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Interoperable Digital Twins   
for Multimodal Transportation:   
Optimizing Passenger and Freight Journeys

A Digital Twin Consortium White Paper

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# Abstract

Today’s multimodal networks are constrained by silos between transport modes, data systems, and public and private actors. Freight shipments are often delayed at intermodal hubs due to poor visibility. Passengers experience disconnected journeys with limited coordination across providers. These inefficiencies raise costs, erode trust, and limit the sector’s ability to support resilience and decarbonization.

What’s missing is not innovation in isolation, but interoperability at scale: a shared approach that enables people, cargo, and information to move efficiently across a diverse network of carriers, systems, and jurisdictions.

This paper offers that approach. It outlines the core business capabilities needed to support end-to-end multimodal journeys. It also describes how disruptive technologies can drive coordinated action across the ecosystem. These technologies include digital twins, AI agents, blockchain, geographic information systems (GIS), and mobile platforms.

Architectural and governance frameworks ensure these technologies work effectively together. These include a System of Systems methodology, Event-Driven and Distributed Architectures, and a Common Information Model. A detailed roadmap guides stakeholders from pilot projects to interoperable systems, with modeling and simulation embedded throughout to reduce risk and improve outcomes.

For leaders in government, industry, and technology, this paper provides a strategic blueprint to transition from fragmented operations to a unified and high-performing multimodal future.

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# 1 Introduction

Multimodal transportation inefficiencies are not merely operational issues - they impose a significant drag on national economies. Economic analysis, such as a 2024 study commissioned by the UK Department for Transport, indicates that deploying an integrated network management digital twin across just five transport use cases could yield £1.85 billion in undiscounted benefits. These gains are primarily driven by improvements in journey time, reliability, and service quality, along with broader non-monetized benefits like reduced public sector costs and enhanced access to services. This underscores the critical economic value of investing in interoperable, digitally coordinated transportation systems.

Multimodal transportation today is constrained by silos between modes, between data systems, and between the public and private sectors. These inefficiencies increase costs, erode trust, and prevent the industry from achieving its full potential as a driver of economic resilience and decarbonization. What is missing is not innovation in isolation, but interoperability at scale.

This white paper presents a strategic, vendor-neutral blueprint for achieving seamless, scalable, and intelligent multimodal transportation. The approach outlines how public and private actors can overcome fragmentation through coordinated governance, open data standards, and system-of-systems architecture. The resulting cohesive roadmap transforms disconnected networks into high-performing, adaptive ecosystems that optimize journeys for people, goods, and infrastructure alike.

## 1.1 Purpose & Audience

The primary purpose of this document is to foster cross-sector alignment and inform decisions that promote interoperability, real-time data sharing, and the deployment of convergent technologies, including digital twins, AI, and blockchain. These technologies are essential to enable more adaptive, connected, and intelligent transportation systems.

The whitepaper serves as a strategic resource for professionals and decision-makers across a broad spectrum of sectors whose collaboration is essential for integrated mobility. These stakeholders include:

* **Government & Policy Makers:** City and regional government officials, urban mobility professionals, and transportation policymakers.
* **Urban & Infrastructure Planners:** Transportation system planners, civil engineers, and accessibility specialists.
* **Sustainability & Environmental Groups:** Organizations focused on reducing emissions and advancing greener infrastructure.
* **Port & Airport Authorities:** Staff and operators focused on maximizing the use of space and schedules while operating secure hubs.
* **Transportation Carriers:** Air carriers, rail operators, public transit agencies, and mobility service providers.
* **Industrial Supply Chain Stakeholders:** Freight logistics coordinators and retail logistics planners.
* **Technology & Innovation Partners:** Mobility tech developers, system integrators, and data scientists.
* **Security & Safety Experts:** Consultants and officials focused on proactive and adaptive safety measures.

## 1.2 What is Multimodal Transportation?

Multimodal transportation refers to the use of two or more different types of transport, such as trains, buses, ships, or planes, within a single journey for people or goods. The goal is seamless integration across these modes so that the journey, despite involving many parts, feels like one cohesive experience.

A diagram of a vehicle and a bus

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[Figure 1.2-1: Fundamentals of Multimodal Transportation](https://store.aci.aero/wp-content/uploads/2024/02/WATF-Executive-Summary.pdf)

In **passenger transportation**, systems must support the entire physical and logistical journey, including walking between platforms, using accessibility features, managing transit time, and handling luggage or assistance needs. Well-integrated systems must accommodate the varied physical, logistical, and personal needs of all travelers, ensuring mobility is both efficient and inclusive. This includes providing wide corridors, accessible routes, real-time updates, streamlined interchanges, and unified ticketing.

In **freight transportation**, multimodal shipping enables goods to move efficiently over long distances by using containers that move through ports, railyards, and warehouses with minimal handling. Modern supply chains rely on centralized coordination, smart scheduling, tracking systems, and real-time data sharing to manage all legs under one contract or multiple agreements. Multimodal logistics form the foundation of global commerce, connecting manufacturing, distribution, and retail.

## 1.3 Integrated Hubs: Enabling Seamless Transfers Across Air, Ground, and Water

Transportation hubs are the critical nodes that make multimodal journeys possible, connecting air, rail, road, maritime, and emerging mobility systems. They enable passengers and cargo to move across transportation networks.

These hubs integrate diverse systems such as aircraft and trains, ships and trucks, metros and autonomous shuttles, while coordinating digital platforms, operational workflows, and regulatory frameworks. Their core complexity lies in synchronizing vehicle movements, data flows, and stakeholder actions to manage thousands of simultaneous interactions.

Their success depends on how seamlessly they connect physically, digitally, and organizationally. This requires aligning the operating speeds, data systems, and regulatory frameworks of different modes. Each hub type must orchestrate thousands of simultaneous interactions involving vehicles, assets, cargo, and people within a unified flow of information.

### 1.3.1 Core Multimodal Hubs

These hubs anchor the transportation network, linking long-distance, regional, and urban systems for passengers and cargo. They serve as consolidation points where multiple modes intersect, enabling reliable, high-capacity, and coordinated transfers.

### 1.3.2 Emerging First/Last Mile Hubs

These hubs extend the reach of the core network, improving accessibility and responsiveness for passengers and cargo. They include new mobility modes such as eVTOLs and drones.

A person carrying a box

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#### 1.3.2.1 Vertiport Hubs for eVTOLs

Vertiports support eVTOL operations for urban and regional air mobility. They provide first/last-mile air connections between airports, station hubs, and suburban areas. Real-world initiatives highlight the emergence of these hubs. For example, Skyports Infrastructure has been appointed the lead vertiport developer for South Korea’s first commercial vertiport network on Jeju Island, identifying initial sites including Jeju International Airport [1]. The project targets early AAM operations later this decade.

Similarly, UrbanV and the Korea Airports Corporation have partnered to jointly develop Korea’s broader Advanced Air Mobility ecosystem, sharing regulatory and operational expertise to design and operate future vertiport networks [2].

#### 1.3.2.2 Distribution Centers for e-Bike and Drone Deliveries

Distribution centers and drone hubs enable first/last-mile freight services by connecting ports, airports, and urban areas through autonomous drones, cargo bikes, and ground robots.

On the ground-mobility side, organizations such as Empire Clean Cities support safe, low-emission first/last-mile mobility [3]. Their SAFE Program expands access to fire-safe, certified e-bikes, particularly for delivery workers, enhancing the reliability and sustainability of micromobility within urban logistics networks.

## 1.4 When Multimodal Fails: Transportation Journeys in the Real World

While multimodal transportation initiatives offer tremendous potential to enhance efficiency, accessibility, and sustainability, they often fall short in practice. Even in regions with well-intentioned investments in public transit, logistics networks, and mobility infrastructure, fragmented systems, poor data sharing, and a lack of real-time coordination can lead to cascading failures. Without the right technologies, governance frameworks, and architectural integration, the promise of seamless transportation turns into a frustrating experience, especially during complex journeys that rely on multiple interconnected providers and modes.

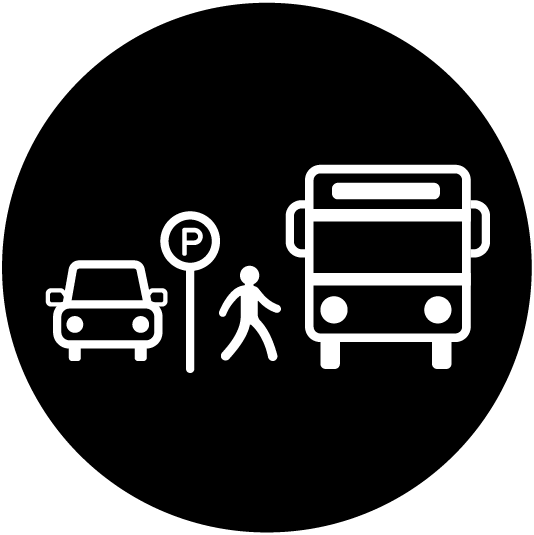
### 1.4.1 Disconnected Vacation Travel: A Passenger’s Multimodal BreakdownA family with luggage and a ship AI-generated content may be incorrect.

The Johnson family’s vacation illustrates how disconnected services create a stressful ordeal. Choosing to drive to DFW Airport, Mr. Johnson was caught in unexpected traffic, arriving late. Operational failures compounded their difficulties: uncoordinated wheelchair assistance led to a 45-minute wait. A flight delay, coupled with conflicting or delayed communications and a last-minute gate change, forced a rush across terminals.

Challenges intensified upon arrival in Miami: one checked bag containing medication was lost, and airline staff could not track the luggage. The family faced heavy traffic en route to the cruise terminal with no updates or alternative routes provided by their shuttle. Key passenger challenges included:

* Missing real-time updates across airlines, ground transport, and cruise lines.
* Uncoordinated accessibility services.
* Disjointed modal handoffs with no unified routing or journey management.

### 1.4.2 Unreliable Daily Commutes: A Worker’s Multimodal Strain

Maya, a healthcare worker, faced daily strain due to disconnected services in her commute. Her park-and-ride lot was unexpectedly full with no digital alerts. She missed her express bus because the app’s arrival time was inaccurate, and a subsequent detour lacked clear wayfinding.

Key commuter challenges included:

* No advance notice of capacity issues at park-and-ride or transit hubs.
* Inaccurate transit arrival times.
* Lack of integrated systems to respond to real-world conditions dynamically.

### 1.4.3 Disconnected Freight Logistics: The Cost of Fragmentation

A black and white image of a crane loading a container

AI-generated content may be incorrect.A shipment of high-value sustainable textiles from Europe to Manhattan revealed how fragmented freight operations can unravel even well-planned supply chains. Although the vessel arrived on time at the Port of New York & New Jersey, congestion and poor berth scheduling caused costly delays. The importer received no alerts and could not adjust downstream deliveries.

A crane malfunction during unloading, compounded by the lack of predictive maintenance or contingency planning, delayed transfer to rail and barge connections. Later, last-mile delivery faced EV fleet downtime and route disruptions, with no centralized visibility to reassign assets or drivers.

The result: missed delivery windows, financial penalties, and reputational damage. This case illustrates how disconnected systems, limited data sharing, and reactive management can turn efficient multimodal logistics into cascading failure.

Key operational challenges included:

* Port congestion and missed berthing.
* Equipment failures with no predictive maintenance.
* Disjointed modal handoffs and lack of real-time coordination.

## 1.5 Aligning Stakeholder Priorities To Enable Seamless Transportation

Transportation failures often stem from fundamental misalignments between the priorities, incentives, and capabilities of the many stakeholders in the multimodal ecosystem. Achieving the vision of seamless transportation requires active coordination to bridge these divides.

The table below illustrates the tensions that stall progress:

|  |  |  |
| --- | --- | --- |
| **Stakeholder Category** | **Goals** | **Challenges** |
| Government & Policy Makers | Build safe, resilient, and connected systems; drive economic prosperity. | Struggle with fragmented policies, funding gaps, and limited data-sharing. |
| Urban & Infrastructure Planners | Create connected, inclusive transport systems that improve reliability. | Struggle to design multimodal systems that can handle growth, technology shifts, and equity needs simultaneously. |
| Port & Airport Authorities | Operate secure, efficient hubs; maximize use of space and schedules. | Bottlenecks and idle capacity from disconnected systems; difficult to sync carriers and people in real time. |
| Transportation Carriers | Drive seamless intermodal travel; keep goods and people moving on time. | Unexpected changes and unpredictable events cascade into enormous delays. |
| Industrial Supply Chain Stakeholders | Unlock real-time visibility and responsiveness for agile logistics. | Must integrate real-time visibility and cybersecurity into complex logistics networks. |
| Technology & Innovation Partners | Enable trusted, data-driven collaboration across transportation systems. | Struggle to deliver interoperable, resilient systems amid gaps in standards and connectivity. |
| Passengers & End Users | Travel affordably and reliably with seamless, stress-free connections. | Face complicated transfers, delays, and a lack of seamless journey experiences. |

Table 1.4-1: Goals and Challenges of Transportation Stakeholders

Alignment between these stakeholder priorities is the foundation for the optimization strategies outlined in subsequent sections, aiming to enable system-wide orchestration.

