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# A standardised Digital Twin design framework for transport system decarbonisation

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ABSTRACT

Decarbonising transport systems is a global necessity for achieving net-zero, and Digital Twin (DT) technologies are emerging as key enablers of this transition. Despite growing interest in DT solutions, their potential support for transport decarbonisation remains in its infancy. This is mainly due to inconsistent methodological development and limited alignment with established standards. The literature shows that IoT, CPS, and embedded systems are increasingly used in DT design across the transport modes. However, they often target fragmented and function-specific use cases rather than integrated, system-level applications. This paper fills these gaps by presenting a novel Digital Twin Design Framework for transport system decarbonisation that, to the authors' knowledge, is the first to adapt the ISO-23247 manufacturing standard to the transport domain. The study combines a systematic literature review of more than 100 studies with a Delphi consultation involving 10 experts from three UK research institutions using more than 10,000 extracted literature and workshop-derived data records. The analysis identifies (1) dominant digital methodologies used in transport DT development, and (2) standardised architectural elements essential for a unified DT design for transport decarbonisation across road, rail, marine/maritime and air. The proposed framework encompasses a layered architecture comprising observable, communication, control, user, and cross-system DT entities. The proposed framework provides a scalable reference architecture for supporting interoperable, climate-aligned DT development across transport systems. It also offers a blueprint for aligning transport digitalisation with climate policy and net-zero objectives.

## 1. Introduction

It is crucial to limit global temperature rise to 1.5°C above pre-industrial levels. This target has placed decarbonisation at the forefront of national and international climate policy. In the UK, the transport sector remains the most significant contributor to domestic emissions, accounting for approximately 30% of total GHG emissions (2024 Provisional greenhouse gas (GHG) emissions statistics - GOV.UK). Transport emissions have remained persistently high over the past three decades. This persistence is mainly due to rising demand, fossil-fuel dependency, and structural reliance on road-based mobility. Transport decarbonisation refers to a set of processes aimed at reducing and ultimately eliminating GHG emissions from the movement of people and goods. The process is a multi-dimensional challenge that involves technological innovation and systemic changes in infrastructure, behaviour, policy, and investment. The UK's strategic approach is articulated through the Transport Decarbonisation Plan (TDP), published by the Department for Transport (DfT) in July 2021. The TDP sets decarbonisation pathways for road, rail, aviation, and maritime transport, including zero-emission road vehicles, diesel reduction in rail transport, net-zero aviation, and cleaner maritime propulsion. Despite the UK decarbonisation targets, multiple challenges remain: first, there is a lack of commercial feasibility for low-emission alternatives due to the high deployment costs of clean technologies and infrastructure, particularly in aviation, maritime, and heavy freight. Second, policy frameworks often disadvantage demand interventions, such as strategies to reduce travel demand, incentivise modal shift towards public and active transport, and modify pricing structures to reflect environmental impacts (Marsden and Docherty, 2021). Third, a further challenge lies in divided coordination across the transport ecosystem. Decarbonisation

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requires alignment among a wide range of actors, including central and local governments, infrastructure operators, private industry, regulators, and end users. The absence of integrated governance mechanisms hinders consistent, timely progress. Fourth, the measurement, monitoring, and reporting of transport emissions remain significant barriers to the sector. Existing methodologies are often inconsistent across transport modes and cannot provide high-fidelity, streaming data to track emissions (House of Commons Transport Committee, 2023).

Digital transformation and, in particular, Digital Twin (DT) technologies are increasingly explored in literature and industry as effective enablers of climate-aligned innovation across transport modes. Existing DT applications in road transport offer promising capabilities such as embedded vehicle sensing (Hsu & Chen, 2005), adaptive traffic control (B. Yang et al., 2024), decentralised EV charging (Mejjaouli & Alnourani, 2024), smart city systems (Shariatpour et al., 2025), safety in autonomous and conventional traffic (Zhang et al., 2025) and edge computing for logistics platforms (Belfadel et al., 2021). Besides, the IoT-driven implementations support dynamic routing (Ahmed and Rani, 2018), congestion prediction (Lopez-Martin et al., 2019), and emissions monitoring (Baluprithviraj et al., 2023), yet these remain isolated in scope. Similarly, early cyber-physical system (CPS) models for Electric Vehicles (EV) to grid integration (Bhaskar et al., 2022) and vehicle safety systems (Roopini et al., 2024) demonstrated technical feasibility without merging into cohesive frameworks for sustainability-driven transformation. Several recent efforts incorporate Artificial Intelligence (AI), blockchain, and federated learning to enhance DT adaptability and trust (Ren et al., 2019; Tan et al., 2023) while logistics-focused twins' adaptive model, and energy-aware DTs manage carbon-sensitive resource flows (Bezrodniy et al., 2024; Liu et al., 2026; Zhao et al., 2025).

