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Abstract

CN provides a comprehensive overview of SIGN-AIR solution, which introduces a platform for the automated generation and monitoring of Data Sharing Agreements (DSAs) and Smart Contracts (SCs) between multimodal Transport Service Providers (TSPs) such as airlines and highspeed railway operators. The solution facilitates the orchestration of intermodal data sharing contractual aspects from the generation until the execution of the contracts. This document summarizes the main operational and performance benefits, including enhanced airport accessibility and synchronized multimodal scheduling for single ticketing between rail and air and introduces the content of the solution's technical deliverables. It concludes with recommendations for the industrialization phase to support the deployment of integrated, passenger-centric transport services.

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SIGN-AIR

IMPLEMENTED SYNERGIES, DATA SHARING CONTRACTS AND GOALS BETWEEN TRANSPORT MODES AND AIR TANSPORTATION PROJECT TITLE

SIGN-AIR

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1 Purpose of the document

This contextual note provides to any interested reader (external and internal to the SESAR programme) an introduction to SIGN-AIR technological solution (SOL0375) in terms of scope, main operational and performance benefits, relevant system impacts, standardization and regulatory considerations. It also contains recommendations to be considered during the industrialisation and/or implementation phases.

This contextual note introduces SIGN-AIR solution´s technical deliverables which are the following:

- Technical specifications/interface requirements (TS/IRS): The TS/IRS document provides the functional, non-functional and interface requirements related to a SESAR Solution. The technical specifications address the “what” and not the “how”, they aim at specifying the functional description and the necessary logical interfaces between the SESAR Solution and other parts of the Air Traffic Management (ATM) system.

- Technological validation plan (TVALP): The validation plan describes the way in which one or more validation exercises or activities are to be prepared and executed to achieve the validation objectives. It includes those validation exercises that are required and sufficient to ensure that the SESAR Technological Solution (TVALP- Technological Validation Plan) will progress from the initial maturity level to the target one. As appendix, it includes the required transversal and performance assessment plans (e.g. safety, Human Performance).

- Technological validation report (TVALR): The validation report consolidates the validation results for a SESAR Technological Solution once the validation activities for a given maturity level have been completed.

- Cost-benefit analysis (CBAT): The cost-benefit analysis (CBA) documents the potential benefits, when deployed in the applicable environment(s), of a SESAR ATM Solution or a SESAR Technological Solution (CBAT), and whether or not they are expected to exceed the costs over a given time horizon.

- Standardisation (STAND): Proposed SESAR solution input to standardisation activities (e.g. EUROCAE) if any.

- Regulation (REG): Proposed SESAR solution input to regulation activities (e.g. EUROCAE) if any.

2 Improvements in air traffic management (ATM)

The SIGN-AIR solution enhances ATM by integrating its operations into a wider multimodal transport network, ensuring that data exchange between air and ground Transport Service Providers (TSPs) is governed by secure, automated contracts. Its scope is the orchestration of multimodal transport through contractual data management: Smart Contracts monitor data sharing conditions in real time, ensuring that technical execution matches the agreed legal rules and building trust between TSPs across modes.

The solution comprises two main components (SIGN-AIR platform and SYNC-REACT module) that work in tandem across planning and operational phases (see Figure 1).

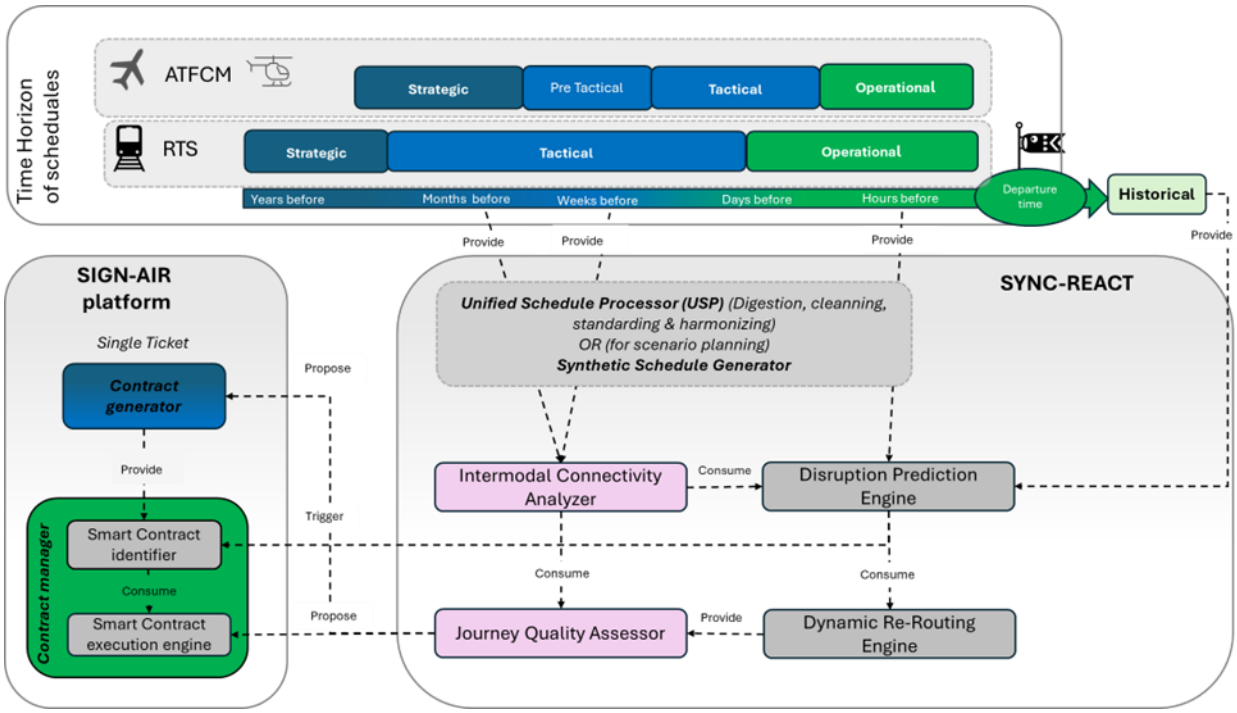


Figure 1: SIGN-AIR solution´s concept

The **SIGN-AIR platform** automates the creation and management of Data Sharing Agreements (DSAs) and Smart Contracts between TSPs. It provides regulation-compliant templates tailored to specific multimodal goals, and handles the full contract lifecycle through two functions: a Contract Generator that supports identification of potential collaborations, automated drafting and negotiation; and a Contract Manager that monitors whether contractual clauses are fulfilled in real time and triggers the appropriate actions — such as controlling data access, logging usage, or checking compliance — when conditions are met. The SIGN-AIR platform automates the full lifecycle of Data Sharing Agreements (DSAs) and Smart Contracts between TSPs, from initial onboarding through to post-signature monitoring. The process unfolds in five stages (as presented at the tutorial):

1. Onboarding: A TSP registers on the platform and creates its entity data catalogue, declaring the data attributes and services it is willing to share.

