Loudness	+5–8 dB above cabin noise	+8–12 dB above cabin noise	+10–15 dB above cabin noise
Voice tone	Calm / neutral	Firm / directive	Command / imperative
Duration	≤ 2 s	2–5 s or until acknowledged	Continuous until resolved
Repetition	Optional	Repeated once if unresolved	Repeated until resolved
Multimodal	Optional	Recommended	Mandatory (audio + visual + optional haptic)
User suppression	Allowed	Discouraged	Not allowed
Cognitive load	Low	Moderate	Minimal & direct
AI output transparency	Optional explanation	Show confidence level	Full rationale and drill-down available
Accessibility	Standard	Enhanced contrast and touch targets	Maximum contrast, accessible to all users, clear labeling

Escalation mode should be supported, with intensification of sound pattern over time and an increase of the pitch, tempo, or repetition rate of the message. Also, messages should be language-Independent where possible.

Finally, the output has to be aligned with trustworthy AI & AI Act, thus include transparent cause–effect correlation, a predictable alert behavior and not include misleading or anthropomorphic language.

Summarising, icons, text and sound are required for an in-vehicle HMI of a dashboard in an autonomous vehicle, allowing a progressive escalation of the size, brightness and flashing rate. Details have to be avoided, especially in waring and emergency modes, in order to allow the driver/passenger to recognize quickly the needed info. Around 80% of the sensory input gathered by humans is visual, with humans possessing a horizontal field of vision spanning approximately 170 degrees. When presenting visual information, it is vital to consider various factors such as intensity, colour choice, contrast, lighting strength, and angle of vision. On the other hand, sound serves as the most attention-grabbing sensory input, unlike vision, it cannot be switched off; the ability to locate sound is highly sensitive, with the ears registering phase differences below 1500 Hz to calculate the direction of the sound, while intensity changes are utilized for frequencies above 3000 Hz [13].

7.3 Mobile app

Although mobile apps are standardized in terms of HMI elements, special characteristics need to be considered for the CARMONY app, not only due to the importance of the information and warning messages to be delivered, but also due to the special needs of the end users, since elderly and disabled persons are considered. For example, specific thresholds for individuals with auditory disabilities need to be defined. Auditory messages intended for elderly individuals may require slight amplification, typically falling within the range of 70 to 80 dB, to ensure optimal clarity and comprehension. Furthermore, when considering individuals with auditory disabilities, the decibel thresholds can vary significantly depending on the specific nature and severity of their condition. Some individuals may benefit from auditory messages that are substantially louder, potentially ranging from 80 to 90 dB or higher [14].

This section is planned to be updated and enriched in WP5, and T5.3 in particular, where the actual mobile tools are going to be developed and more information will be available on the exact types of disabilities to be addressed in each of the pilot sites, as well as the types of messages (visual, auditory, etc.) that shall be delivered to the users.

8. Summary and definition of interlinked orchestrator

Based on the material in this report as well as other deliverables from WP2 and on-going work in WP3, we define the interlinked orchestrator as decision systems for traffic management operating at different levels, where each level corresponds to a different time-scale for decisions. At the lowest, real-time level (called reactive layer in CARMONY), the process must be completely automated. The time-scale of this layer is minutes or seconds. The second layer (called preventive layer), which updates the guidelines used by the automatic decision logic in the reactive layer and whose time-scale is days or weeks, is mostly automatic: some human input could be needed. Finally, the governance layer has a time-scale of several months to years. In this layer, governance, business models, and incentive mechanisms of the orchestration are updated, and human input will be needed. Figure 16 shows these layers and how they use different kinds of simulations and data. Further perspectives on the interlinked orchestrator are presented in D3.1.