# 2 Optimizing Transportation Journeys

Efficient multimodal transportation requires aligning the diverse priorities of public sector entities, private sector operators, and end-users. These stakeholders may emphasize goals like safety, sustainability, cost reduction, or revenue optimization. Translating their strategic intent into cohesive operational capabilities is essential for achieving end-to-end journey optimization.

Transportation journeys can be broken down into three interrelated optimization domains: **passenger flow**, **freight movement**, and **asset and resource utilization**. Optimizing these domains necessitates decomposing high-level goals into capabilities that can be monitored, measured, and continuously improved.

## 2.1 Meeting Stakeholder Goals

Effective multimodal transportation requires more than strategic alignment; it demands a capability-driven approach that enables traceability from stakeholder intent to system performance. This involves decomposing high-level goals into modular capabilities that can be orchestrated across diverse systems, measured through Key Performance Indicators (KPIs), and continuously refined. By embedding stakeholder priorities into the architecture of transportation systems, planners and operational systems alike can ensure that optimization efforts are technically sound, contextually relevant, and outcome-driven.

This alignment is the foundation for the optimization strategies outlined in subsequent sections, aiming to enable system-wide orchestration. The optimal mix of transport modes must balance the individual goals of each passenger or shipper, such as speed, cost, convenience, or baggage handling, with broader sustainability objectives, including emissions reduction, efficient asset utilization, and modal shift toward lower-impact systems.

To support this balance, transportation systems increasingly rely on **multi-criteria decision-making (MCDM)** methods embedded within interoperable digital twins [4]. These methods compute weighted comparisons across competing objectives and enable real-time decision support. By integrating these models into digital twin ecosystems, transportation networks can dynamically evaluate trade-offs, simulate outcomes, and adapt to changing conditions while maintaining alignment with stakeholder priorities.

For example, the European Commission and member states are actively promoting the use of their extensive rail network for intra-continental travel while reserving air transportation for longer, inter-continental routes. This approach, part of the updated Trans-European Transport Network (TEN-T) strategy, exemplifies how policy, infrastructure, and digital orchestration can converge to support system-wide optimization and sustainability targets [5].

### 2.1.1 Aligning Stakeholder Goals with a Capability Hierarchy

The strategic intent of **Optimizing Transportation Journeys** captures the overall goal of seamless, safe, and efficient movement across networks. This strategic intent maps directly to the **Transportation Journey Optimization** capability, which is realized through a federated, interoperable digital twin ecosystem.

The Digital Twin Consortium’s **Capability Periodic Table (CPT)** provides a structured framework for organizing and visualizing these capabilities. Capabilities are systematically organized into a hierarchy:

* **Atomic Capabilities:** These are fundamental operations, such as sensing, localization, status aggregation, or data validation.
* **Tactical Capabilities:** These are aggregations of atomic capabilities, including route planning, scheduling, load balancing, Passenger Flow Management, or Transit Coordination.
* **Composite Capabilities:** These represent end-to-end functions, such as passenger journey orchestration, freight logistics management, and multimodal coordination.

Decomposing capabilities down to atomic levels provides significant architectural and operational advantages, including the **reuse of capabilities** across multiple use cases and the avoidance of redundant development by multiple service providers. This structure also enables a flexible combination of capabilities for new multimodal initiatives and supports more precise Key Performance Indicator (KPI) measurement.

### 2.1.2 Translating Capabilities into Measurable Value

Capabilities must be intrinsically linked to measurable outcomes. KPIs quantify performance and enable continuous optimization.

**Sample KPIs for Multimodal Transportation Capabilities**:

* **Efficiency:** Average travel time, transfer efficiency, throughput per mode.
* **Reliability:** On-time performance, variance from schedule, Reliability (% of planned operations executed without delay).
* **Resource Utilization:** Vehicle occupancy rates, freight container usage, Load Balancing (utilization, energy consumption).
* **Cost & Revenue:** Operational cost per passenger/freight unit, Cost Efficiency.
* **User Experience:** Wait times, transfer success rate, Net Promoter Score (NPS).

## 2.2 Optimizing the Passenger Journey

Optimizing the passenger journey focuses on improving efficiency, convenience, and user satisfaction by minimizing delays, enhancing comfort, and providing continuous real-time information.

The implementation relies on core capabilities that continuously feed into digital twin platforms:

* **Dynamic Routing:** Real-time adjustments to routes based on congestion, passenger flow, or service disruptions.
* **Multimodal Transfer Coordination:** Synchronizing schedules across various modes (e.g., trains, buses, ferries).
* **Real-Time Information Updates:** Providing live notifications to passengers via mobile apps or station displays.
* **Accessibility & Experience Enhancements:** Ensuring inclusive design, comfort, and enhanced wayfinding.

Atomic capabilities supporting passenger optimization include **sensing**, **scheduling**, **crowd monitoring**, **predictive analytics**, and **data validation**.

## 2.3 Optimizing the Freight Journey

Freight optimization strategies aim for load efficiency, resilient intermodal coordination, and strict regulatory compliance. This coordinated movement across multiple carriers and hubs eliminates poor visibility and costly handoff failures.

Key tactical capabilities for freight optimization include:

* **Route Planning & Scheduling:** Selecting the most efficient paths based on real-time conditions.
* **Load Balancing & Resource Allocation:** Dynamically matching available vehicles, containers, and personnel with demand.
* **Predictive Maintenance & Asset Tracking:** Monitoring cargo conditions and fleet health to prevent unexpected delays.

Performance is measured using metrics such as delivery timeliness, cost, utilization, and time to delivery. Atomic capabilities supporting this include **tracking**, **sensing**, **routing**, **load calculation**, and **data integration**.

## 2.4 Optimizing Asset and Resource Utilization

Maximizing asset and resource utilization is critical for cost efficiency, reducing congestion, and lowering emissions. This optimization moves beyond simple tracking toward prediction and dynamic allocation.

Key capabilities include:

* **Fleet Allocation:** Matching vehicles to real-time passenger or freight demand.
* **Depot & Warehouse Management:** Optimizing handling, storage, and turnover.
* **Energy & Sustainability Management:** Reducing energy consumption and emissions per journey.
* **Predictive Maintenance:** Utilizing AI analytics to forecast equipment failures and schedule maintenance *before* operational downtime occurs, potentially reducing breakdowns by up to 75% and cutting maintenance costs by up to 25%.

## 2.5 A Unified Blueprint: Capabilities, Technologies, and Governance

Multimodal transportation transformation requires more than isolated innovation; it demands a unified blueprint that integrates business capabilities, enabling technologies, and governance frameworks into a cohesive, adaptive system. This blueprint is designed to optimize operations, foster trust across stakeholders, and deliver seamless user experiences through spatially aware, real-time coordination.

At its core is the **Observe-Orient-Decide-Act (OODA)** loop, enabling dynamic responsiveness across the transportation ecosystem:

* **Observe**: Sense and collect real-time data on assets, passengers, freight, and environmental conditions using Digital Twins, IoT sensors, and Geographic Information Systems (GIS). This establishes the **spatial context** necessary for situational awareness and predictive modeling.
* **Orient**: Contextualize and analyze aggregated data to identify constraints, predict emergent states, and optimize system performance using AI agents, GIS, and Digital Twins.
* **Decide**: Select optimal actions that balance operational efficiency, **stakeholder** **trust**, and user **experience**. Decision support is enhanced by AI agents, Digital Twins, and Blockchain for transparent verification.
* **Act**: Execute decisions via mobile platforms, automated systems, and Blockchain-enabled coordination, feeding outcomes back into the system to support continuous learning and **optimization**.

This blueprint links foundational capabilities, such as journey orchestration, asset visibility, dynamic scheduling, and stakeholder coordination, to measurable outcomes. It ensures that technology investments are traceable to operational goals and that governance frameworks reinforce trust, interoperability, and performance. A diagram of a diagram of a business

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Figure 2.5-1: Elements of a Unified Blueprint

The technologies introduced in Section 3, including Digital Twins, AI agents, Blockchain, GIS, and mobile platforms, enable spatially contextualized data sharing and coordinated action. Section 4 builds on this by introducing architectural and governance principles, including System of Systems methodology, Event-Driven and Distributed Architectures, and a Common Information Model. Together, these elements support the transition from fragmented operations to a unified, optimized, and high-performing multimodal future.

Digital Twins provide a neutral foundation where other technologies are integrated. AI systems simulate decisions within the Digital Twin environment, while GIS ensures spatial accuracy and consistency. Together, they form a Digital Twin System of Systems (SoS), enabling synchronized orchestration between virtual models and their physical counterparts.

# 3 How Technologies Enable Data Sharing in Multimodal Transportation

A diagram of a diagram

AI-generated content may be incorrect.Seamless and intelligent multimodal transportation depends on the ability to overcome data fragmentation and siloed operations. This requires the convergence of key enabling technologies that work together to support real-time data exchange, contextual awareness, and coordinated decision-making across diverse transportation modes and stakeholders.

Figure 3-1: Technologies supporting the OODA Loop

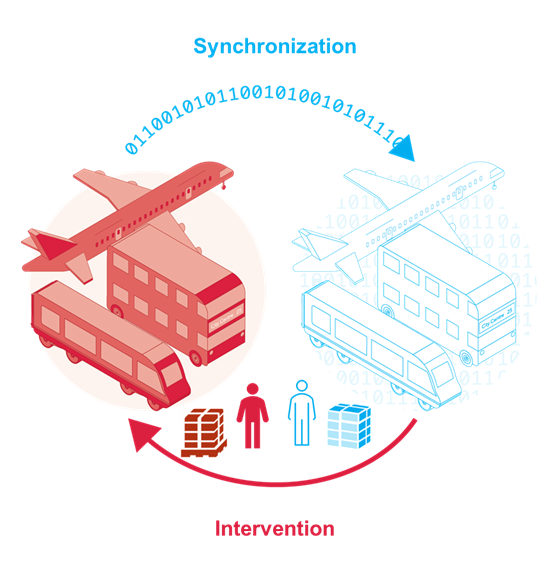
These technologies do more than support connectivity; they activate atomic and tactical capabilities by enabling continuous sensing, secure data transmission, semantic interoperability, and predictive analytics. Their integration forms the backbone of a shared data environment where vehicles, infrastructure, passengers, freight, and control systems can interact dynamically and adaptively. Together, these technologies enable coordinated action at scale by supporting the full Observe–Orient–Decide–Act (OODA) loop. Each step of the loop is mapped to specific technological capabilities:

|  |  |  |
| --- | --- | --- |
| **Technology** | **Supported Capabilities** | **OODA Steps** |
| Digital Twin | Sensing, Monitoring, Synchronization | Observe, Orient |
| AI Agents | Prediction, Prescription, Optimization | Orient, Decide |
| Blockchain | Verification, Coordination | Decide, Act |
| GIS | Spatial Contextualization, Route Planning | Observe, Orient |
| Mobile App | Communication, Interaction | Act |

Table 3-1: Technology and Capability mapping to the OODA loop

This integrated approach can transform fragmented transportation systems into responsive, data-driven ecosystems capable of continuous optimization and stakeholder alignment.

## 3.1 Digital Twins as the Living Core

Per the Digital Twin Consortium, a digital twin (DT) is an integrated, data-driven virtual representation of real-world entities and processes, with synchronized interaction at a specified frequency and fidelity. In multimodal transport, DTs serve as the "living core," integrating real-time data from vehicles, infrastructure, environment, and operations into a coherent, evolving representation of transportation networks. 

This scope extends beyond physical assets to include dynamic representations of passengers and freight. DTs can maintain the current state, journey history, and behavioral patterns of individual passengers, including declared intents and preferences, which can be matched to transportation services in real time. Freight units are similarly modeled, with DTs tracking location, condition, and handling requirements, including temperature compliance.

Figure 3.1-1: Fundamentals of Digital Twins

**Key Roles**

* **Observe/Orient**: DTs support the Observe and Orient steps by ingesting real-time data from IoT, mobile apps, and GIS, then contextualizing that data to maintain historical and predictive states.
* **Data Foundation**: They capture the live state of systems via sensing and monitoring, integrating passenger, freight, and asset data into a unified operational view.
* **Visualization and Prediction**: DTs enable situational awareness and support predictive and prescriptive decision-making. They are essential for modeling intermodal transfers, congestion impacts, and emergent system behaviors.
* **Intervention and Feedback**: DTs do not operate in isolation. Their prescriptive outputs, such as optimized routing, load balancing, or schedule adjustments, are fed back into the physical twin through automated systems, mobile platforms, and control interfaces. This closed-loop feedback enables real-time intervention, ensuring that digital insights translate into tangible operational improvements.