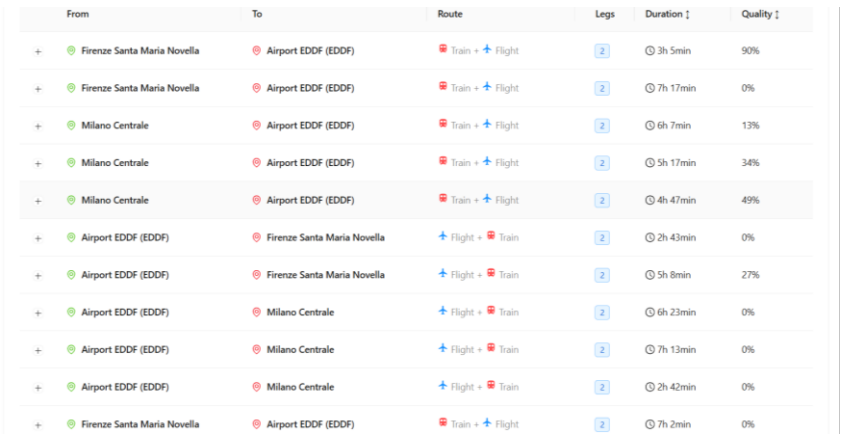
2. Discovery: The platform cross-references all registered catalogues — the catalogue of catalogues — to automatically identify potential collaboration opportunities between TSPs based on complementary data and operational goals.

3. Negotiation: A TSP can invite a counterpart to negotiate. The platform provides regulation-compliant templates tailored to the specific multimodal goal (e.g., single ticketing, timetable synchronisation) and a user-friendly interface to discuss and agree on contractual clauses. For the goals of single ticketing and timetable synchronisation, the platform offers access to the SYNC-REACT module at this stage, enabling both parties to identify and evaluate feasible combined itineraries as the basis for their agreement (see Figure X).

4. Settlement: Once both TSPs agree on the terms of the DSA and Smart Contract, they proceed to settlement, which includes testing the Smart Contract logic before formal signature to verify that execution conditions behave as intended.

5. Monitoring: After signature, the Contract Manager monitors in real time whether the clauses of the active Smart Contract are being fulfilled, and automatically triggers the appropriate actions — such as controlling data access, logging usage, or flagging non-compliance — when conditions are met.

The **SYNC-REACT** module integrates multimodal schedules from different transport modes (synchronization jobs, see as example Figure 2 and — including aircraft, trains and eVTOLs — to generate combined itineraries that respect Minimum Connection Times (MCT) and maximise multimodal connectivity. Upon receiving disruption alerts from TSPs, the module assesses the impact on planned itineraries, predicts cascading effects on subsequent legs, and proposes real-time rerouting options. For emerging modes not yet in operation, such as eVTOLs, a Synthetic Schedule Generator allows the module to simulate operational scenarios and assess future connectivity potential. SYNC-REACT is integrated with SIGN-AIR platform but is also a stand-alone module.



From	To	Route	Legs	Duration	Quality
Firenze Santa Maria Novella	Airport EDDF (EDDF)	Train + Flight	2	3h 5min	90%
Firenze Santa Maria Novella	Airport EDDF (EDDF)	Train + Flight	2	7h 17min	0%
Milano Centrale	Airport EDDF (EDDF)	Train + Flight	2	6h 7min	13%
Milano Centrale	Airport EDDF (EDDF)	Train + Flight	2	5h 17min	34%
Milano Centrale	Airport EDDF (EDDF)	Train + Flight	2	4h 47min	49%
Airport EDDF (EDDF)	Firenze Santa Maria Novella	Flight + Train	2	2h 43min	0%
Airport EDDF (EDDF)	Firenze Santa Maria Novella	Flight + Train	2	5h 8min	27%
Airport EDDF (EDDF)	Milano Centrale	Flight + Train	2	6h 23min	0%
Airport EDDF (EDDF)	Milano Centrale	Flight + Train	2	7h 13min	0%
Airport EDDF (EDDF)	Milano Centrale	Flight + Train	2	2h 42min	0%
Firenze Santa Maria Novella	Airport EDDF (EDDF)	Train + Flight	2	7h 2min	0%

Figure 2: Synchronization job for Bologna Airport (BLQ)

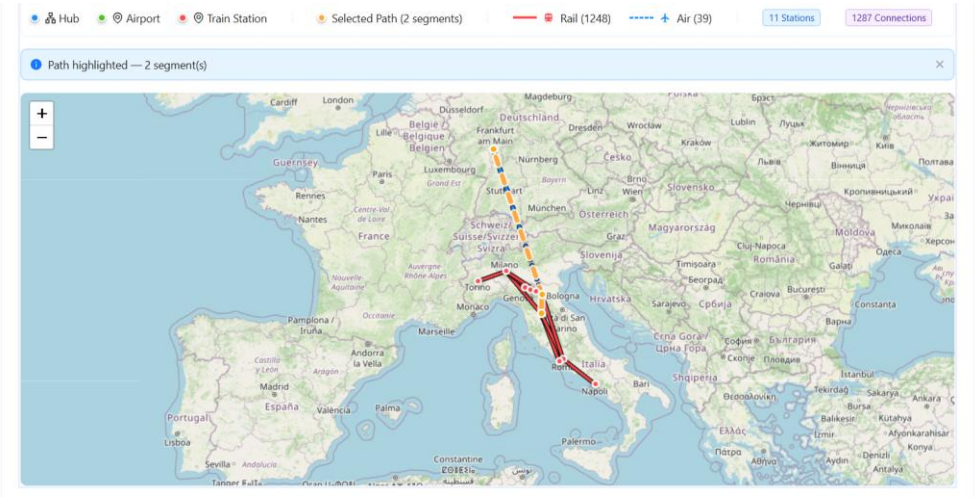


Figure 3: Combined itinerary highlighted

Together, these two components serve three categories of multimodal data sharing goals:

- **Mobility packages**, covering seasonal tickets, combined tickets and single tickets, which allow travellers to purchase one entitlement for a complete multimodal journey under a unified contractual framework.