This paper makes three distinct contributions: First, it provides a cross-modal synthesis of the dominant digital methodologies used in transport DT development, including IoT, CPS, embedded systems, hybrid systems, and emerging data architectures, across road, rail, marine/maritime, and air domains (Giering and Dyck, 2021; Jan et al., 2019; Luo et al., 2019; Zhang et al., 2024; Zhou et al., 2022). Second, it identifies a set of recurring architectural limitations in the existing literature, namely fragmentation across use cases and transport modes, weak semantic interoperability, limited alignment with international reference architectures, underdeveloped control and governance functions, and limited structural integration of decarbonisation-related requirements within DT design (Campolo et al., 2024; Chartrain et al., 2024; Fonseca et al., 2023; Salin, 2025; Yigit et al., 2024). Third, it addresses these gaps by proposing an ISO 23247-aligned DT framework, conceptualised as a reference architecture, that integrates observable, device communication, core (or digital twin), user, and cross-system entities into a standardised, scalable structure. In this way, the paper moves beyond the descriptive mapping of prior studies and offers a framework-oriented contribution to the scalable, climate-aligned digitalisation of transport. ISO-23247 is used in this study as a domain-independent reference architecture whose functional entity logic can be scaled and adapted beyond its original manufacturing context. The purpose is not to replace ISO-23247, but to translate and extend its architectural structure for transport decarbonisation. This research aims to identify leading digital methodologies, map relevant architectural entities, and synthesise a scalable, cross-modal DT architecture through a systematic literature review (SLR) of more than one hundred studies and a Delphi-based expert validation process. The paper is structured around the following Research Objectives:

- **RO1:** To identify and classify the existing digital methodologies for designing DTs in transport systems, including IoT, CPS, embedded systems, hybrid systems, and data architectures.
- **RO2:** To propose an ISO-23247-aligned reference architecture outlining the physical entities, cyber entities, user roles, cross-system functions, and analytical methods required for DT-enabled transport decarbonisation across multiple transport modes.

To the best of the authors' knowledge, no prior study within the reviewed literature has adapted the ISO-23247 DT reference architecture from manufacturing to the specific requirements of transport system decarbonisation across road, rail, maritime, and air domains. The novelty of this study, therefore, lies in translating the ISO 23247 entities into the context of decarbonising cross-modal transport. The proposed framework embeds decarbonisation-related observables, interoperability functions, governance considerations, user roles, and cross-system entities within a standardised architectural structure, without claiming to constitute a pilot-level implementation.

The remainder of the paper is structured as follows: Section 2 details the research methodology used to develop the proposed DT design framework. Section 3 provides a comprehensive literature review of the state of the art, identifying the current research trends and gaps in transport-related DT designs. Section 4 outlined the proposed standardised design framework for DT for transport decarbonisation. Section 5 presents a critical discussion of the literature findings and the development of the framework to address key architectural challenges and limitations in existing approaches. Finally, Section 6 draws the concluding remarks and reflects on the contributions and future directions of this research.

## 2. Research methodology

This study adopted a multi-method qualitative research design to develop and validate reference architecture for designing DT technologies for transport decarbonisation. The methodology comprised six stages: secondary data collection through an SLR, primary data collection through a Delphi consultation, digital methodology mapping, framework development, verification and validation, and the formulation of insights and concluding remarks.