## 3.2 AI Agents for Autonomous Optimization

AI agents refer to autonomous, goal-seeking systems capable of continuous decision-making and self-directed action. These systems represent a critical shift from reactive algorithms to proactive, goal-oriented orchestration. AI agents act dynamically on shared data to optimize multimodal logistics or passenger flows.

**A diagram of a company

AI-generated content may be incorrect.**

[Figure 3.2-1: Fundamentals of](https://store.aci.aero/wp-content/uploads/2024/02/WATF-Executive-Summary.pdf) AI Agents

**Role and Benefits:** Embedded in interoperable digital twins, AI agents gain holistic situational awareness, enabling coordination between different transport modes.

* **Optimization:** They autonomously optimize asset utilization, trigger predictive maintenance, and adjust schedules to match demand.
* **Resilience:** For freight, they can negotiate carrier contracts or reroute shipments in response to disruptions.
* **Personalization:** For passengers, they create hyper-responsive experiences by suggesting real-time route changes and automating rebookings during disruptions.

AI agents require access to shared, standardized, and interoperable data to operate collaboratively and make system-wide decisions. At full scale, they can manage entire transportation systems autonomously, resulting in networks that are resilient, adaptive, and self-governing.

## 3.3 Blockchain for Trust, Coordination, and Audits

Blockchain provides a decentralized and tamper-proof architecture that addresses the critical lack of trust in fragmented, multi-stakeholder transportation ecosystems. It acts as a trust layer, ensuring data integrity and transparency across shared networks.

The following diagram provides a simple overview of how blockchain organizes and links information across different nodes. Each block contains a transaction document hash and connects to the next, illustrating the basic structure of a distributed ledger.

A screenshot of a computer screen

AI-generated content may be incorrect.

[Figure 3.3-1: Fundamentals of Blockchain](https://store.aci.aero/wp-content/uploads/2024/02/WATF-Executive-Summary.pdf)

**Role and Benefits:**

* **Logistics & Auditing:** Blockchain streamlines documentation (e.g., bills of lading, customs clearance) and enables trusted provenance tracking for cargo. Smart contracts can automate handoffs between carriers and customs, potentially reducing documentation costs by up to 40%. It is used to log shipment milestones and track energy usage for sustainability reporting.
* **Passenger Systems:** It supports interoperable ticketing and identity management, combating fraud and enabling automated refunds through tamper-proof digital credentials.
* **Data Integrity:** By enabling permissioned, auditable data exchange, blockchain allows agencies and operators to collaborate without relinquishing control over data sovereignty.

Blockchain systems are being adopted globally to verify carbon offsets, streamline container transfers, and unify transit data across rail, bus, and bike-sharing.

## 3.4 Geographic Information Systems (GIS) as the Spatial and Temporal Backbone

Geographic Information Systems (GIS) collect, analyze, and visualize spatial data, making them fundamental to route planning, mode switching, and infrastructure management. Geospatial technology provides the shared spatial framework required for a unified, adaptive ecosystem.



[Figure 3.4-1: Fundamentals of GIS](https://store.aci.aero/wp-content/uploads/2024/02/WATF-Executive-Summary.pdf)

**Role and Benefits:**

* **Spatial Context:** GIS transforms static maps into dynamic spatial engines that provide positional accuracy and temporal alignment across platforms. This is essential when embedding GIS in digital twins to ensure spatial consistency.
* **Analysis and Planning:** GIS enables infrastructure-aware planning by identifying choke points, optimizing intermodal hubs, and supporting equitable mobility planning. It helps visualize key metrics like congestion, usage heatmaps, dwell time, and accessibility gaps.
* **Emissions & Compliance:** Shared geospatial layers support scenario modeling for climate impact and land use, essential for emissions analysis and tracking compliance with local zoning and safety regulations (e.g., for hazardous cargo).

Cities like Dallas-Fort Worth and New York are utilizing GIS to support zero-emission freight routing and optimize marine freight logistics.

## 3.5 Mobile App for Seamless Travel Experiences

In today’s connected world, travelers expect a seamless and personalized journey that begins with trip planning and continues through every touchpoint. Mobile apps are essential for delivering this continuity, offering real-time updates, wayfinding, mobile ordering, loyalty integration, and personalized recommendations.

A screenshot of a computer

AI-generated content may be incorrect.

[Figure 3.5-1: Example mobile user interfaces](https://store.aci.aero/wp-content/uploads/2024/02/WATF-Executive-Summary.pdf) spanning the passenger journey

Despite these capabilities, the travel ecosystem remains fragmented. Passengers often manage multiple disconnected apps for service providers such as airlines, airports, parking, concessions, and ground transport. This leads to inconsistent experiences, app fatigue, and missed opportunities for integrated engagement. To address these challenges, a personal travel portal offers a transformative solution. Rather than juggling multiple apps, travelers can use a single unified mobile interface that generates tailored content for each provider. This experience is powered by a traveler digital twin, a secure and dynamic profile that maintains preferences, trip context, and real-time status. With this foundation, stakeholders can deliver relevant and frictionless services through one cohesive platform.

**Core Capabilities**

1. **Plan Multimodal Journeys:** Enables users to create end-to-end trip plans across diverse modes (e.g., transit, micromobility, ride-hail) within a single interface.
2. **Access Real-Time Information:** Provides live updates on arrivals, delays, and disruptions to support timely decision-making.
3. **Book and Pay Across Modes:** Facilitates seamless booking and fare payment across multiple service providers, reducing transactional friction.
4. **Navigate Physical Environments:** Offers wayfinding support through complex spaces such as airports, stations, or transfer points.

# 4 Enabling Multimodal Through Governance and Architecture

Achieving seamless, interoperable multimodal transportation requires more than deploying advanced technologies in isolation. It demands a cohesive governance and architectural framework that enables these technologies to converge, compose, and orchestrate in real time. This foundation transforms fragmented systems into intelligent ecosystems capable of continuous decision-making across diverse transportation modes. Governance and architecture principles ensure that capabilities are not just embedded within systems but exposed as modular, reusable services—what we define as “capability as a service**”**. These services can be dynamically composed, orchestrated, and scaled across operational contexts, enabling adaptive responses to changing conditions, passenger intents, and freight requirements. To support this transformation, the framework must deliver:

* **Real-time responsiveness**: Systems must sense, interpret, and act on live data from vehicles, infrastructure, passengers, and freight.
* **Interoperability**: Standardized semantics and interfaces allow diverse systems to communicate and collaborate seamlessly.
* **Composable architecture**: Capabilities are modular and reusable, enabling flexible scenario assembly and rapid deployment.
* **Orchestration logic**: Coordinated workflows align services, stakeholders, and technologies to deliver unified outcomes.
* **AI-ready data**: Structured, contextualized data supports predictive analytics, simulation, and autonomous decision-making.

These principles are embodied in four foundational domains that guide system interoperability and capability exposure:

* **System of Systems (SoS)**: Enables independently managed transportation systems to collaborate and produce emergent capabilities through federated governance.
* **Common Information Model (CIM)**: Establishes semantic interoperability by standardizing actions, entities, attributes, and KPIs across domains.
* **Event-Driven Architecture (EDA)**: Treats system events as triggers for real-time coordination, enabling responsive and asynchronous communication across platforms.
* **Distributed Systems Architecture**: Supports decentralized processing and control, ensuring resilience, scalability, and secure data exchange across jurisdictions.

## 4.1 Digital Twins as the Living Core

A diagram of a system

AI-generated content may be incorrect.Multimodal transportation inherently operates as a System of Systems (SoS), a dynamic federation of independently managed systems such as airports, seaports, rail networks, and urban transit. By incorporating an SoS methodology into transportation initiatives, each system is designed to expose modular capabilities as services that can be composed and reused across operational scenarios. This enables coordinated action while preserving the autonomy, governance, and specialization of each constituent system.

Figure 4.1-1: Multi-tier Transportation System of Systems

A multi-tiered SoS structure begins at the foundational level with domain-specific subsystems such as baggage handling, curbside check-in, and gate management, each operating within a single facility. These subsystems are composed into mid-tier systems like airport or port operations, which coordinate internal functions and services. At the highest tier, these facilities contribute to the composition of a broader multimodal transportation system that includes regional rail, maritime logistics, and urban mobility networks. This layered composition supports scalable orchestration, cross-domain interoperability, and continuous optimization across transportation modes and jurisdictions.

**SoS Fundamentals and Application**

* **Definition**: A System of Systems is a configuration of autonomous systems that collaborate to deliver emergent capabilities and shared outcomes.
* **Structure**: SoS decomposes capabilities into reusable actions (e.g., Transport, Schedule, Notify) and entities (e.g., Passenger, Freight, Asset), enabling flexible composition across scenarios.
* **Governance**: SoS methodology provides the governance scaffolding to manage complexity, ensuring each system maintains operational independence while aligning through standardized data models and service contracts.
* **Benefits**: SoS enables scalable integration of heterogeneous systems, promotes capability reuse, supports real-time cross-network decision-making, and fosters a holistic perspective that incorporates the intents and capabilities of all stakeholders and their systems.

## 4.2 Common Information Model for Interoperability and Scale

To enable true interoperability, all systems must "speak the same language." The Common Information Model (CIM) achieves semantic interoperability by standardizing actions, entities, attributes, and KPIs across domains. It provides a shared structure that allows systems to expose capabilities as services, with each service semantically grounded in well-defined action and entity classes. Capabilities inherit attributes from both action and entity classes, enabling consistent interpretation and reuse across systems. In a “Transport Freight” capability, attributes from the Transport action class define operational parameters such as origin and destination. Attributes from the Freight entity class, such as size and weight, can define constraints like minimum and maximum thresholds that govern how the service is composed and executed.

A diagram of a company

AI-generated content may be incorrect.

[Figure 4.2-1: Information](https://store.aci.aero/wp-content/uploads/2024/02/WATF-Executive-Summary.pdf) Class Relationships for SoS

CIM also defines foundational relationships between space, asset, party, and system classes to clarify how physical and digital components interact. These relationships provide the spatial and functional context necessary for orchestrating capabilities as services across distributed environments, enabling consistent interpretation and coordination among diverse systems.

**CIM Implementation and Benefits**

* **Standardization**: CIM defines standard classes for actions, entities, and attributes. Action classes describe what can be done, such as Transport or Dispatch, while entity classes describe what is acted upon, such as Passenger or Freight.
* **Consistency and Simplicity**: Subclasses inherit properties from parent classes, ensuring semantic consistency and simplicity through a minimalistic information model.
* **Value Creation**: CIM is essential for enabling digital twin interoperability, reducing system integration costs, and ensuring data is AI-ready for scalable deployments. It also provides the semantic foundation for simulation platforms, supporting modular scenario composition and traceable orchestration logic.

By grounding capabilities and relationships in a shared semantic model, CIM enables systems to interoperate fluidly while maintaining clarity, extensibility, and alignment across stakeholder systems.

## 4.3 Event-Driven and Distributed Systems Architectures for Situational Awareness

Multimodal transportation networks require continuous situational awareness and rapid response to dynamic state changes such as delays, reroutes, and incidents. Event-Driven Architecture (EDA) and Distributed Systems Architecture work in tandem to provide the structural backbone for real-time coordination, scalable responsiveness, and resilient decision-making across geographically and organizationally diverse systems.