- **Timetable synchronisation**, enabling TSPs to align their schedules at shared nodes such as airports to maximise flight connections, extend reach to underserved passenger segments, support substitution of short-haul flights by long-distance rail, and integrate on-demand services dynamically.

- **Disruption management**, providing a coordinated process across airports, railway and bus operators to detect and classify events — from minor delays to major disruptions — calculate their impact on connected itineraries, and execute automated responses including passenger notifications, rebooking or rerouting recommendations, and resource optimisation actions.

The solution is applicable across airports of all sizes, from small to very large, and delivers the following improvements:

- Single ticketing capability: TSPs can identify promising intermodal itineraries and offer passengers a seamless single ticket covering multiple modes, with unified fare reconciliation, ticket validation and enforcement of passenger rights in the event of disruption.

- Enhanced airport accessibility: New connectivity indices measure the impact of integrating additional routes via different transport modes into hub airports, transforming the airport into a true intermodal hub where physical and digital networks converge.

- Multimodal performance management: Air travel performance is evaluated and optimised in conjunction with ground transport, treating different systems as a single integrated network.

- Beyond-ATC disruption management: The platform introduces the ability to manage connections and prioritise flights based on disruptions originating outside ATC — such as train

cancellations or ground transport delays — by sharing real-time status updates based on pre-negotiated contractual rules, ensuring that Minimum Connection Times are respected even under unplanned conditions.

More specifically the contract generation works as follows: A TSP has to onboard to SIGN-AIR platform. By onboarding we mean the registration of the end user and of its entity data catalogue creation. Then the platform proceeds to the discovery process and identifies potential collaborations based on the catalogue of catalogues. Then the TSP is able to send an invitation for negotiation to another TSP. The platform offers templates of the multimodality goal and a friendly interface to negotiate. For the specific goals of timetables synchronization and single ticketing SIGN-AIR solution offers the opportunity to identify the combined itineraries by providing SYNC-REACT module. When the two TSPs finally agree on the terms of the Data Sharing Agreements and Smart Contract then they proceed to the settlement and test the SC before its signature. The post settlement is the monitoring of the data sharing.

3 Applicable enablers

This section lists the enablers supporting SIGN-AIR solution and provide their definition.

1. AOC-ATM (or FOC)-01853 ¨ Advanced route planning for the identification of appropriate air–rail connections¨. Required/Fully covered
2. AOC-ATM (or FOC)-01876 ¨Assessment Airports accessibility via Intermodal Connectivity calculation¨. Required/Fully covered
3. AOC-ATM (or FOC)-01877 ¨Enhance airlines passenger Notification System and Travel Companion (TC) with multimodal information and intermodal alternative itineraries¨. Required/Fully covered
4. HUM-01855 ¨ Modify responsibility of a Data Maintenance Officer for fragmented data models and ownership of data attributes across departments/systems¨ Required/Fully covered
5. HUM-01878 ¨ Passenger Services Desk (within Operations Control Center- OCC) staff able to propose intermodal itineraries. ¨. Required/Fully covered
6. HUM-01879 ¨Network Planning Department able to analyse rail-air and air-rail connectivity index to propose intermodal appropriate itineraries¨ Required/Fully covered
7. HUM-01880 ¨ Update the role for Passenger Notification and Multimodal Updates¨ Required/Fully covered

4 Background and validation process

This section outlines the validation process/path that contributed to mature the SIGN-AIR solution from TRL2 to the exit maturity level TRL6.

The overall aim of the validation process is to present the identified **essential operational use cases** to validate the SIGN-AIR solution to measure its effects (positive and negative) to the ATM.

Essential operational use cases refer to the core, representative scenarios that must be addressed to demonstrate that the SESAR technological solution (system enabler) works. Specifically, they:

1. Represent the minimum required functionalities that the solution must support.
2. Are used in laboratory or pre-industrial validation and real time simulation (RTS) exercises, typically with standalone research prototypes.
3. Are designed to prove that the solution performs as intended in controlled but realistic setting.
4. Are designed to cover the services offered by the solution (e.g., Creation of data catalogue, Data Sharing Agreements and Smart Contracts, Calculation of actions based on the predefined rules and execute contracts and monitor contractual aspects of data sharing.)

Although, the solution can bring effects to various stakeholders the focus of the project and of this validation plan is on **air and railway transportation pairs** namely airport-high speed railway operators, airport-regional railway operators, airline-high speed railway operators, airline-regional railway operators.

The essential use cases are the following:

- UC1: Creation of a DSA and/or a SC: Defines how two transportation service providers (TSPs) establish a contractual agreement, covering onboarding, negotiation, and settlement.
- UC2: Monitoring a DSA and SC: Ensures all aspects of the contract are monitored and managed effectively throughout its lifecycle.
- UC4: Synchronization of Timetables: Ensures synchronization of timetables between two TSPs so combined itineraries are possible ensuring efficient and seamless schedule alignment to ease connections, meaning that the passenger connection time at the hub.

To cover these essential use cases, we choose to orient the exercises towards the following scenarios:

1. **Booking, Purchasing, and Issuing a Single Ticket DSA and SC**
2. **Disruption Management when Single Ticket DSA and SC are singed**

The creation and monitoring of a DSA and SC for the multimodal goal of Single Ticketing needs:

1. **Necessity of Timetable Synchronization**
    a. Identification of Minimum Connecting Time: To offer a single ticket, the system must guarantee that the connection is physically possible and appealing to the traveller.
2. **Clear Framework for Revenue and Responsibility Sharing.** Single ticketing transforms a vague partnership into a precise financial and legal commitment offering:

a. **Enforceable Revenue Splits**: The system must define exactly how the revenue is divided (e.g., 70% to the airline, 30% to the rail operator). Without the fixed segments of a single ticket, these "cost-sharing rules" would be impossible to automate via Smart Contracts.

b. **Legal Accountability**: It defines the "Chain of Responsibility." When a passenger purchases one ticket for an intermodal journey, its rights need to be respected and the legal burden for missed connections or cancellations is pre-assigned. This allows the system to identify which TSP is liable for rebooking or compensation is case of a disruption.