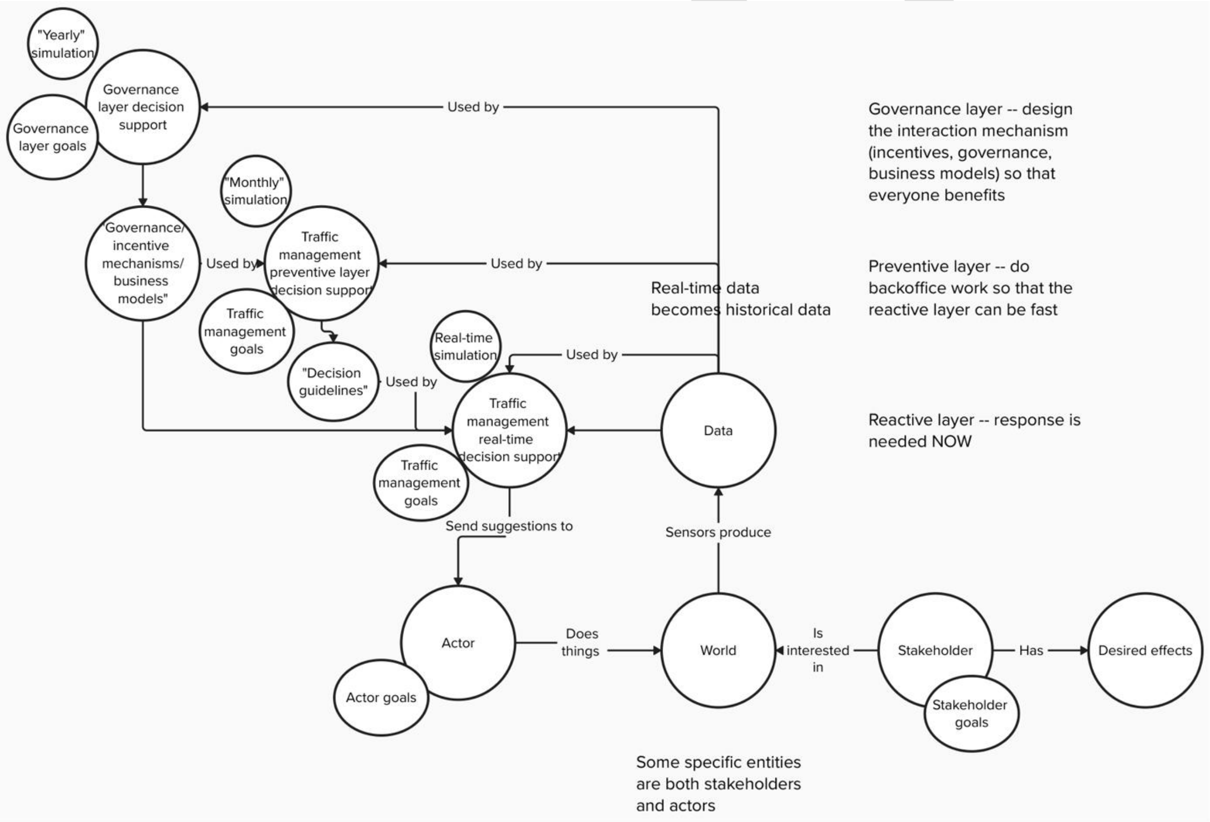

Figure 16. Interlinked orchestrator.

In this report, we collected background knowledge on orchestration along with SoS models of use cases, data exchange requirements, and HMI high level requirements. Together with deliverables D2.1 and D2.3, it will serve as design input to the technical and governance WPs in CARMONY. Requirements and models will be refined further in T4.2 and WP5.

9. Abbreviations

Term	Definition
DEC	Websites, Patent Filings, Videos etc.
DEM	Demonstrator, Pilot, Prototype
CARMONY	Safe, Resilient Transport and Smart Mobility services for passengers and goods
CS	Constituent System
SES	Single European Sky
CV	Connected Vehicle
PU	Public
LEZ	Low Emission Zones
R	Document, Report
SEN	Sensitive
SoS	System-of-systems
VRU	Vulnerable Road User
WP	Work Package

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