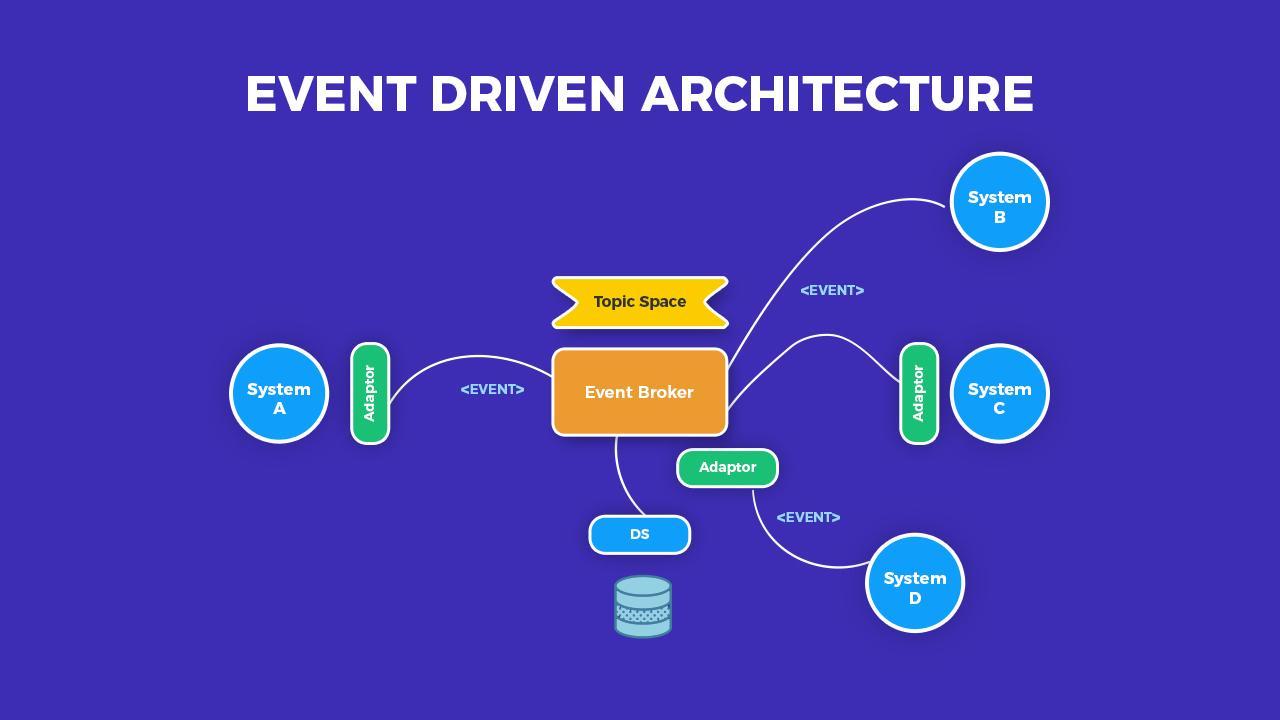
EDA treats state transitions—such as “vehicle arrived,” “ticket validated,” or “cargo delayed”—as first-class system messages. These events are broadcast asynchronously to relevant systems, allowing each to react independently while remaining contextually aligned. Distributed Systems Architecture ensures that these reactions can occur locally while maintaining global coherence, enabling decentralized control and computation across jurisdictions. Key characteristics and benefits include:

Figure 4.3-1: EDA Fundamentals

* **Real-Time Responsiveness**: Event brokers enable systems to detect disruptions and trigger corrective actions immediately.
* **Semantic Interoperability**: Events structured using the Common Information Model (CIM) carry standardized meanings, ensuring consistent interpretation across platforms.
* **Digital Twin Synchronization**: Events update both physical and digital twins in near real time, maintaining alignment between virtual models and real-world conditions.
* **Simulation and Forecasting**: Chronological event streams support Discrete Event Simulation (DES), allowing systems to model behavior and predict outcomes.
* **Decentralized Decision-Making**: Distributed architecture supports local autonomy while preserving system-wide coordination and scalability.
* **Trust and Traceability**: Events can be cryptographically recorded using blockchain, enabling smart contracts and auditable workflows.
* **Data Sovereignty**: Distributed models respect jurisdictional boundaries, supporting secure data exchange across public and private stakeholders.

Together, these architectures transform multimodal networks from reactive silos into orchestrated ecosystems capable of real-time, interoperable, and intelligent operations.

# 5 Economic Value Assessments for Key Use Cases

Multimodal transport inefficiencies extend beyond operational friction—they represent a measurable economic burden on national systems.

A single transportation disruption is not an isolated event; its shockwave propagates through the entire supply chain, with every $1 in lost sales for an impacted firm costing its customers an average of $2.40, revealing a profoundly fragile system on the brink of collapse [[source](https://www.richmondfed.org/publications/research/economic_brief/2025/eb_25-02)].

Research suggests that interoperable multimodal logistics can reduce overall transportation costs by 15 to 20 percent, and the integration of blockchain for coordination and transparency could unlock up to $500 billion in annual global savings. [[source](https://worldmetrics.org/multimodal-statistics/)]

A 2024 study commissioned by the UK Department for Transport found that implementing an integrated network management digital twin across five targeted use cases could generate £1.85 billion ($2.3 billion USD) in undiscounted benefits. These gains stem from improved journey times, enhanced reliability, and elevated service quality, alongside broader non-monetized impacts such as reduced public sector overhead and expanded access to essential services.

A screenshot of a computer screen

AI-generated content may be incorrect.

[Figure 5-1: Value Assessment of Targeted Transportation Use Cases](https://store.aci.aero/wp-content/uploads/2024/02/WATF-Executive-Summary.pdf)

The following subsections provide an example scenario for each use case, demonstrating how the capabilities, technologies, and governance frameworks outlined earlier in this whitepaper can reduce the cost, risk, and time required to unlock these economic benefits.

## 5.1 Capacity Optimization at Intermodal Freight Hubs

Ports and inland freight hubs depend on tightly coordinated operations such as vessel unloading, container handling, storage, and outbound traffic. These activities must align across cranes, berths, and staging zones to prevent bottlenecks and idle capacity. Disruptions like delayed arrivals or misaligned transfers can cascade across intermodal interfaces, amplifying inefficiencies. Interoperable digital twins and decision-support systems enable adaptive coordination among customs, logistics firms, and land transport operators to balance throughput and sustain operational flow.

This use case demonstrates how event-driven orchestration can address capacity constraints in multimodal freight hubs. By integrating AI agents and blockchain governance with GIS-based spatial logic, inland terminals become more resilient to disruption and better able to manage fluctuating demand. Real-time coordination across water and ground modes improves cargo transfer efficiency, reduces dwell time and emissions, and enhances collaborative decision-making. The orchestration logic supporting this response is detailed below.

|  |  |
| --- | --- |
|  | **Triggering Event**  A barge arrives late at an intermodal hub, disrupting yard capacity and truck dispatch. |
| **System Orchestration**  Interoperable **digital twins** update ETAs, manifests, and yard capacity in real time.  **AI agents** simulate unloading and dispatch scenarios to balance KPI-based goals.  **Blockchain** logs proposed slot reallocation and prompts operator approval.  **GIS** updates yard zones and issues routing changes to truck drivers via mobile alerts |
| **Outcome**  The delay is absorbed with minimal operational impact as dynamic slot management and real-time coordination reduce dwell times, idle emissions, and delivery delays. | |

Table 5.1-1: Example of event-driven system orchestration to optimize capacity

## 5.2 Real-Time Passenger Re-Routing During Service Disruptions

Multimodal journey efficiency depends on a complex web of interdependencies—interchange timing, facility readiness, wayfinding, weather, and the ability to mitigate disruptive events such as breakdowns or infrastructure failures. Improving the timeliness, accuracy, and richness of transport network data is critical to enhancing operational resilience and passenger experience, especially during peak-hour disruptions.

This use case explores how a mechanical failure on an urban rail line activates a coordinated digital response across systems. Enabled by digital twins, anomaly detection, GIS, agentic AI, blockchain, and mobile apps, the orchestration logic dynamically reroutes passengers, reallocates service capacity, and maintains situational awareness. The full orchestration sequence is detailed below.

|  |  |
| --- | --- |
|  | **Triggering Event**  Mechanical failure on an urban rail line during peak hours |
| **System Orchestration**  **Digital twins** detect infrastructure anomalies via sensors.  **Anomaly detection AI** flags the issue.  **GIS systems** analyze transit routes and congestion to perform real-time routing.  **Agentic AI** forecasts ripple effects. |
| **Outcome**  Passengers are notified through a mobile app with updated routing options, and operators reallocate service capacity. | |

Table 5.2-1: Example of event-driven system orchestration to re-route passenger

## 5.3 Cargo Integrity Monitoring in Intermodal Freight Transport

Port environments are dynamic ecosystems where cargo handling, vessel operations, storage, and intermodal transfers must be precisely coordinated across a diverse set of stakeholders—from customs and maritime authorities to global logistics firms and land transport operators. Disruptions during container transfer, such as environmental anomalies, can compromise cargo integrity and ripple across interconnected systems.

This use case demonstrates how digital twins, sensor telemetry, and AI-powered inference can enhance situational awareness and operational trust. When an anomaly is detected, the system localizes the risk, logs custody and condition via blockchain, and dispatches real-time alerts through mobile apps and control systems. This orchestration, detailed below, exemplifies how port digitalization and decision support systems can proactively safeguard cargo while maintaining flow continuity across modes.

|  |  |
| --- | --- |
|  | **Triggering Event**  Environmental anomaly detected during container transfer |
| **System Orchestration**  **Sensors** capture temperature or shock data.  **AI models** infer possible causes and urgency.  **GIS integration** identifies the exact location of risk.  **Blockchain** logs custody, location, and condition across all nodes.  **Mobile app** provides real-time alerts and container status updates to shippers, carriers, and logistics personnel. |
| **Outcome**  Alerts are dispatched to all relevant parties (shippers, carriers, customs) through control systems and mobile apps, ensuring traceability and operational trust. | |

Table 5.3-1: Example of event-driven system orchestration to monitor cargo integrity

## 5.4 Coordinated Emergency Response in Transit Hubs

Emergencies and unplanned incidents—whether caused by accidents, weather, infrastructure failures, or IT disruptions—routinely impact transit hubs and often cascade across multiple transport modes. These events are frequently exacerbated by fragmented systems, delayed detection, and reactive coordination. Digital twin technology, combined with centralized dashboards and enriched data streams, offers a pathway to more timely, accurate, and coordinated response.

This use case illustrates how an integrated digital ecosystem can localize threats, guide safe evacuation, and synchronize cross-agency communication during a fire alarm event in a multimodal terminal. The orchestration logic and system components supporting this response are detailed below.

|  |  |
| --- | --- |
|  | **Triggering Event**  Fire alarm activated in a multimodal terminal |
| **System Orchestration**  **Facility digital twins** localize the threat.  **Blockchain** ensures secure communication between agencies and transport providers.  **Mobile app** delivers real-time alerts, personalized routing, and safety instructions to passengers and staff.  **GIS overlays** identify safe exit paths and nearby response assets.  **AI logic** suggests rerouting for in-transit vehicles and crowd management. |
| **Outcome**  Evacuation protocols are activated instantly. Responders are guided by live digital maps, and post-event data enables analytics and future risk reduction. | |

Table 5.4-1: Example of event-driven system orchestration for emergency response

## 5.5 Predictive Maintenance of Infrastructure Assets

The reliability of transport networks depends on the continuous upkeep of infrastructure assets—bridges, rail lines, terminals, and utility corridors—often managed by a diverse set of actors including transport authorities, asset owners, and utility providers. Poorly coordinated maintenance can lead to duplicated works, modal bottlenecks, and limited travel alternatives.

This use case demonstrates how predictive maintenance, powered by digital twins, remote condition monitoring, and event-driven orchestration, can mitigate these risks. When sensor data reveals early signs of structural degradation, the system dynamically schedules targeted interventions, reroutes traffic, and notifies travelers via mobile apps. This approach enables smarter coordination, minimizes disruption, and ensures asset integrity. The full orchestration logic is detailed below.

|  |  |
| --- | --- |
|  | **Triggering Event**  Structural degradation pattern emerges from sensor data |
| **System Orchestration**  **Real-time telemetry** feeds into asset digital twins.  **AI-powered inference** detects early-stage degradation.  **GIS** visualizes affected zones in spatial context.  **Event-driven orchestration** schedules targeted maintenance and reroutes traffic.  **Mobile app** notifies travelers of reroutes, delays, and safety advisories based on real-time asset conditions. |
| **Outcome**  Maintenance occurs proactively before failure, optimizing cost and safety. Travelers receive advanced notifications via the mobile app. | |

Table 5.5-1: Example of event-driven system orchestration to prescribe maintenance

# 6 Case Studies: Realizing the Vision of Multimodal Transportation

The preceding sections outlined the technologies, governance models, and architectural frameworks needed to transform fragmented transportation environments into intelligent, orchestrated, and user-centric multimodal ecosystems.

This section presents real-world case studies demonstrating how disruptive technologies can improve efficiency, accessibility, and sustainability across transportation networks. While each of the following case studies describes significant value creation through a Vision Scenario, they represent an envisioned future state of seamless multimodal travel and may not yet fully incorporate all the technologies and methodologies discussed in this paper.

* **City of Columbus**Demonstrates how a federated data platform and collaborative governance can enable integrated trip planning and data-driven, inclusive urban mobility.
* **DFW Airport**Illustrates how multi-modal digital twins and real-time data fusion enable predictive, adaptive operations across airside and regional transport systems.
* **Korean Railroad and Incheon Airport**Highlights an interoperable System-of-Systems architecture uniting air, rail, and urban transport through AI, AR, and digital twin technologies.
* **New York Blue Highways**Envisions a blockchain-enabled maritime logistics network using System-of-Systems digital twins to decarbonize and modernize urban freight.

By adopting a System-of-Systems (SoS) approach, these initiatives can further improve interoperability, scalability, and the overall traveler experience. Each case study can be described using a common SoS metamodel generated through an engineered large language model (LLM) prompt (see Appendix A). This approach standardizes documentation, enables simulation of complex system interactions, and provides a framework for extending these initiatives toward a fully seamless multimodal travel ecosystem.