The solution partners conducted the validation exercises at TRL4 and TRL6 as listed in Table 1. EXE1 and EXE2 were focused validated the synchronization of timetables. EXE3 and EXE9.2 were performed on TransiTool platform. EXE 9.1 was performed in Roger Travel Companion. The rest of the exercises were performed at SIGN-AIR platform. In the exercises, reference and solution scenarios were compared to determine the benefits of the improved digitalization and passenger experience. At EXE7, 44 experts (including consortium partners) from different entities (e.g., THALESIT, ECTL, IST, BLQ, Aegean Airlines, public transport authorities). and with diverse expertise participated in a 5h stakeholders´ workshop held at BLQ airport.

The results of the validation exercise were evaluated at the exercise level and summarized at the solution level. Conclusions and recommendations were derived from this.

Table 1: SIGN-AIR validation exercises

TRL	#	Title	Validation Technique	Organizations	Sub Operating Environment	Datasets
TRL4	EXE1	Assessment of synchronization functionality of SYNC-REACT module	Laboratory Test	UPC, UB-FTTE, ENAC	Very large, large, medium airport,	IST CDG (from ECTL) BLQ
	EXE2	Validation of Disruption Management functionality of SYNC-REACT module towards increasing digitisation elements	Laboratory Test	UPC, UB-FTTE, SPA, BLQ	medium airport,	BLQ
	EXE3	Assessment TT extension/data conversion	Laboratory Test	AETHON	medium airport,	BLQ
	EXE4	Assessment of Scenario 1 in nominal situations	Laboratory Test	UPC, SPA, FD	medium airport,	BLQ
	EXE5	Assessment of Scenario 1 with SYNC-REACT	Laboratory Test	UPC, SPA, FD	medium airport,	BLQ
	EXE6	Assessment of Scenario 2	Laboratory Test	UPC, SPA, FD	medium airport	BLQ
TRL6	EXE7	Validation of Scenario 1	Real-Time Simulation	UPC, UB-FTTE, ENAC, FD, Timelex, BLQ,	medium airport	BLQ ECTL
	EXE8	Validation of Scenario 2	Real-Time Simulation	UPC, UB-FTTE, ENAC, FD, Timelex, BLQ,	medium airport	BLQ ECTL
	EXE9.1	Validation of Travel Companion	Real-Time Simulation	UPC, BLQ, TPER, EPF	medium airport	BLQ
	EXE9.2	Validation of TT (conversion of Bologna data)	Real-Time Simulation	AETHON, BLQ, TPER	medium airport	BLQ

5 Results and performance achievements

This section outlines the main validated findings, results, and performance achievements of SIGN-AIR solution on digitalization and on passenger experience.

Digitalization Achievements

- **Automated Contract Lifecycle:** Validation confirmed that the platform successfully automates the full lifecycle of Data Sharing Agreements (DSAs) and Smart Contracts (SCs) including the monitoring of contractual aspects of data sharing for a total data governance.
- **Catalogue of Catalogues:** The platform achieved a high maturity for discoverability. TSPs were able to digitally declare the existence, quality, and integrity of their datasets, creating a transparent registry of available transport data (Schedules, Fares, and Real-time updates).
- **Interoperability of Heterogeneous Data:** A key digital achievement was the seamless orchestration of different transport standards in both SYNC-REACT external module and TransiTool. The solution successfully integrated IATA SSIM (Air) with GTFS and NeTEx (Rail/Ground), allowing for a unified digital view of intermodal journeys. This allows the identification of disruptions coming from ground transport modes and the beyond-ATC Disruption Management.

These achievements are reflected by the results conducted under the SESAR Digitalisation Index (SDI) methodology for TRL6, evaluates the solution across three primary pillars:

- DIGI1 – Digitisation (98%): This pillar assesses the transition of information from analog to digital formats, focusing on data origin, existence, and quality. SIGN-AIR achieves near-perfect performance by ensuring that contract data is standardized and digitally native, providing a high-integrity foundation for multimodal services.
- DIGI2 – Connectivity (88%): This pillar measures the ability of systems to exchange data across the network, focusing on accessibility, latency, and interoperability. SIGN-AIR demonstrates high maturity by reducing contract processing latency from days to minutes, though it accounts for the inherent complexities of diverse TSP technical infrastructures.
- DIGI3 – Data Sharing (100%): This pillar focuses on the governance, cybersecurity, and legal frameworks required for trusted exchange. SIGN-AIR reaches maximum achievement here, providing a secure, automated environment for legal licensing that ensures all stakeholders adhere to interoperable protocols.

Passenger Experience Achievements

By improving the underlying data coordination, the SIGN-AIR solution directly enhances the reliability and convenience of the multimodal passenger journey.

- **Enhanced Connectivity Planning:** Validation exercises showed that the system's connectivity indices perfectly matched expert manual rankings. This ensures passengers are offered the most reliable and efficient transfer options and establishes metrics to enhance the accessibility of the airports.
- **Reduction in Transfer Friction:** The synchronization of schedules between air and rail modes, validated through the SYNC-REACT module, significantly reduces the risk of missed

connections. This leads to a "Single Ticketing" experience where the complexity of the transfer is hidden from the passenger.

- **Quality of Travel Suggestions**: All multimodal travel plans generated during the validation were assessed as "High Quality." The system successfully identified and filtered out "infeasible" pairs (e.g., transfers with insufficient time), ensuring that passengers are only presented with realistic, stress-free travel options.