In **Stage 1** (Secondary Data Collection), to identify existing methodologies, architectures, and frameworks for DT development in the transport sector, an SLR was conducted in accordance with PRISMA guidelines. This review aimed to identify the digital and cyber-physical technologies in transport systems, with a particular focus on DT frameworks and design models relevant to decarbonisation. Scopus was selected as the principal search database for its broad, multidisciplinary coverage of peer-reviewed literature in engineering, computer science, transport, energy, decision sciences, and related fields. This coverage was considered suitable for the present framework-development study because DTs for transport decarbonisation draw on multiple research domains, including IoT, CPS, embedded systems, data architectures, smart mobility, and sustainable transport. The search query was carefully constructed to balance specificity and breadth, using Boolean logic to combine four concept groups, as follows:

```
(TITLE ("digital shadow" OR "physical twin*" OR "digital twin*" OR "digital thread" OR
"virtual twin" OR "cyber twin" OR "digital replica" OR "cognitive twin" OR "cognitive
digital twin" OR "digital data hub" OR "digital mirror" OR "cyber physical system" OR
"cyber-physical system" OR cps OR iot OR "internet of thing*" OR "embedded
system*") AND TITLE (framework OR architectur* OR conceptual OR design OR
approach) AND TITLE (logistic OR commut* OR transport* OR "transport network"
OR "Multimodal transport" OR road* OR highway OR traffic OR street* OR vehicle*
OR motorway OR "last mile" OR "road cargo" OR "road freight" OR jet OR airline* OR
aircraft OR aviation OR aerospace OR aeroplane OR airplane OR airport OR "air
cargo" OR "air freight" OR rail* OR ship* OR maritime OR waterway OR marine OR
vessel) AND NOT TITLE-ABS-KEY (education OR textile OR "structural design" OR
"built environment" OR healthcare OR construction OR property OR housing OR
residential OR pavement* AND agriculture))
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The document search is restricted to English-language articles, conference papers, and book chapters in the subject areas of Engineering, Computer Science, Decision Science, Mathematics, Energy, and Physics & Astronomy. No restrictions were applied regarding publication year.

All relevant documents published up to March 2026 were included in the review. The search protocol was designed to capture the most directly relevant literature on transport digital twin frameworks by limiting retrieval to documents whose titles explicitly contain the selected keywords, rather than documents in which these terms appear only in the abstract, main body, or keyword list. The initial search returned 919 documents. This was followed by an additional validation of the search, and 5 more documents were included. Then, for eligibility assessment, the initial screening of titles and abstracts is completed. The first review removed studies related to vehicle design, production logistics, manufacturing logistics, space, assembly, and asset design, focusing instead on maintenance and asset management, supply chain, and automated guided vehicles; after this step, 340 papers remained. For the second screening process, a refined exclusion criterion was applied to eliminate works that made no new methodological contributions, as well as papers focused on the built environment, chemistry, the oil industry, maintenance diagnostics, and asset management. This step narrowed the set to 205 documents. The final eligibility and inclusion criteria limited the documents offering novel frameworks, conceptual designs, or methodological models relevant to transport DTs to those retained. After checking PDF availability and additional full-text screening for duplication and relevance, 112 full papers were reviewed in depth and included in the final synthesis. The PRISMA chart is illustrated in Fig. 1.

In **Stage 2** (Primary Data Collection), a Delphi approach is used to establish expert perspectives to develop the framework. The Delphi method is a structured, iterative process that collects and refines expert opinion through multiple rounds of consultation. A three-stage Delphi study was conducted between October 2024 and June 2025 involving ten experts from three UK institutions. The three rounds focused, respectively, on an initial framework review, refinement of ISO-23247 entity mappings, and a final assessment of completeness, terminology, and transport-sector relevance. The participants represent diverse professionals – several had substantial applied experience through previous industry roles, including digital