## 6.1 Smart Columbus

The Smart Columbus case study highlights a collaborative smart city initiative that brought together various stakeholders—including government agencies, private vendors, researchers, and community advocates—to transform urban mobility. Central to this effort was the Smart Columbus Operating System (SCOS), which served as the central data platform, providing a model for data-driven, inclusive urban mobility. The system utilized capabilities such as Integrated Data Exchange and Multimodal Trip Planning.

A diagram of a smart city

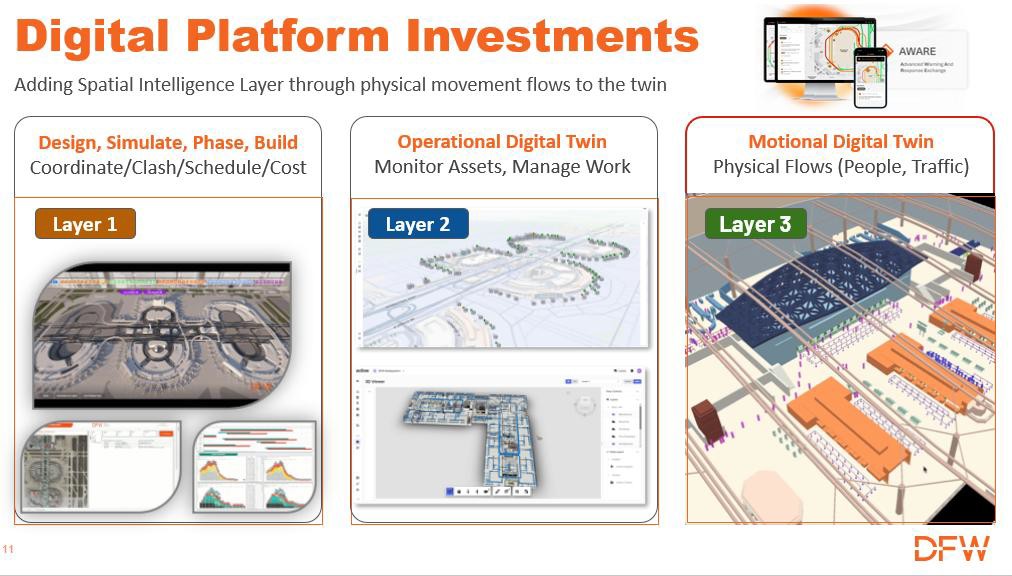
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[Figure 6.1-1: Smart Columbus Vision](https://store.aci.aero/wp-content/uploads/2024/02/WATF-Executive-Summary.pdf)

**Vision Scenario: Optimized Passenger Journey (Urban Commute)**

Maya, a healthcare worker who previously struggled with inaccurate bus times and full parking lots, now relies on the integrated Smart Columbus ecosystem. Utilizing the Pivot Trip Planning App, Maya initiates her commute using her regional rail pass. The system, leveraging Integrated Data Exchange and real-time parking data, predicts capacity and notifies her early, assuring her of space at the park-and-ride lot. When unexpected construction causes a major detour downtown, the Multimodal Trip Planning app immediately detects the change via transport ops feeds. Leveraging GIS for spatial awareness, the app dynamically renders detour options in real-time maps and connects her seamlessly to a nearby shared e-scooter (a component of Mobility Hub Integration) for the final leg. Maya arrives on time, demonstrating the system’s ability to use aggregated, real-time data to Adapt journeys based on real-time context, restoring trust in her daily commute.

## 6.2 Dallas-Fort Worth (DFW) Airport

DFW Airport, one of the world’s busiest hubs, is leveraging digital transformation to manage growing demand, particularly in preparation for the 2026 FIFA World Cup. The strategy relies on multi-modal digital twins, specifically the Motional Digital Twin and AWARE traffic forecasting platform. This system fuses over 20 real-time data streams, including LiDAR, video analytics, and flight telemetry, enabling operations to shift from reactive firefighting to anticipatory decision-making. The Athena project is leveraging these digital twins to integrate mobility, energy, and operational systems across complex transportation hubs. The Operational Digital Twin continuously monitors airport systems to predict and prevent failures and ensure uptime.

**Bentley SYNCHRO | Willow Digital Twin | Outsight.io Motional Digital Twin**

Figure 6.2-1: DFW Airport’s Digital Platform Vision

**Vision Scenario: Optimized Passenger Journey**

The Johnson family’s vacation began with a smooth arrival at DFW Airport, guided by a unified travel app powered by DFW Motional and Operational Digital Twins. Before leaving home, the app flagged a major event near their planned parking area and redirected them to a guaranteed alternate spot. Wheelchair support was pre-registered, and thanks to flow forecasting and passenger counters, airport staff were ready and waiting when they arrived. When the weather delayed their flight, real-time updates were synchronized across airport displays and their mobile devices. A gate change triggered dynamic re-routing through the terminal, accounting for congestion and mobility needs. Their checked luggage remained trackable throughout the journey. When a delay was flagged during transfer in Miami, the app offered a contingency plan and automatically alerted the cruise terminal.

## 6.3 Korea National Railroad and Incheon International Airport

The Korea National Railroad (KNR) and Incheon International Airport case study illustrates a seamless, technology-integrated journey utilizing an SoS architecture that spans air, rail, and urban transport. Advanced systems like AR-guided wayfinding, AI surveillance, and interoperable digital twins are deployed to guide navigation, manage passenger flows, and ensure coordinated emergency response. The success hinges on Integration & Interoperability as a foundational requirement throughout the journey.

A screenshot of a computer

AI-generated content may be incorrect.

Figure 6.3-1: Dynamic Guidance to Manage Transit Transfer Bottlenecks at Incheon Airport

**Vision Scenario: Optimized Passenger Journey**

Mr. Kim’s integrated journey begins at Incheon International Airport. He uses his mobile app, which provides Extended Reality (XR) for AR guidance through customs and immigration. The Interoperable Digital Twin ensures data flow between the airport and the KTX rail system, providing him with real-time updates on flight and train schedules. Upon arriving at Seoul KNR Station, Mr. Kim receives AR-guided directions via the Smart Station Guidance System, which uses spatial awareness technology. The resilience of the system is tested when an unexpected fire incident occurs. The Emergency Evacuation System, powered by the Digital Twin Facility Management and Intelligent Video Surveillance (AI surveillance), dynamically generates safe evacuation routes and alerts Mr. Kim via the app. After the incident is resolved, he resumes his journey to Busan, benefiting from continuous System Monitoring and real-time performance data feeds from the train. The journey concludes with a smooth transition in Busan, utilizing local transit through Smart Station Guidance and Integration & Interoperability with city systems.

## 6.4 New York Blue Highways

The New York Blue Highways case study details the city’s initiative to revive its 520-mile coastline of maritime freight routes to shift nearly 90% of goods movement off trucks, reducing congestion and emissions. The program envisions a multimodal network using regional maritime services, intra-harbor transport, and micro-distribution hub centers. The initiative leverages a System-of-Systems Digital Twin architecture and integrates Digital Product Passports (DPPs) using blockchain principles for secure tracking.

A diagram of a transportation system

AI-generated content may be incorrect.

Figure 6.4-1: New York Blue Highways Vision

**Vision Scenario: Optimized Freight Journey**

A high-value shipment of sustainable textiles was en route to a major retailer in Chicago via the Blue Highways network. The journey began on a barge timed to align with a scheduled rail transfer at an intermodal hub. From departure, the shipment was tracked in real time, with its profile shared across the logistics ecosystem. Operators at the port, rail terminal, and distribution center had synchronized visibility into its location and status. As the barge neared the port, the system detected early signs of congestion and automatically reassigned the rail slot to avoid delay and keep the delivery on schedule. Near the final leg, a road closure disrupted the planned truck route. The system quickly rerouted the shipment through a nearby micro-distribution hub, dispatching a low-emission cargo cycle to complete the last mile. Throughout the journey, Digital Product Passports securely logged each handoff, condition update, and custody event. Emissions data was captured via GIS to support sustainability reporting and compliance.

# 7 Implementation Roadmap to Minimize Risk, Cost, and Time-to-Value

Transforming fragmented transportation systems into unified, adaptive ecosystems requires a coordinated, phased roadmap that aligns diverse stakeholders, technologies, and data models. The implementation process moves methodically from establishing governance and shared objectives to defining common information structures, designing the system architecture, and building a network that connects intents and capabilities across organizations. A successful roadmap treats complexity not as a barrier, but as a condition to be managed through continuous testing and adaptation, with Modeling and Simulation(M&S)embedded at every step to reduce risk and maximize impact.

## 7.1 The Role of Modeling and Simulation

M&S is indispensable for guiding the implementation process, offering the foresight and precision needed to ensure solutions are resilient, cost-effective, and scalable. M&S allows stakeholders to test assumptions, anticipate outcomes, and evaluate system behavior before committing extensive resources to physical deployment.

Key contributions of M&S to the roadmap include:

* **Risk Reduction:** Validates assumptions, tests potential failures, and verifies data flows before making real-world changes.
* **Foresight:** Forecasts operational performance, costs, system stress points, and resource dependencies.
* **Stakeholder Alignment:** Communicates complex tradeoffs and system impacts through visual models.
* **Scalability:** Projects pilot outcomes to regional or national levels with greater accuracy.
* **Iterative Learning:** Quickly tests and refines solutions across organizational silos.

Early simulations help align stakeholder priorities by making complex systems and plans tangible. As design progresses, simulation reveals bottlenecks, delays, and coordination issues, leading to more resilient and scalable solutions. Simulation tools also support ongoing learning, helping to measure performance and project how benefits or risks will scale.

## 7.2 Implementation Phases and M&S Integration

The implementation process is structured into phases, from initial governance to full-scale deployment. Each phase integrates M&S activities to align with technical and organizational goals.

|  |  |  |
| --- | --- | --- |
| **Phase** | **Core Activities** | **M&S Integration** |
| 1. Initiate Governance | Form steering committee; Define shared objectives and KPIs; Identify stakeholders and pilot boundaries. | Simulate governance structures (System-of-Systems models); Use stakeholder modeling to forecast coordination challenges. |
| 1. Define Common Information Model (CIM) | Align on shared semantics and data formats; Define entity relationships and capability models. | Use data ontology modeling tools to simulate CIM effectiveness across use cases; Validate data flows via mock systems. |
| 1. Design the Architecture & Infrastructure | Establish technical blueprint (EDA, distributed systems, APIs); Define data-sharing protocols. | Simulate network loads and failure scenarios across distributed systems; Stress-test event workflows in digital twins. |
| 1. Build the Interoperable Environment | Set up a distributed system testbed (physical or virtual); Deploy data brokers, connectors, and APIs. | Simulate network latency, service interdependencies, and message delivery reliability; Emulate stakeholder behavior. |
| 1. Implement Priority Use Cases | Launch operational pilots (e.g., intermodal routing, unified ticketing); Capture real-time data. | Run digital twin simulations of each use case pre-launch; Use agent-based modeling to simulate user behavior and response. |
| 1. Monitor, Evaluate, and Adapt | Measure KPIs (efficiency, revenue, emissions); Conduct retrospectives; Refine CIM, APIs, governance. | Use system dynamics modeling to assess long-term impacts; Visualize outcomes through simulation dashboards. |
| 1. Plan for Scaling | Identify successful patterns; Address integration bottlenecks; Develop broader rollout strategy. | Simulate scale-up scenarios across regions; Model data governance risks at scale; Forecast ROI using pilot data. |

Table 7.2-1: Implementation Phases with integrated Modeling & Simulation

## 7.3 Pilot Implementation Example

To illustrate the application of the implementation roadmap, consider a real-world pilot initiative in a regional multimodal transportation corridor. Unlike a testbed, which provides a controlled, reusable environment for experimentation (as described in Section 10.2), a pilot applies interoperable systems, capability models, and governance frameworks directly to operational conditions. Pilots validate assumptions, demonstrate value, and provide actionable insights that can inform subsequent scaling or broader adoption.

### 7.3.1 Core Goals of a Pilot

A pilot creates a structured space for experimentation within an actual operational context, enabling iterative learning and phased deployment:

* **Test interoperability** of systems, standards, and APIs across stakeholders in real operational settings.
* **Validate business capabilities**, such as cross-modal ticketing, dynamic cargo rerouting, and real-time scheduling.
* **Refine governance models** and stakeholder coordination mechanisms using System-of-Systems (SoS) principles and event-driven architectures.
* **Demonstrate measurable value** through KPIs tied to cost efficiency, throughput, user satisfaction, and environmental impact.