The aforementioned achievements are reflected by the results of validation measured against specific mathematical thresholds to ensure a high standard of service:

- PAX1 – Travel Time (Efficiency): This KPA focuses on minimizing the total duration of the journey (TTT). It ensures that multimodal alternatives remain competitive by keeping total travel time under 240 minutes and limiting transfer and waiting periods to less than 33% of the total trip time. It also benchmarks the chosen route against the fastest available alternative to ensure optimal routing.
- PAX3 – Resilience (Disruption Management): This area measures the journey's ability to maintain continuity during perturbations. It requires the availability of at least one tactical alternative for any given Origin-Destination pair and mandates that final arrival time adherence stays within the "minimum connection time" threshold to prevent missed connections.
- PAX4 – Ease (Simplicity): To ensure a seamless and intuitive user experience, this KPA tracks the physical complexity of the trip. A "successful" journey under SIGN-AIR parameters is designed to involve two or fewer legs, reducing the cognitive and physical effort required by the passenger.
- PAX6 – Robustness (Structural Stability): This pillar assesses the long-term reliability of the transport offer. It utilizes a Connectivity Index (> 0.7) to evaluate strategic options and sets strict frequency requirements—demanding at least 4 services per hour during peak times—to guarantee that the multimodal network is a dependable alternative to mono-modal travel.

6 Recommendations for deployment

This section provides recommendations based on the technical specifications (TS-IRS) and validation results (TVALR) to ensure the successful deployment and operational integration of the SIGN-AIR solution.

Technical and architectural considerations

Based on the TS-IRS, the following technical measures are recommended for full-scale deployment:

- Federated Deployment and Data Space Integration: The SIGN-AIR solution should be implemented as a Contractual Governance Layer within a federated hub-and-spoke architecture, where SIGN-AIR serves as the central orchestrator providing regulation-compliant templates (DSAs and SCs) to define the rules of engagement, while federated data spaces (e.g., Eona-X) provide the secure, sovereign data pipes for actual transmission. This ensures Transport Service Providers maintain control over their data while adhering to a common legal and technical framework.

- Semantic and Syntactic Harmonisation: To ensure rapid adoption and cross-border interoperability, the Intermodal Action Manager should prioritise the harmonisation of existing standards (GTFS, NeTEx, IATA SSIM) rather than introducing new proprietary formats, through robust transformation adapters that map diverse datasets into a unified internal model for the synchronisation graph.

- Modular Smart Contract Logic: Smart Contracts within SIGN-AIR should be treated as modular, pluggable execution blocks rather than monolithic structures. This allows Transport Service Providers to connect specialised tools (e.g., AI predictors, ticketing engines) directly to the governance framework, accommodating the varying conditions and triggers across different use cases such as delay compensation or baggage transfer.

- Automated Disruption Injection: The disruption handling process, which currently relies on manual data re-uploads, must be automated to reflect the asynchronous, multi-source nature of real operational disruptions. This is a prerequisite for validating true real-time disruption management ahead of deployment.

- Graph Database Integration: The Sparksee graph database integration, deferred during validation due to time constraints, must be completed and assessed under realistic data volumes to confirm that connectivity calculations perform adequately at scale.

- Strategic Use of SYNC-REACT: Beyond real-time disruption response, stakeholders are encouraged to use the SYNC-REACT module as a strategic planning tool — simulating connectivity improvements at candidate hubs, assessing airport access alternatives during closures, and exploring integration with emerging transport modes such as eVTOLs and seaplanes.

- Predictive Disruption Modelling: The development of AI-driven predictive models is recommended to proactively suggest pre-emptive Data Sharing Agreements based on

historical route-level delay data, strengthening the contractual and operational resilience of the multimodal offer before disruptions occur.

Human enablers

Although SIGN-AIR is classified as a technological solution, its operational viability is fundamentally dependent on human roles that the platform cannot automate. The following measures are recommended:

Validation of Human Roles: Dedicated validation exercises assessing how the key roles — Data Maintenance Officer, Operations Control Officer, Flight Schedule Planner, Route Network Manager and Decision Support Officer — interact with the platform under realistic operational conditions should be designed and executed as a priority. These exercises should examine training needs, information usability, decision support adequacy and accountability mechanisms.

Operational readiness

Drawing on the findings from the TVALR, the following measures are recommended to ensure operational readiness:

- Transition to Real-World Data: Initial deployment phases should use real-world data feeds from Transport Service Providers to calibrate the system against authentic operational conditions, replacing the synthetic datasets used during validation. Broader coverage, beyond the airports and rail operators included in the validation exercises, is also recommended to test semantic alignment and connectivity calculations under greater data heterogeneity.

- Stakeholder Involvement in Workflows: The negotiation and synchronisation workflows require broader stakeholder involvement in particular legal experts and airline ticketing personnel to ensure that Data Sharing Agreement and Smart Contract logic is operationally sound and legally finalised before rollout.

- End-User Interface Testing: Platform interfaces should be tested with more real end-users who are less familiar with the system, to validate the usability of data entry and parameter-setting procedures. Data quality at the point of ingestion is as critical as the underlying technology.

- Training for TSP Administrators: Deployment plans should include targeted training covering: the coherent declaration of data attributes in the catalogue to ensure data integrity; and the logic of rail-air and air-rail connectivity index parameters to support informed identification of intermodal itineraries

7 Recommendations for future R&I activities

The validation campaign surfaced several research questions that extend beyond the current scope and are suitable for future research and innovation programmes:

- Scalability and high-concurrency contract execution: Future R&I should investigate the architectural and algorithmic requirements for executing multiple Smart Contracts simultaneously, including conflict resolution mechanisms, transaction throughput optimisation, and the performance of blockchain-based audit trails under real operational load.
- Cascading disruption management: Real-world multimodal disruptions rarely affect a single leg in isolation. Future research should develop more sophisticated disruption propagation models and investigate how Smart Contracts can be designed to handle cascading and simultaneous disruptions across legs, modes and contractual obligations while preserving passenger rights and Transport Service Provider accountability.
- Integration of emerging transport modes: The validation demonstrated the feasibility of incorporating seaplane schedules into the SIGN-AIR ecosystem, opening a broader research agenda around Advanced Air Mobility, autonomous ground vehicles and on-demand services. Future R&I should develop the data standards, contractual frameworks and connectivity modelling approaches needed to integrate these modes into multimodal networks.
- AI-assisted decision support and predictive analytics: Future research should explore the introduction of machine learning capabilities to support proactive functions — anticipating minimum connection time violations before they occur, recommending contract renegotiation based on historical patterns, or dynamically proposing itinerary alternatives based on predicted disruption trajectories — while ensuring that AI-generated proposals remain subject to human decision-making authority.
- Data governance and organisational interoperability: Future R&I should investigate how data sovereignty requirements, GDPR obligations, and the varying data governance maturity levels across Transport Service Providers affect practical deployment, including research into federated data architectures and the design of data sharing agreements that are robust to decentralised data management structures.
- Standardisation of the Passenger Experience assessment: The PAX assessment methodology developed for SIGN-AIR fills a gap in the current SESAR Performance Framework. Future R&I should work towards formalising this into a reusable, validated framework so that future multimodal solutions can assess their passenger experience contributions on a consistent and comparable basis.
- Environmental and sustainability impact: Multimodal integration has the potential to shift demand from short-haul air legs to rail connections, directly contributing to EU sustainability goals. Future research should develop methodologies for quantifying the modal shift and carbon reduction potential of platforms like SIGN-AIR, positioning this work within the broader SESAR and Horizon Europe sustainability agenda.