engineering, AI, autonomous transport, CPS, infrastructure monitoring, and sustainable mobility, with multidisciplinary experience in DT development, transport systems, and decarbonisation policy. The panel included a balanced mix of senior academics, early-career researchers, and technical specialists, as shown in Table 1. The Delphi process was used not only to review the draft framework but also to refine specific architectural design choices identified in the literature review. Expert feedback was used to confirm underrepresented entity categories, identify missing transport-specific and decarbonisation-relevant elements, strengthen user-role distinctions, and refine cross-system requirements related to interoperability, governance, and cybersecurity.

The reference to more than 10,000 input data refers to the combined volume of coded literature records, extracted framework elements, methodological classifications, and workshop-derived inputs used to support framework development. Delphi workshop inputs were collected using Miro and then consolidated in Excel for comparison and synthesis. Where interpretation or categorisation required clarification, the authors revisited the material and resolved issues through iterative review and discussion to maintain consistency in the final framework.

**Table 1**
List of academic experts involved in the delphi study.

| Expert Code | Position | Institution | Areas of Expertise |
|---|---|---|---|
| EXP-01 | Professor | University 1 | Digital Engineering, Lifecycle Data Systems |
| EXP-02 | Senior Lecturer | University 1 | DT architectures, CPS, smart cities |
| EXP-03 | Lecturer | University 1 | CAD/CAM integration, digital manufacturing |
| EXP-04 | Lecturer | University 1 | AI, DT, real-time control systems |
| EXP-05 | Research Fellow | University 2 | Simulation, Digital Modelling |
| EXP-06 | Research Fellow | University 2 | Urban Transport, Sustainable Mobility |
| EXP-07 | Senior Lecturer | University 2 | Mechatronics, Intelligent Control Systems |
| EXP-08 | Research Associate | University 2 | Digital Infrastructure, Environmental Sensing |
| EXP-09 | Research Associate | University 3 | Transport Analytics, AI Applications |
| EXP-10 | Associate Professor | University 3 | Systems engineering, Sustainability in transport |

In **Stage 3** (**RO1** – digital methodologies mapping): Building on the insights from the SLR and the expert-driven Delphi method, the identification and mapping of existing digital methodologies within transport systems is completed, and the results are presented in Section 3.1. In **Stage 4** (**RO2** – framework development): Based on data collected from the existing literature and experts' knowledge, a novel conceptual design framework is developed, aligned with ISO-23247 – the international standard for DT. It integrates the physical layer, cyber components, data flows, analytical methods, and the cybersecurity layer, tailored to decarbonisation across multiple transport sectors. The outcomes are detailed in Section 4. Following the development phase, in **Stage 5** (verification and validation), the authors applied a twofold process to assess the soundness and relevance of the proposed reference architecture. Verification focused on internal consistency, logical coherence, and alignment with the literature and ISO-23247. This involved revisiting the literature base to examine whether the proposed entities and relationships were grounded in existing DT theories, architectural models, and transport decarbonisation requirements. The framework structure and contents were cross-checked against the

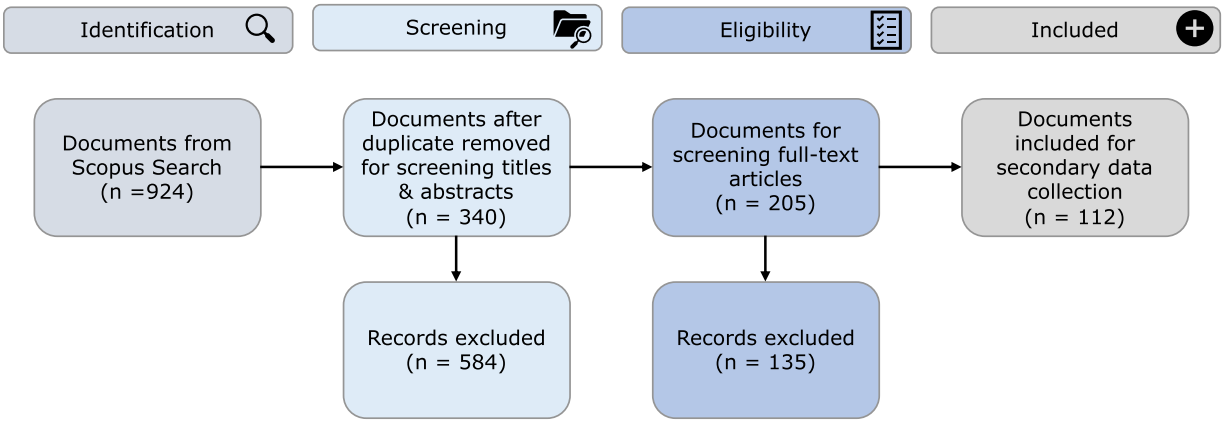



**Fig. 1.** PRISMA flow diagram for the systematic literature review process.

reviewed literature to confirm consistency with established DT design principles and the structure of ISO-23247. Validation was interpreted in relation to the research's conceptual scope using expert-informed assessment of the framework's relevance, completeness, and applicability to transport decarbonisation, rather than to the empirical validation of a deployed DT system. Validation was therefore conducted through structured Delphi feedback workshops involving 10 domain experts. These workshops enabled expert review of the framework's structure, terminology, transport-specific entities, relevance to decarbonisation, user roles, and cross-system functions. The feedback cycles informed us of iterative refinement and helped ensure its suitability as reference architecture for transport decarbonisation. In addition, an illustrative air-road interface use-case was developed to demonstrate how the architectural entities may be applied in a cross-modal decarbonisation context involving EV-based ground operations and SAF-enabled aviation systems. In **Stage 6** (insight and recommendations), several key recommendations are provided for researchers, policy-makers and practitioners, based on the framework's development and validation, and are summarised in Section 6.