### 7.3.2 Pilot Structure and Components

A modular, scalable pilot framework supports multiple mode-specific pilots, each focusing on a segment of the multimodal ecosystem. Together, they validate the interoperability of digital twins, AI-driven orchestration, and governance models across real-world transport modes and regions.

|  |  |  |
| --- | --- | --- |
| **Mode** | **Example Use Case** | **KPIs (with Benchmarks)** |
| Rail/Metro | Passenger and cargo flow optimization and platform assignment | Dwell time reduction: 15–25% Platform utilization: >85% On-time performance: >95% |
| Bus Transit | Real-time scheduling and fare reconciliation | Schedule adherence: +10–15% Passenger wait time: ≤5 min  Fare accuracy: 99.5% |
| Micromobility | First/last-mile integration and usage incentives | First/last-mile adoption: +20% Average trip completion time: <10 min User satisfaction: ≥4.5/5 rating |
| Airport Operations | Staff transportation and gate coordination | Gate turnaround reduction: 10–20% Workforce transit reliability: >95% Operational delay reduction: 15% |
| Port Operations | Cargo integrity monitoring and berth scheduling | Berth utilization: >85%  Container dwell time reduction: 20–30% On-time vessel departure: >90% |
| Paratransit & Accessibility | Dynamic routing and equitable access tracking | Response time: <10 min average Accessibility coverage: >90% Passenger satisfaction rating: ≥4.6 |

Table 7.3.2-1: Example Collection of Interoperable Mode-Specific Pilots

The pilot also includes a horizontal infrastructure layer that integrates these mode-specific initiatives:

* **Federated digital twins** for system-wide monitoring and scenario simulation.
* **Cross-mode AI agents** for traveler itinerary planning, cargo scheduling, and asset balancing.
* **Blockchain ledger** for secure, auditable data exchange and transaction tracking.
* **Geospatial analytics** to assess demand, equity, and resilience across the corridor.
* **Mobile app** for real-time traveler and operator notifications, status updates, and dynamic routing guidance.

### 7.3.3 Outcomes and Insights

The pilot demonstrates how interoperable digital systems can improve operational efficiency, reduce delays, optimize resource utilization, and enhance customer experience. By tracking KPIs in real-world conditions, the pilot provides evidence for refining governance models, validating capability alignment, and informing investment decisions.

A feedback loop can be established between the pilot and consortium-supported testbeds: lessons learned from the pilot, such as bottlenecks, operational trade-offs, and KPI performance, are fed into the testbed environment for further experimentation and model refinement. In turn, insights from testbed simulations (e.g., stress-testing interoperability, validating AI-driven coordination, or testing policy scenarios) inform iterative improvements in pilot operations. This synergy ensures continuous learning, reduces the risk of broader implementation, and accelerates the adoption of interoperable, multimodal systems across regions.

# 8 Risks, Ethics, and Governance

The deployment of intelligent, distributed, and data-driven transportation systems introduces significant risks that must be managed through intentional, systemic governance. These challenges are not limited to technical implementation but extend to social, ethical, and organizational issues that directly impact public trust and system viability.

## 8.1 Risks and Ethical Challenges

The core risks arise from the nature of the convergent technologies utilized and the complexity of managing a distributed, multi-stakeholder ecosystem.

* **AI Bias in Decisions:** Unintended discrimination in service delivery, such as routing algorithms favoring certain demographics over others, which requires mitigation through algorithm audits and fairness metrics.
* **Blockchain Energy Consumption:** The potential for increased carbon footprint and infrastructure strain if energy-intensive consensus protocols are chosen, requiring the use of energy-efficient protocols.
* **Data Privacy and Sovereignty:** The challenge of ensuring compliance across various jurisdictions and mitigating the risk of data misuse, particularly with personalized travel data.
* **Lack of Interagency Coordination:** Failure to align policies and standards across different organizations, leading to fragmented implementation, inefficiencies, and conflicting policies.
* **Unclear Ethical Accountability:** The difficulty in assigning responsibility when autonomous AI agents make critical decisions, potentially eroding public trust.
* **Runaway Costs:** Risk of duplication of efforts and unsustainable maintenance costs due to a lack of shared services and centralized oversight.

## 8.2 Governance and Mitigation Strategies

A System of Systems (SoS) model is essential for managing this complexity, allowing organizations to maintain operational independence while coordinating through shared protocols and oversight mechanisms. Governance must be designed to scale with the system, minimizing risk and ensuring fairness. Ethical guardrails require transparent handling of algorithmic decisions, protection of sensitive data through privacy-by-design principles, and interagency coordination to avoid regulatory conflict. Governance must ensure that every new integration or deployment is safe, fair, and aligned with broader societal goals.

# 9 The Future of Interoperable Transportation Twins

Interoperable digital twins are increasingly being explored as tools that extend beyond localized planning, potentially enabling more connected and dynamic representations of transportation systems. Current developments suggest that such digital models can play a growing role in supporting sustainable urban and regional mobility, offering insights that can influence how cities and transport networks evolve.

Trends in digital twin development indicate potential shifts in convergence, autonomy, and personalization within transportation systems:

* **Hyper-personalization of mobility:** Digital twins can increasingly support real-time adaptation of routes and services based on individual preferences, needs, and contextual constraints. Such approaches can enhance user experience and encourage a modal shift toward public and shared mobility options.
* **Convergence with broader SoS domains:** Transportation twins can increasingly exchange data across complementary domains such as energy grids, logistics networks, supply chains, and environmental monitoring systems (“climate twins”). This convergence can enhance predictive coordination and optimize traffic or energy flow in response to regional events or climate conditions.
* **AI-informed cities:** Emerging applications of digital twins can support automated planning for infrastructure, zoning, and urban design. While still developing, these tools can contribute to longer-term resilience and operational efficiency when combined with human decision-making.
* **Digital twin marketplaces:** New digital economies may evolve where cities, agencies, and private operators can license models, share scenarios, and contribute data in a controlled, governed environment. Such marketplaces can accelerate innovation while reducing costs associated with developing and maintaining individual twin systems.
* **Urban metaverse convergence:** Converging technologies are enabling transportation systems to be modeled, governed, and prototyped within an immersive digital layer where physical and virtual mobility infrastructure co-evolve. This environment can support deeper stakeholder engagement and provide a safe space for experimental policy exploration.

Considering these trends, it is becoming increasingly important to adopt shared protocols, trusted data practices, and governance structures that support interoperability, security, and compliance across jurisdictions. Observing these trends can help ensure that investments in multimodal transportation initiatives remain forward-looking and adaptable to evolving technological and societal contexts.

# 10 Conclusions and Next Steps

The future of multimodal transportation depends on overcoming persistent fragmentation through coordinated action, shared data, and interoperable technologies. This whitepaper presents a unified blueprint that connects business capabilities, digital innovation, and scalable governance to create a seamless, intelligent, and resilient transportation ecosystem. It defines strategic priorities for achieving end-to-end optimization across modes and provides a practical roadmap for implementation through pilots, modeling, and simulation.

The next phase moves from design to demonstration through a Digital Twin Testbed proposed under the Digital Twin Consortium. Guided by a common System of Systems metamodel, this initiative provides a collaborative environment for validating interoperability, measuring performance, and refining the frameworks described in this paper. Together, these efforts form the bridge between strategy and execution, turning the vision of seamless multimodal mobility into measurable, real-world outcomes.

The Mobility and Transportation Working Group of the Digital Twin Consortium invites government agencies, industry leaders, technology innovators, and research partners to join in advancing this initiative. By working together, consortium members can shape the standards, testbeds, and implementations that will define the next generation of connected, efficient, and sustainable transportation systems.

## 10.1 Solving Multimodal Transportation Challenges Through a Unified Blueprint

Fragmented multimodal transportation systems impose significant economic, operational, and societal costs. This whitepaper presents a unified blueprint for transforming these disconnected networks into seamless, adaptive ecosystems through interoperable digital twins. Six strategic takeaways define the path forward:

* **Integrated Hubs Enable Seamless Transfers**   
  Optimizing core nodes—airports, stations, ports, and first/last-mile connectors—ensures fluid transitions across air, ground, and water modes, reducing delays and improving journey reliability.
* **End-to-End Optimization Requires Capability and Stakeholder Alignment**   
  Aligning business capabilities with quantifiable KPIs and fostering cross-sector coordination enables efficient freight movement, optimized passenger experiences, and better asset utilization.
* **Advanced Technologies Unlock Real-Time Intelligence**   
  Digital twins, AI agents, GIS, blockchain, and mobile platforms deliver predictive analytics, autonomous optimization, and trusted coordination across all transport modes.
* **Scalable Governance and Architecture Are Foundational**   
  System-of-Systems methodology, a Common Information Model, and event-driven architectures provide the structural backbone for integrating diverse data systems, transport modes, and stakeholder priorities.
* **Economic Value Is Tangible and Use Case–Driven**   
  From passenger re-routing to cargo integrity monitoring, interoperable systems deliver measurable economic returns while enhancing resilience, sustainability, and service quality.
* **Pilots and Roadmaps De-Risk Transformation**   
  Modeling, simulation, and phased implementation through targeted pilot programs offer a controlled pathway to validate solutions, reduce risk, and accelerate adoption.

By leveraging interoperable digital twins alongside aligned capabilities, advanced technologies, and robust governance frameworks, stakeholders can move from fragmented operations to a unified multimodal system. Through integrated hubs, optimized journeys, and strategic orchestration, governments, industry leaders, and technology partners can realize a scalable, resilient, and efficient transportation ecosystem—one that maximizes economic value while enhancing passenger and freight experiences.

## 10.2 Initiating a Testbed within Digital Twin Consortium

The blueprint outlined in this paper can be brought to life through a collaborative testbed to be proposed for the Digital Twin Testbed Program of the Digital Twin Consortium. The testbed will allow consortium members to develop, validate, and demonstrate seamless multimodal transportation across air, ground, and water networks. The testbed provides a practical environment to optimize passenger journeys, freight logistics, and asset utilization while measuring tangible improvements through clear performance indicators.

Ultimately, the testbed acts as a living demonstration of the whitepaper’s vision, providing a roadmap for translating conceptual strategies into measurable outcomes and a path toward a fully seamless multimodal travel ecosystem.

A diagram of a testbed proposal

AI-generated content may be incorrect.

Figure 10.2-1: Digital Twin Consortium’s Testbed Proposal Framework

A common System-of-Systems (SoS) metamodel serves as the foundation, standardizing documentation, enabling simulation of complex interactions, and ensuring interoperability across diverse modes and operators. This structured approach allows the Consortium to test advanced capabilities—including real-time routing, predictive scheduling, AI-driven coordination, and blockchain-enabled trust—before scaling solutions across the broader ecosystem.

For example, the testbed can evaluate the SoS metamodel’s ability to provide the shared semantic and structural framework that enables Multi-Agent Coordination Protocol (MCP) and Agent-to-Agent (A2A) systems to discover, interpret, and coordinate capabilities and intents across heterogeneous systems.

The testbed will also support real-world pilots by providing a validated, interoperable platform that stakeholders can use to implement and evaluate operational initiatives in live environments. Insights and performance data gathered from pilots will feed back into the testbed to:

* Refine models, algorithms, and governance frameworks.
* Validate interoperability and technical scalability.
* Accelerate adoption across regions and transport modes.

By integrating digital engineering practices, composable systems, and AI-enabled optimization, the testbed creates a controlled space for experimenting with high-value use cases while tracking maturity and readiness. It demonstrates how the combination of capabilities, technologies, governance frameworks, and structured simulation can deliver a resilient, scalable, and fully interoperable multimodal transportation system.

# 11 References

[1] Skyports Infrastructure, “Skyports Infrastructure appointed lead vertiport developer & operator for Korea’s first commercial vertiport network, on Jeju Island,” Sep. 2025. [Online]. Available:<https://www.skyports.net/skyports-infrastructure-appointed-lead-vertiport-developer-koreas-first-vertiport-jeju-island/>

[2] UrbanV, “UrbanV and Korea Airports Corporation join forces to develop an Advanced Air Mobility ecosystem,” Oct. 31, 2024. [Online]. Available: <https://www.urbanv.com/en/urbanv-and-korea-airports-corporation-join-forces-to-develop-an-advanced-air-mobility-ecosystem/>

[3] Empire Clean Cities, *The E-Mobility Project (TEMP)*, 2024. [Online]. Available: <https://www.empirecleancities.org/ecp.html>

[4] F. Jiang, J. Li, L. Ma, Z. Dong, W. Chen, T. Broyd, and G. Wang, “Sustainable urban road planning under the Digital Twin–MCDM–GIS framework considering multidisciplinary factors,” *Journal of Cleaner Production*, vol. 469, 2024, Art. no. 143097, doi: 10.1016/j.jclepro.2024.143097.   
Available: <https://www.sciencedirect.com/science/article/abs/pii/S0959652624025460>

[5] European Commission, “Regulation (EU) 2024/1679 of the European Parliament and of the Council establishing the revised Trans-European Transport Network (TEN-T) guidelines for a sustainable and resilient transport infrastructure,” *Official Journal of the European Union*, Jun. 13, 2024.

[6] M. Werling, “Leveraging Data Sharing to Transform Transportation,” Digital Twin Consortium, May 9, 2025. [Online]. Available: <https://www.digitaltwinconsortium.org/2025/05/leveraging-data-sharing-to-transform-transportation/>

[7] Digital Twin Hub, *Cross-Sector UK Data Sharing Infrastructure: Data sharing initiatives – high-level landscape snapshot*, Oct. 2024. [Online].