8 Impact on roles and responsibilities

This section presents the changes in roles and responsibilities with the required / developed human enablers identified in section 3.

Actors/roles directly affected by the SESAR Solution are:

- Data Maintenance Officer
- Airport CDM Project Manager
- Decision Support Officer
- Operations Control Officer
- Flight Schedule Planner
- Route Network Manager
- Operations Control Officer

9 Impact on aircraft system

SIGN-AIR solution does not have an impact on aircraft systems.

10 Impact on ground systems

This chapter links the changes in terms of ground systems with the required / developed ground related system enablers identified in chapter 3.

The systems directly affected by the SESAR Solution are:

- Route Network Management
- Disruption and Recovery Management
- Passenger Booking Management

11 Regulatory considerations

The development of the solution the core of the solution the drafting of the Data Sharing Agreements and the Smart Contracts templates and templating mechanisms, hence applicable regulations considered were the following:

- the Data Act: Regulation (EU) 2023/2854 of the European Parliament and of the Council of 13 December 2023 on harmonized rules on fair access to and use of data and amending Regulation (EU) 2017/2394 and Directive (EU) 2020/1828
- the Data Governance Act: Regulation (EU) 2022/868 of the European Parliament and of the Council of 30 May 2022 on European data governance and amending Regulation (EU) 2018/1724
- the Platform-to-business relations Regulation: Regulation (EU) 2019/1150 of the European Parliament and of the Council of 20 June 2019 on promoting fairness and transparency for business users of online intermediation services
- the Artificial Intelligence Act (AI ACT): Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonized rules on artificial intelligence and amending Regulations (EC) No 300/2008, (EU) No 167/2013, (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1139 and (EU) 2019/2144, and Directives 2014/90/EU, (EU) 2016/797 and (EU) 2020/1828.
- the GDPR: Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC
- the NIS 2 Directive: Directive (EU) 2022/2555 of the European Parliament and of the Council of 14 December 2022 on measures for a high common level of cybersecurity across the Union, amending Regulation (EU) No 910/2014 and Directive (EU) 2018/1972, and repealing Directive (EU) 2016/1148
- the Digital Services Act: Regulation (EU) 2022/2065 of the European Parliament and of the Council of 19 October 2022 on a Single Market For Digital Services and amending Directive 2000/31/EC
- the Copyright DSM Directive: Directive (EU) 2019/790 of the European Parliament and of the Council of 17 April 2019 on copyright and related rights in the Digital Single Market and amending Directives 96/9/EC and 2001/29/EC
- the Trade Secrets Directive: Directive (EU) 2016/943 of the European Parliament and of the Council of 8 June 2016 on the protection of undisclosed know-how and business information (trade secrets) against their unlawful acquisition, use and disclosure
- the Database Directive: Regulation (EU) 2022/2065 of the European Parliament and of the Council of 19 October 2022 on a Single Market For Digital Services and amending Directive 2000/31/EC
- the Updated ITS Directive: Directive (EU) 2023/2661 of the European Parliament and of the Council of 22 November 2023 amending Directive 2010/40/EU on the framework for the

deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport

- the MMTIS Delegated Regulation: Commission Delegated Regulation (EU) 2017/1926 of 31 May 2017 supplementing Directive 2010/40/EU of the European Parliament and of the Council with regard to the provision of EU-wide multimodal travel information services
- the E-commerce Directive: Directive 2000/31/EC of the European Parliament and of the Council of 8 June 2000 on certain legal aspects of information society services, in particular electronic commerce, in the Internal Market (Directive on electronic commerce).
- the eIDAS Regulation: Regulation (EU) No 910/2014 of the European Parliament and of the Council of 23 July 2014 on electronic identification and trust services for electronic transactions in the internal market and repealing Directive 1999/93/EC.
- the Rome I Regulation: Regulation (EC) No 593/2008 of the European Parliament and of the Council of 17 June 2008 on the law applicable to contractual obligations.
- the Brussels Ibis regulation: Regulation (EU) No 1215/2012 of the European Parliament and of the Council of 12 December 2012 on jurisdiction and the recognition and enforcement of judgments in civil and commercial matters
- the Consumer Rights Directive (CRD): Directive 2011/83/EU of the European Parliament and of the Council of 25 October 2011 on Consumer Rights.
- the Unfair Contract Terms Directive (UCTD): Council Directive 93/13/EEC of 5 April 1993 on Unfair Terms in Consumer Contracts
- the Code of Conduct for computerized reservation systems: Regulation (EC) No 80/2009 of the European Parliament and of the Council of 14 January 2009 on a Code of Conduct for computerised reservation systems and repealing Council Regulation (EEC) No 2299/89
- the Common Rules for the Operation of Air Services in the Community: Regulation (EC) No 80/2009 of the European Parliament and of the Council of 14 January 2009 on a Code of Conduct for computerized reservation systems and repealing Council Regulation (EEC) No 2299/89
- the common rules on compensation and assistance to passengers in the event of denied boarding and of cancellation or long delay of flights: Regulation (EC) No 261/2004 of the European Parliament and of the Council of 11 February 2004 establishing common rules on compensation and assistance to passengers in the event of denied boarding and of cancellation or long delay of flights, and repealing Regulation (EEC) No 295/91
- the common rules for the allocation of slots at Community airports: COUNCIL REGULATION (EEC) No 95/93 of 18 January 1993
- the Air navigation Services provision regulation: REGULATION (EC) No 550/2004 of the European Parliament and of the Council of 10 March 2004 on the provision of air navigation services in the single European sky (the service provision Regulation)
- the requirements for air traffic management/air navigation services, design of airspace structures and data quality, runway safety: REGULATION (EU) 2020/469 amending Regulation (EU) No 923/2012, Regulation (EU) No 139/2014 and Regulation (EU) 2017/373 as regards

requirements for air traffic management/air navigation services, design of airspace structures and data quality, runway safety and repealing Regulation (EC) No 73/2010