## 3. State-of-the-art

This section reviews the relevant literature published between 2005 and March 2026 on road, maritime, rail, and air transport systems. The focus is on the use and role of key technologies and methodologies in developing IoT, CPS, and DTs within the transport sector.

### 3.1. Cyber-physical systems (CPS)

Limited research in transportation applications has focused exclusively on CPS. Sampigethaya and Poovendran (2012) presented a CPS framework for next-generation aircraft and air traffic control. They proposed integrating cyber infrastructure with physical aviation systems, introducing 'group flight' using automatic dependent surveillance-broadcast (ADS-B) and IP-based coordination. Levshun et al. (2021) introduced a methodology-driven framework that emphasises security-by-design in railway CPS. Their framework enhances both functional verification and security assurance by modelling railway infrastructure as sets of interacting building blocks. Jin et al. (2013) proposed a CPS architecture for scheduling EV charging, targeting grid stability. Their CPS reflects real-time EV behaviour and system-wide grid interaction using sliding-window optimisation and vehicle clustering. In more recent research, Yang et al. (2023) addressed cybersecurity challenges in Industrial CPS (ICPS) by proposing a hybrid anomaly detection approach that integrates BERT and 1D-CNN within an unsupervised learning framework. Their method combines Long Short-Term Memory (LSTM)-based word segmentation with deep classification to capture complex short- and long-term dependencies in payload, significantly improving detection performance. Overall, CPS research in transport remains less extensive than IoT and DT research, but it is particularly important for linking sensing, decision-making, and actuation in safety-critical and energy-sensitive transport operations.

### 3.2. Internet of things (IoT)

IoT technologies have been widely recognised as a leading approach in the transportation sector. Less than a decade ago, Godavarthi et al. (2017) explored basic real-time navigation for school vehicles using GPS and IoT systems, reflecting early-stage DT concepts. Jiménez et al. (2017) proposed an IoT-based traffic estimation system using optical flow and cloud processing. Ren et al. (2019) studied the integration of blockchain and IoT in traffic systems, emphasising the need for decentralised data exchange for secure and trustworthy DT operations. Moreover, Jan et al. (2019) proposed a four-layer smart transportation architecture using IoT, Hadoop, Spark, and SDN (Software-Defined Networking). Public transport research, especially in the bus sector, has also become more prominent (Andruccioli et al., 2026). Luo et al. (2019) introduced an IoT-powered public transport framework that covers buses, subways, and ridesharing. Recently, Hosseini et al. (2025) proposed a bus-specific digital twin architecture centred on lifecycle cost analysis, predictive maintenance, and fleet renewal planning across diesel, CNG, and electric buses. Yang et al. (2021) developed a software-defined IoT system using a modified PPO (Proximal Policy Optimisation) algorithm within a multi-agent reinforcement learning setup. In a more recent study, Vanitha et al. (2023) developed an IoT-based real-time traffic monitoring system that uses image processing to regulate traffic signals based on vehicle count dynamically.

IoT technologies have also been extensively investigated in the contexts of EV charging and energy integration. Existing studies cover residential EV charging, blockchain-enabled EV energy systems, EV-to-station communication, solar-powered charging, and cloud-based charging-station management (Bhaskar et al., 2022; Debadarshini and Saha, 2022; Divyapriya et al., 2018). These studies show that IoT provides a strong basis for real-time energy monitoring and charging coordination, but they remain largely focused on specific charging scenarios rather than integrated transport-energy DT architectures. In more recent studies, Chitra et al. (2024) developed an IoT-enabled, solar-powered EV charging station that incorporates a DC-to-DC boost converter and maximum power point tracking to efficiently use solar energy. Similarly, Aldeen et al. (2024) proposed an IoT- and cloud-computing-based architecture for managing EV charging stations to support green