Available: <https://digitaltwinhub.co.uk/download/cross-sector-uk-data-sharing-infrastructure/>

[8] N. Morales, “Supply Chain Resilience and the Effects of Economic Shocks,” *Federal Reserve Bank of Richmond Economic Brief*, no. 25-02, Jan. 2025. [Online]. Available:

<https://www.richmondfed.org/publications/research/economic_brief/2025/eb_25-02>

[9] Worldmetrics.org, *Multimodal Statistics*, May 2025. [Online]. Available: <https://worldmetrics.org/multimodal-statistics/>

[10] Department for Transport, “Integrated network management digital twin: Economic benefits analysis,” Sep. 26, 2024. [Online]. Available:

<https://www.gov.uk/government/publications/integrated-network-management-digital-twin-economic-benefits-analysis>

[11] City of Columbus, *Smart Columbus Final Report*, Jun. 2021. [Online]. Available: <https://smartcolumbus.com/insights/smart-city-grant-era-reports>

[12] Digital Twin Consortium, *Digital Twin System Interoperability Framework: A Digital Twin Consortium Whitepaper*, 2021. [Online]. Available:

<https://www.digitaltwinconsortium.org/pdf/Digital-Twin-System-Interoperability-Framework-12072021.pdf>

[13] Digital Twin Consortium, *Platform Stack Architectural Framework: An Introductory Guide*, 2023. [Online]. Available: <https://www.digitaltwinconsortium.org/wp-content/uploads/sites/3/2023/07/Platform-Stack-Architectural-Framework.pdf>

[14] Digital Twin Consortium/Industry IoT Consortium, “System-of-Systems Models for Interoperability and Value Creation,” Sep. 2024. Available: <https://www.iiconsortium.org/wp-content/uploads/sites/2/2024/09/System-of-Systems-Model-for-Value-Creation-2024-09-13-1.pdf>

[15] K. Alexandridis, S. Sabri, J. Smith, B. Logan, K. Bartfai-Walcott, and D. Migliori, “Distributed AI modeling and simulation for smart airport digital twin applications,” in *Digital Twins, Simulation, and the Metaverse: Simulation Foundations, Methods and Applications*, M. Grieves and E. Y. Hua, Eds., Springer Nature, 2024, pp. 195–224. [Online]. Available: <https://doi.org/10.1007/978-3-031-69107-2_9>

[16] TM Forum, “Transforming Passenger Experiences with Continuous Decision Intelligence: A Metaverse Catalyst Project,” Sep. 2023. Available: <https://www.tmforum.org/catalysts/projects/M23.0.567/transforming-passenger-experiences-with-continuous-decision-intelligence>

[17] Digital Twin Consortium, “Digital Twin Value for Airport Operations,” Mar. 2025. Available: <https://www.digitaltwinconsortium.org/digital-twin-value-overview-and-use-cases-for-airport-operations/>

[18] Digital Twin Consortium, “Digital Twin Business Maturity Model,” Mar. 2025. Available: <https://www.digitaltwinconsortium.org/publications/digital-twin-business-maturity-model/>

[19] Digital Twin Consortium, “Spatial Intelligent Digital Twin Capabilities and Characteristics for Digital Twins,” Mar. 2025. Available:

<https://www.digitaltwinconsortium.org/publications/spatially-intelligent-digital-twins/>

[20] National Renewable Energy Laboratory, *Transportation Hub Infrastructure Expansion: Decision Support Under Uncertainty*, NREL/TP-2C00-80637, 2021. Golden, CO. [Online]. Available: <https://www.nrel.gov/manufacturing/news/program/2021/long-term-investments-at-major-transportation-hubs>

[21] Michigan Central, “MDOT, the City of Detroit and Michigan Central to build a new multimodal transportation hub in Detroit,” *Michigan Central*, Oct. 15, 2025. [Online]. Available: [https://michigancentral.com/mdot-the-city-of-detroit-and-michigan-central-to-build-a-new-multimodal-transportation-hub-in-detroit/](https://michigancentral.com/mdot-the-city-of-detroit-and-michigan-central-to-build-a-new-multimodal-transportation-hub-in-detroit/?utm_source=chatgpt.com). [Accessed: Nov. 16, 2025].

[22] Digital Twin Consortium, “Composing Intelligent Transportation Hubs,” YouTube video, uploaded by Digital Twin Consortium, [Dec. 20, 2023] Accessed: Nov. 19, 2025. [Online]. Available: <https://www.youtube.com/watch?v=wfgmTxlrsZI>

# 12 Authors & Legal Notice

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# 13: Appendices Overview

This whitepaper is supported by a series of appendices that provide detailed prompts, case studies, and frameworks. Together, they form a living document series designed to evolve alongside consortium research and implementation. Appendix A is included in this initial release, while Appendices B–F will be published sequentially, each expanding on specific case studies and culminating in a top-level system of systems. The appendices are structured as follows:

**Appendix A: An LLM Prompt to Model a Case Study as a System of Systems (included)**

Introduces the engineered large language model (LLM) prompt that generates a System‑of‑Systems (SoS) metamodel. Provides a worked example showing how a transportation case study can be represented through semantic entities such as Party, Intent, Asset, System, Capability, Action, Entity, Service, Contract, Relation, and Service Usage.

A**ppendix B: Smart Columbus Case Study (forthcoming)**

Demonstrates how a federated data platform and collaborative governance can be modeled as a System‑of‑Systems. Shows how integrated trip planning and inclusive urban mobility services fulfill stakeholder intents and are traceable through standardized Service Usages.

**Appendix C: Dallas–Fort Worth Airport Case Study (forthcoming)**

Illustrates how multimodal digital twins and real-time data fusion can be modeled as a System‑of‑Systems. Highlights predictive, adaptive operations across airside and regional transport systems, with Contracts and Relations formalizing governance across airlines, regulators, and transit operators.

**Appendix D: Korean National Railroad and Incheon Airport Case Study (forthcoming)**

Highlights how interoperable System‑of‑Systems architectures unite air, rail, and urban transport through AI, AR, and digital twin technologies. Shows how integrated ticketing and real-time travel guidance fulfill stakeholder intents across national and municipal Parties.

**Appendix E: New York Blue Highways Case Study (forthcoming)**

Envisions a blockchain-enabled maritime logistics network modeled as a System‑of‑Systems. Demonstrates how digital twins and secure Contracts can decarbonize and modernize urban freight, with Service Usages capturing emissions reduction and supply chain resilience.

**Appendix F: A Global Transportation System of Systems (forthcoming)**

Creates an LLM prompt to standardize Capabilities, Actions, and Entity classes across the four case studies (Columbus, Dallas–Fort Worth, Korean Railroad/Incheon, and New York Blue Highways). By harmonizing these elements, the appendix composes a higher‑level System‑of‑Systems that supports seamless multimodal travel across states (e.g., Dallas, Columbus, New York) and countries (e.g., United States, South Korea).

# Appendix A: An LLM Prompt to Model a Case Study as a System of Systems

## A.1 Introduction

Digital transformation initiatives can be systematically analyzed and documented using a System-of-Systems (SoS) metamodel generated through an engineered large language model (LLM) prompt. This approach transforms case study narratives[[1]](#footnote-1) into structured, human-readable, and machine-actionable representations based on a common information model (CIM).

By using this framework, practitioners can:

* Standardize the documentation of complex socio-technical systems.
* Simulate and evaluate system interactions and outcomes.
* Trace how stakeholder goals (intents) are realized through coordinated services, systems, and spaces.
* Guide early-stage planning and coordination of multimodal Digital Twins

The following prompt and worked example demonstrate how an LLM can be used to convert any case study into a structured SoS model.

## A.2 LLM Prompt: System-of-Systems Metamodel Generation

**Instructions to the LLM:**

Convert the following case study into a System-of-Systems (SoS) metamodel, represented as a series of structured tables. Each table corresponds to one of the core entities or relationships within the SoS framework.

Above each table, include a short paragraph (1–2 sentences) that describes the unique aspects or challenges related to that table’s content within the case study context. Use clear, human-readable names rather than code or ontology syntax.

At the beginning of the output, include an introductory Executive Summary that orients the reader to the case study context (e.g., location, age, unique characteristics of the PAE Living Building). This Executive Summary must describe the project’s vision, challenges, and how the System‑of‑Systems methodology (using semantic names such as Party, Intent, Asset, System, Capability, Action, Entity, Service, Contract, Relation, Service Usage) addresses these challenges and realizes the vision.

After the Executive Summary, include a Vision Scenario written in third‑person, event‑driven style (similar to a user story). The scenario should demonstrate orchestration across the System‑of‑Systems, where events trigger Services, Contracts, Relations, and Service Usages to fulfill Intents. The scenario must avoid describing tables and instead use semantic names to narrate the orchestration.

### A.2.1 System-of-Systems Relationship Model

Each relationship expresses how entities interact within the SoS metamodel:

|  |  |  |
| --- | --- | --- |
| **Subject** | **Predicate** | **Object** |
| Space | contains | Asset |
| Space | located in | Space |
| Asset | may contain | Space |
| Asset | may contain | System |
| System | possesses | Capability |
| Capability | enables | Action |
| Capability | affects | Entity |
| Capability | is delivered as | Service |
| Service | is consumed by | Other System |
| Contract | is type of | Relation |
| Service | is bound to | Contract |
| Contract | constrains | Intent |
| System | establishes | Relation |
| System | interacts with | Other System |
| Party | owns or governs | Asset |
| Party | expresses | Intent |
| Party | located in | Space |
| Service | fulfills | Intent |
| Service | generates | Service Usage |
| Person | is type of | Party |
| Organization | is type of | Party |
| Vehicle | is type of | Asset |
| Party | possesses | Capability |
| Capability | defines | Role |
| Capability | composed of | Capabilities |
| Contract | defines | Party Role |
| Party | consumes | Service |
| Party | provides | Service |

### A.2.2 Tables to Be Generated

The LLM should generate tables corresponding to each SoS entity listed below.  
 Each table captures structured metadata describing how systems, services, and capabilities interact to fulfill stakeholder intents. Each table must be preceded by a short contextual paragraph describing the unique aspects or challenges of that entity within the case study.

#### Spaces

Spaces contextualize where systems and services operate — physical, digital, or logical environments.

|  |  |
| --- | --- |
| **Column** | **Example Values** |
| Space ID | S1, S2 |
| Name | Gate 1, Terminal 1 |
| Type | Neighborhood, Transit Hub, Corridor, Airport Terminal, Virtual Zone |
| Space | Containing Space |
| Description | Operational context |

#### 

#### Parties

Parties represent organizations or actors that own assets, provide services, or declare intents. All persons or organizations referenced in other tables must be listed here.

|  |  |
| --- | --- |
| **Column** | **Example Values** |
| Party ID | P1, P2 |
| Name | Airport Authority, Mobility Operator |
| Type | Organization, Vendor, Regulator |
| Description | Organizational role |

#### Intents

Intents are stakeholder goals that drive system orchestration.

|  |  |
| --- | --- |
| **Column** | **Example Values** |
| Intent ID | I1, I2 |
| Name | Reduce Emissions |
| Party | Declaring Party |
| Description | Desired outcome |
| Fulfilled By | Capability |

#### Assets

Assets are physical or digital resources within a space that host or support systems.

|  |  |
| --- | --- |
| **Column** | **Example Values** |
| Asset ID | A1, A2 |
| Name | IoT Network, Edge Gateway |
| Type | Physical, Digital, Hybrid |
| Space | Associated Space |
| Owner/Governor | Owning or Governing Party |
| Description | Function within the space |

#### Systems

Systems integrate assets and software to deliver capabilities.

|  |  |
| --- | --- |
| **Column** | **Example Values** |
| System ID | SY1, SY2 |
| Name | Mobility Management Engine |
| Type | Operational, Analytical, Control, Simulation |
| Provider | Party Providing the System |
| Asset | Containing Asset |
| Description | System role and function |

#### Capabilities

Capabilities define what systems can do — the functions that enable services and fulfill intents.

|  |  |
| --- | --- |
| **Column** | **Example Values** |
| Capability ID | C1, C2 |
| Name | Predictive Maintenance |
| System | Providing System |
| Action | Associated Action |
| Entity | Entity acted upon |
| Description | Purpose and measurable outcome |

#### Actions

Actions are the operational verbs that capabilities perform. Each Action must include attributes that define operational parameters (e.g., origin, destination, flow rate, setpoint, schedule).

|  |  |
| --- | --- |
| **Column** | **Example Values** |
| Action ID | AC1, AC2 |
| Name | Monitor, Optimize |
| Description | Description of the operation |
| Attributes | List of attributes that define operational parameters |

#### Entities

Entities represent the real-world or digital things that actions act upon. Each Entity must include attributes that define constraints and contextual properties (e.g., size, weight, temperature, humidity, occupancy, hazard class).