- the Common Project: COMMISSION IMPLEMENTING REGULATION (EU) 2021/116 of 1 February 2021 on the establishment of the Common Project One supporting the implementation of the European Air Traffic Management Master Plan provided for in Regulation (EC) No 550/2004 of the European Parliament and of the Council, amending Commission Implementing Regulation (EU) No 409/2013 and repealing Commission Implementing Regulation (EU) No 716/2014
- One supporting the implementation of the European Air Traffic Management Master Plan: COMMISSION IMPLEMENTING REGULATION (EU) 2021/116 of 1 February 2021 on the establishment of the Common Project One supporting the implementation of the European Air Traffic Management Master Plan provided for in Regulation (EC) No 550/2004 of the European Parliament and of the Council, amending Commission Implementing Regulation (EU) No 409/2013 and repealing Commission Implementing Regulation (EU) No 716/2014
- the Union guidelines for the development of the trans-European transport network: REGULATION (EU) 2024/1679 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 June 2024 on Union guidelines for the development of the trans-European transport network, amending Regulations (EU) 2021/1153 and (EU) No 913/2010 and repealing Regulation (EU) No 1315/2013
- the requirements for the operation of manned aircraft with a vertical take-off and landing capability: COMMISSION IMPLEMENTING REGULATION (EU) 2024/1111 of 10 April 2024 amending Regulation (EU) No 1178/2011, Implementing Regulation (EU) No 923/2012, Regulation (EU) No 965/2012 and Implementing Regulation (EU) 2017/373, as regards the establishment of requirements for the operation of manned aircraft with a vertical take-off and landing capability
- the requirements for the management of information security risks with a potential impact on aviation safety for organizations: REGULATION (EU) 2023/203 of 27 October 2022 laying down rules for the application of Regulation (EU) 2018/1139 of the European Parliament and of the Council, as regards requirements for the management of information security risks with a potential impact on aviation safety for organizations
- the requirements for manned aviation operating in U-space airspace: COMMISSION IMPLEMENTING REGULATION (EU) 2021/666 of 22 April 2021 amending Regulation (EU) No 923/2012 as regards requirements for manned aviation operating in U-space airspace, COMMISSION IMPLEMENTING REGULATION (EU) 2021/665 of 22 April 2021 amending Implementing Regulation (EU) 2017/373 as regards requirements for providers of air traffic management/air navigation services and other air traffic management network functions in the U-space airspace designated in controlled airspace, COMMISSION IMPLEMENTING REGULATION (EU) 2021/664 of 22 April 2021 on a regulatory framework for the U-space
- the common rules in the field of civil aviation and establishing a European Union Aviation Safety Agency: REGULATION (EU) 2018/1139 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, of 4 July 2018 on common rules in the field of civil aviation and establishing a European Union Aviation Safety Agency, and amending Regulations (EC) No 2111/2005, (EC)

No 1008/2008, (EU) No 996/2010, (EU) No 376/2014 and Directives 2014/30/EU and 2014/53/EU of the European Parliament and of the Council

SIGN-AIR solution single ticketing has **regulatory needs** for the multimodal passengers' rights which is currently a proposed regulation, which is not published yet.

12 Standardisation considerations

The applicable standards considered are the following:

- Airlines or airports should use the IATA SSIM format to provide the schedules as input to the SYNC-REACT module for the synchronization of timetables.
- High speed railway operators, regional railway operators, bus operators provide their planned schedules in GTFS format.

SIGN-AIR solution does not require new or an amendment of a published standard.

13 SESAR solution technical deliverables

The relevant technical deliverables for this Solution include the following documents:

- VALP for TRL4 and TRL6, Edition 00.07.00, 20/01/2026. The document details the validation exercises planned for the solution.
- VALR for TRL6, D2.9, Edition 00.02.00, 15/05/2026. The document collects and describes the results of the validation exercises.
- STAND for TRL6, D2.12, Edition 00.01.00, 26/02/2026. The document maps the multimodality applied standards and identifies if the is a need for an amendment or an introduction of a new standard.
- REG for TRL6, D2.13, Edition 00.01.00, 28/02/2026. The document maps the multimodality applied regulations and identifies if the is a need for an amendment or an introduction of a new regulation.
- TS/IRS for TRL6, D2.10, Edition 00.08.00, 15/05/2026. The document collects and describes the Technical System Requirements.
- CBAT for TRL6, D2.11, Edition 00.03.00, 20/02/2026. This document provides the Cost Benefit Analysis.

Appendix A Draft SESAR solution implementation objective

A.1 Draft implementation objective title and description

The SIGN-AIR Implementation Objective refers to the establishment of an Automated Data Sharing and Contractual Framework for multimodal transport, as defined in the SIGN-AIR Technical Specifications (D2.10) and aligned with the European Common Mobility Data Space (EMDS) goals.

The scope of this Objective covers the digital interface between Air Transport and Surface Transport within the catchment areas of large and medium airport hubs. It specifically addresses the "contractual friction" that currently hinders seamless intermodal synchronization and "Single Ticketing" capabilities.

Operational Purpose

The SIGN-AIR platform contributes to multimodal operations as a coordination improvement, enabling Transport Service Providers (TSPs) to automate the legal and technical requirements for data exchange. This Service depends on the existence of digital data catalogues from participating TSPs.

The platform supports TSPs and Airport Operators and airlines by:

- Streamlining Onboarding: Providing a digital Identity and Access Management (IAM) system to verify legal entities across different transport sectors.
- Automating Agreement Generation: Utilizing a library of templates to generate legally binding Data Sharing Agreements (DSAs) without manual legal intervention for every new partnership.
- Executing Smart Contracts (SC): Translating legal prose into executable code on a blockchain to automate triggers for data exchange, compensation, or synchronization during operational disruptions.

Core Functions

The implementation is designed on the basis of the following core functional modules, which may be introduced incrementally depending on the digital maturity of the local transport ecosystem:

- Discoverability: Allowing TSPs to declare and discover available datasets (Schedules, Fares, Real-time feeds) and also identify the missing datasets to achieve a predefined multimodality goal.
- Negotiation & Settlement: A digital environment for agreeing on terms and conditions, culminating in the "signing" of a digital contract.
- Identification of intermodal routes: A digital tool that allows the digestion and harmonization of schedules of different modes and with criteria implemented proposes intermodal itineraries via a certain hub airport.
- Post-Settlement/Monitoring: An active monitoring process that tracks the fulfilment of contractual obligations and manages intermodal synchronization triggers (e.g., notifying an airline that a single ticket passenger is going to be delayed and if possible to catch the flight via fast track lane could be provided else assign the his/her seat to another passenger and reroute the delayed passenger)

Co-funded by the European Union

A.2 List of applicable enablers

1. AOC-ATM (or FOC)-01853 ¨ Advanced route planning for the identification of appropriate air–rail connections¨.
2. AOC-ATM (or FOC)-01876 ¨Assessment Airports accessibility via Intermodal Connectivity calculation¨.
3. AOC-ATM (or FOC)-01877 ¨Enhance airlines passenger Notification System and Travel Companion (TC) with multimodal information and intermodal alternative itineraries¨.
4. HUM-01855 ¨ Modify responsibility of a Data Maintenance Officer for fragmented data models and ownership of data attributes across departments/systems¨
5. HUM-01878 ¨ Passenger Services Desk (within Operations Control Center- OCC) staff able to propose intermodal itineraries. ¨
6. HUM-01879 ¨Network Planning Department able to analyse rail-air and air-rail connectivity index to propose intermodal appropriate itineraries¨
7. HUM-01880 ¨ Update the role for Passenger Notification and Multimodal Updates¨

A.3 Expected performance benefits

The SIGN-AIR solution serves as a digital orchestrator for contract management and data-sharing among Transport Service Providers (TSPs), directly addressing the SESAR Digitalisation (DIGI) Key Performance Area. By automating legal licensing and governance, the solution enables a seamless transition from manual, time-consuming processes to an agile, multimodal data ecosystem. The assessment, conducted under the SESAR Digitalisation Index (SDI) methodology for TRL6, evaluates the solution across three primary pillars:

- DIGI1 – Digitisation (98%): This pillar assesses the transition of information from analog to digital formats, focusing on data origin, existence, and quality. SIGN-AIR achieves near-perfect performance by ensuring that contract data is standardized and digitally native, providing a high-integrity foundation for multimodal services.
- DIGI2 – Connectivity (88%): This pillar measures the ability of systems to exchange data across the network, focusing on accessibility, latency, and interoperability. SIGN-AIR demonstrates high maturity by reducing contract processing latency from days to minutes, though it accounts for the inherent complexities of diverse TSP technical infrastructures.
- DIGI3 – Data Sharing (100%): This pillar focuses on the governance, cybersecurity, and legal frameworks required for trusted exchange. SIGN-AIR reaches maximum achievement here, providing a secure, automated environment for legal licensing that ensures all stakeholders adhere to interoperable protocols.

The assessment tracks four primary KPAs, measured against specific mathematical thresholds to ensure a high standard of service:

- PAX1 – Travel Time (Efficiency): This KPA focuses on minimizing the total duration of the journey (TTT). It ensures that multimodal alternatives remain competitive by keeping total travel time under 240 minutes and limiting transfer and waiting periods to less than 33% of the total trip time.

It also benchmarks the chosen route against the fastest available alternative to ensure optimal routing.

- PAX3 – Resilience (Disruption Management): This area measures the journey's ability to maintain continuity during perturbations. It requires the availability of at least one tactical alternative for any given Origin-Destination pair and mandates that final arrival time adherence stays within the "minimum connection time" threshold to prevent missed connections.
- PAX4 – Ease (Simplicity): To ensure a seamless and intuitive user experience, this KPA tracks the physical complexity of the trip. A "successful" journey under SIGN-AIR parameters is designed to involve two or fewer legs, reducing the cognitive and physical effort required by the passenger.
- PAX6 – Robustness (Structural Stability): This pillar assesses the long-term reliability of the transport offer. It utilizes a Connectivity Index (> 0.7) to evaluate strategic options and sets strict frequency requirements—demanding at least 4 services per hour during peak times—to guarantee that the multimodal network is a dependable alternative to mono-modal travel.

A.4 Initial list of applicable stakeholders

Civil APT operator

Civil Scheduled Aviation

Civil Flight Operations Centre

Railway operator

A.5 Initial list of applicability areas(s) and timescales

The applicability area are large and medium airports. These locations serve as the critical nodes where air transport intersects with high-speed rail and regional ground transportation, requiring the highest level of data orchestration. The following dates represent our best-informed estimation for the deployment

Initial Operational Capability (IOC): 31/12/2028

Full Operational Capability / Target Date (FOC): 31-12-2035

Our estimations took into account:

- **Complexity of Multi-Sector Integration**: Unlike single-mode solutions, SIGN-AIR requires the synchronization of disparate transport sectors (Air, Rail, local transit, advanced air mobility). While the technological validation (TVALR) proved that the Smart Contracts Framework and API Orchestration are functional, the period leading to the IOC is required to align the varying operational cultures, legacy IT systems, and data-sharing readiness of diverse stakeholders at large/medium airport hubs.
- **Policy and Regulatory Alignment**: The path to industrialization is significantly influenced by different levels of European and national policy (e.g., U-space regulations, GDPR, and the European Common Mobility Data Space). The timeline to 31/12/2027 allows for the necessary legal and regulatory "onboarding" of Transport Service Providers (TSPs) to ensure that the

automated Data Sharing Agreements (DSAs) are fully compliant with evolving cross-border transport policies.

- Transition from Synthetic to Real-World Data: The TVALR highlighted that while performance was exceptional with synthetic data, a phased approach is necessary to calibrate the SYNC-REACT module against real-life operational disruptions. The gap between IOC and FOC (2027–2028) is essential for this "stress-testing" phase, ensuring the system can handle the high transaction volumes and unpredictable delay patterns inherent in large-scale airport operations.

In summary, while the SIGN-AIR process is technically robust, these dates acknowledge that the industrialization of a multimodal ecosystem is a non-linear process dependent on multi-stakeholder coordination and policy maturity.

A.6 Supporting material

Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on passenger rights in the context of multimodal journeys (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52023PC0752)