|  |  |
| --- | --- |
| **Column** | **Example Values** |
| Entity ID | E1, E2 |
| Name | Passenger, Vehicle |
| Type | Person, Object, Dataset, Process |
| Description | Contextual role |
| Attributes | List of attributes that define constraints and contextual properties |

#### Services

Services realize capabilities as standardized offerings that can be bound to relations or contracts.

|  |  |
| --- | --- |
| **Column** | **Example Values** |
| Service ID | SV1, SV2 |
| Service Name | Passenger Flow Analytics |
| Action | Associated Action |
| Entity Class | Person, Vehicle |
| Provider | Providing Party or System |
| Space | Context of execution |
| Attributes | Performance or operational characteristics |

#### Relations

Relations define interactions or data exchanges between systems, services, or parties.

|  |  |
| --- | --- |
| **Column** | **Example Values** |
| Relation ID | R1, R2 |
| Type | Data Exchange, Orchestration, Governance |
| Participants | Systems or Parties |
| Roles | Roles of Participants |
| Description | Purpose or function |

#### Contracts (Formalized Relations)

Contracts formalize relations through agreed terms and responsibilities.

|  |  |
| --- | --- |
| **Column** | **Example Values** |
| Contract ID | CT1, CT2 |
| Provider | Party or System |
| Consumer | Party or System |
| Service ID | Associated Service |
| Terms | Key conditions |
| Status | Active, Pending, Expired |

#### Service Usages

Service usages record each execution of a service and its measured impact.

|  |  |
| --- | --- |
| **Column** | **Example Values** |
| Usage ID | U1, U2 |
| Service ID | Associated Service |
| Timestamp | 2025-06-12T14:30Z |
| Status | Pending, In Process, Completed |
| Metrics Captured | KPIs such as throughput or emissions |

### A.2.3 Output Expectation

The generated tables together form a **System-of-Systems metamodel** that connects stakeholder intents to the capabilities, systems, and services that realize them.  
 This provides a unified framework for both human understanding and machine-based orchestration, supporting traceability and evaluation across the entire system lifecycle.

The generated output must include:

* **An introductory Executive Summary** that situates the case study in context and explains the vision, challenges, and methodology using semantic names.
* **A Vision Scenario** at the end, written in third‑person, event‑driven style, demonstrating orchestration across the SoS using semantic names.
* **Structured tables** for each SoS entity, each preceded by a short contextual paragraph.

This provides a unified framework for both human understanding and machine‑based orchestration, supporting traceability and evaluation across the entire system lifecycle.

## A.3 Worked Example — Airport Digital Twin Case Study

### A.3.1 Overview

The City’s International Airport is implementing a Digital Twin System-of-Systems to improve passenger flow, reduce congestion, and enhance sustainability.  
 This initiative connects physical infrastructure, operational systems, and data-driven services through shared intents and capabilities.

### A.3.2 Generated Tables

#### Spaces

|  |  |  |  |
| --- | --- | --- | --- |
| **Space ID** | **Name** | **Type** | **Description** |
| S1 | Terminal 1 | Airport Terminal | Main passenger terminal |
| S2 | Ground Transit Hub | Transit Hub | Shuttle and public transit interchange |
| S3 | Data Integration Layer | Virtual Zone | Logical environment for analytics and orchestration |

#### Parties

|  |  |  |  |
| --- | --- | --- | --- |
| **Party ID** | **Name** | **Type** | **Description** |
| P1 | Airport Authority | Organization | Oversees airport operations |
| P2 | City Mobility Operator | Organization | Provides ground transportation |
| P3 | Technology Vendor | Vendor | Supplies IoT and analytics solutions |

#### Intents

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Intent ID** | **Name** | **Party** | **Description** | **Fulfilled By** |
| I1 | Improve Passenger Flow | Airport Authority | Reduce wait times and congestion | SV1 |
| I2 | Reduce Emissions | City Mobility Operator | Lower ground transport emissions | SV2 |
| I3 | Enhance Operational Resilience | Airport Authority | Simulate and anticipate disruptions | SV3 |

#### Assets

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Asset ID** | **Name** | **Type** | **Space** | **Description** |
| A1 | IoT Sensor Network | Physical | Terminal 1 | Detects passenger flow and occupancy |
| A2 | Edge Gateway Cluster | Digital | Ground Transit Hub | Processes shuttle data in real time |
| A3 | Data Orchestration Engine | Hybrid | Data Integration Layer | Coordinates data sharing across systems |

#### Systems

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **System ID** | **Name** | **Type** | **Asset** | **Description** |
| SY1 | Passenger Flow Monitor | Operational | A1 | Tracks occupancy and movement using AI analytics |
| SY2 | Mobility Management Engine | Control | A2 | Manages shuttle scheduling and optimization |
| SY3 | Airport Digital Twin Platform | Analytical | A3 | Provides integrated visualization and simulation |

#### Capabilities

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Capability  ID** | **Name** | **System** | **Action** | **Entity** | **Description** |
| C1 | Flow Analysis | SY1 | Monitor | Passenger | Predicts congestion based on movement patterns |
| C2 | Route Optimization | SY2 | Optimize | Vehicle | Improves shuttle routing efficiency |
| C3 | Predictive Simulation | SY3 | Simulate | Process | Tests operational scenarios before deployment |

#### Services

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Service ID** | **Service Name** | **Action** | **Entity Class** | **Provider** | **Space** | **Attributes** |
| SV1 | Passenger Tracking | Monitor | Person | Airport IoT Platform | Terminal 1 | Real-time location data |
| SV2 | Shuttle Coordination | Optimize | Vehicle | City Mobility Operator | Ground Transit Hub | Energy-efficient routing |
| SV3 | Operations Simulation | Simulate | Process | Digital Twin Platform | Data Integration Layer | Predictive analytics |

#### 

#### Contracts

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Contract ID** | **Provider** | **Consumer** | **Service ID** | **Terms Summary** | **Status** |
| CT1 | City Mobility Operator | Airport Authority | SV2 | Shuttle data integrated with flight schedules | Active |
| CT2 | Airport IoT Platform | Operations Center | SV1 | Sensor data shared under privacy rules | Active |

#### Service Usages

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Usage ID** | **Service ID** | **Timestamp** | **Status** | **Metrics Captured** |
| U1 | SV1 | 2025-06-12T14:30Z | Completed | Queue time reduced by 12% |
| U2 | SV2 | 2025-06-12T14:35Z | Completed | Shuttle emissions reduced by 8% |
| U3 | SV3 | 2025-06-12T15:00Z | Completed | Throughput improved by 9% |

### A.3.3 System-of-Systems Summary

This Airport Digital Twin exemplifies an integrated System-of-Systems, in which:

* **Spaces** define operational context.
* **Assets** host **Systems** that provide **Capabilities**.
* **Capabilities** are realized as **Services** fulfilling **Intents**.
* **Relations** and **Contracts** govern trust and interoperability.
* **Service Usages** provide evidence of outcomes and performance.

Together, these elements create a traceable framework that links stakeholder goals to measurable system outcomes, forming a reusable template for analyzing and designing other digital transformation initiatives.

# Appendix B: Smart Columbus Case Study *(Forthcoming)*

This appendix will present the City of Columbus initiative as a System‑of‑Systems (SoS) model, generated using the engineered LLM prompt introduced in Appendix A. Building on the consortium’s methodology, the case study will demonstrate how a federated data platform and collaborative governance can be represented based on a common information model (CIM).

The Smart Columbus program has been recognized for its ability to enable integrated trip planning and data-driven, inclusive urban mobility. By modeling this initiative as a System‑of‑Systems, the appendix will show how:

* Intents expressed by city leaders and community stakeholders (e.g., improving accessibility, reducing emissions) are fulfilled through Services such as integrated trip planning and real-time mobility analytics.
* Assets like connected vehicles, charging infrastructure, and transit hubs are orchestrated by Systems that deliver measurable Capabilities.
* Contracts and Relations formalize governance across public agencies, private operators, and technology providers.
* Service Usages provide traceability and accountability, capturing metrics on accessibility, efficiency, and sustainability.

This appendix will be released in a future version of the whitepaper, providing a complete worked example of DFW Airport modeled as a System‑of‑Systems.

# Appendix C: Dallas-Fort Worth Airport Case Study *(Forthcoming)*

This appendix will present the Dallas–Fort Worth (DFW) Airport initiative as a System‑of‑Systems (SoS) model, generated using the engineered LLM prompt introduced in Appendix A. The case study will demonstrate how multimodal digital twins and real-time data fusion can be represented based on a common information model (CIM).

DFW Airport illustrates how digital twin technology can enable predictive, adaptive operations across both airside and regional transport systems. By modeling this initiative as a System‑of‑Systems, the appendix will show how:

* Intents expressed by airport authorities and passengers are fulfilled through Services such as predictive routing and adaptive scheduling.
* Assets, including aircraft, terminals, and ground transport hubs, are orchestrated by Systems that deliver measurable Capabilities.
* Contracts and Relations formalize governance and interoperability across airlines, regulators, and regional transit operators.
* Service Usages capture metrics on operational efficiency, passenger throughput, and sustainability outcomes.

This appendix will be released in a future version of the whitepaper, providing a complete worked example of DFW Airport modeled as a System‑of‑Systems.

# Appendix D: Korean National Railroad and Incheon Airport Case Study *(Forthcoming)*

This appendix will present the Korean National Railroad and Incheon International Airport initiative as a System‑of‑Systems (SoS) model, generated using the engineered LLM prompt introduced in Appendix A. The case study will demonstrate how interoperable architectures uniting air, rail, and urban transport can be represented based on a common information model (CIM).

This initiative highlights how AI, augmented reality (AR), and digital twin technologies can be integrated to create seamless multimodal travel experiences. By modeling this initiative as a System‑of‑Systems, the appendix will show how:

* Intents expressed by national rail authorities, airport operators, and passengers are fulfilled through Services such as integrated ticketing and real-time travel guidance.
* Assets, including trains, aircraft, and urban transit nodes, are orchestrated by Systems that deliver measurable Capabilities.
* Contracts and Relations formalize governance across national, regional, and municipal stakeholders.
* Service Usages capture metrics on travel time reduction, passenger satisfaction, and emissions savings.

This appendix will be released in a future version of the whitepaper, providing a complete worked example of Korean National Railroad and Incheon Airport modeled as a System‑of‑Systems.

# Appendix E: New York Blue Highways Case Study *(Forthcoming)*

This appendix will present the New York Blue Highways initiative as a System‑of‑Systems (SoS) model, generated using the engineered LLM prompt introduced in Appendix A. The case study will demonstrate how blockchain-enabled maritime logistics networks can be represented based on a common information model (CIM).

The Blue Highways initiative envisions a blockchain-enabled maritime logistics network using System‑of‑Systems digital twins to decarbonize and modernize urban freight. By modeling this initiative as a System‑of‑Systems, the appendix will show how:

* Intents expressed by city planners, logistics providers, and regulators are fulfilled through Services such as secure freight tracking and emissions monitoring.
* Assets, including barges, ports, and distribution hubs, are orchestrated by Systems that deliver measurable Capabilities.
* Contracts and Relations formalize governance across shipping companies, municipal authorities, and technology providers.
* Service Usages capture metrics on freight throughput, emissions reduction, and supply chain resilience.

This appendix will be released in a future version of the whitepaper, providing a complete worked example of New York Blue Highways modeled as a System‑of‑Systems.

# Appendix F: A Global Transportation System of Systems *(Forthcoming)*

This appendix will present a vision for a Global Transportation System of Systems (SoS), generated using the engineered LLM prompt introduced in Appendix A. The case study will demonstrate how multimodal networks across cities and countries can be represented based on a common information model (CIM).

The purpose of this appendix is to create an LLM prompt that standardizes Capabilities, Actions, and Entity classes across the four case studies (Smart Columbus, Dallas–Fort Worth Airport, Korean National Railroad and Incheon Airport, and New York Blue Highways). By harmonizing these elements, the appendix will show how they can be composed into a higher‑level System of Systems that supports seamless multimodal travel across states (e.g., Dallas, Columbus, New York) and countries (e.g., United States, South Korea).

This appendix will also reflect the framework proposed for a testbed within the Digital Twin Consortium, demonstrating how the methodology presented in the whitepaper can be applied, validated, and refined in a collaborative environment. The testbed will serve as a proving ground for interoperability, scalability, and traceability across diverse transportation ecosystems, laying the foundation for a unified global travel network.

This appendix will be released in a future version of the whitepaper, providing a complete worked example of how standardized prompts can unify regional and international case studies into a global System‑of‑Systems, while also serving as the basis for a Digital Twin Consortium testbed.

1. Example of Case Study narrative is [USDOT Grant Final Report on Smart Columbus, June 15, 2021](https://smartcolumbus.com/s/2021-06-USDOT-Final-Report-Executive-Summary-1-compressed-compressed.pdf) [↑](#footnote-ref-1)