transportation. Focusing on smart city development, Jabbar et al. (2020) highlighted the importance of formal testing by validating IoT-blockchain vehicular communications using model-based simulations. Their work presented the groundwork for secure transport data exchange. Yue et al. (2021) proposed a vision-based IoT system for obstacle avoidance in intelligent vehicles. Xia et al. (2022) showed that GIS-BIM integration, and more broadly, city information modelling, provides an important basis for city-scale DT by enabling the fusion of spatial, infrastructure, and lifecycle information across urban systems. Cui and Lei (2023) designed a highway Intelligent Transportation System (ITS) using IoT and AI. Their proposed ITS is structured into perceptual, transport, and application layers. Adil Khan et al. (2023) presented an IoT-enabled, non-intrusive driver drowsiness detection system using edge-computing cameras and facial behaviour analysis. In more recent studies, Hassain et al. (2024) designed an IoT-based road monitoring system using embedded sensors and the ESP-NOW communication protocol. Moreover, Saini et al. (2024) introduced an IoT-Fog-based framework to detect and prevent vehicle accidents caused by self-visual driver distractions. IoT frameworks have also been applied in both marine and maritime transportation systems. Sahay et al. (2019) proposed CyberShip-IoT, which is an SDN-based framework using a high-level policy language that automates the enforcement of security rules, reducing reliance on error-prone, low-level configurations. Tiwari et al. (2021) focused on the growing cybersecurity threats in marine environments and proposed an IoT-based intrusion detection system. Han et al. (2024) proposed Turbo-DSA as a transformer-based deep semantic autoencoder with integrated turbo coding for end-to-end semantic communication in marine IoT. Their approach enables joint source-channel coding, adapting to channel conditions through iterative training. Overall, IoT provides the dominant observability layer for transport DTs, enabling sensing, monitoring, and data acquisition across vehicles, infrastructure, users, and environments. However, most IoT-based studies remain constrained by weak semantic integration, fragmented data governance, and insufficient alignment with system-level control or decarbonisation objectives.

### 3.3. Digital twins (DTs)

Over the past decade, researchers have extensively explored the role of DTs in transportation systems, with scholarly interest rising significantly since 2024. Back in 2014, Johnson et al. (2014) developed a

physical DT for roadway safety by automating highway illumination validation using embedded systems on moving vehicles. Later, Nasr et al. (2016) implemented a lightweight DT for vehicle accident reporting that incorporated shock sensors, BLE, GPS, and HTTP interfaces. DTs are increasingly integrated into smart cities and multi-modal transport contexts, emphasising urban-scale decision support and policy implications. Belfadel et al. (2021) proposed a DT for adaptive last-mile logistics to support urban policy design and planning. Xiong et al. (2022) developed a DT-assisted simulation for autonomous navigation, fusing IoT sensor data to achieve dynamic adaptability under variable traffic conditions. Zhang et al. (2023) created a collaborative DT for ITS that integrates heterogeneous urban data sources to enhance real-time multimodal mobility decision-making, laying the foundation for cross-platform DT fusion in smart cities.

Exploring the use of DT at the ecosystem level, Chowdhury et al. (2018) simulated a vehicle-to-vehicle (V2V) communication system using LabVIEW and SQL integration. Liao et al. (2022) presented practical DT solutions in cooperative ramp merging, powered by vehicle-to-cloud (V2C) communication. Shin et al. (2023) took this further by introducing a spatiotemporal prediction model for network traffic in DT networks. Moreover, Tan et al. (2023) presented a cloud-based DT system for vehicular data sharing, empowered by federated learning and game-theory-based incentives. Recently, Zhao et al. (2025) employed deep reinforcement learning (DRL) within the energy-transport nexus to enable real-time decision-making. Their proposed DT framework integrates cyber-physical feedback loops with electro-thermal modelling to enable adaptive, safe energy balancing.

Several research studies focus on simulation-based DTs that link virtual and physical transport systems to evaluate system performance under realistic conditions. Wang et al. (2023) developed a co-simulation DT which includes CARLA-SUMO traffic simulation with CAVE-Virtual Reality (VR) (Cave Automatic Virtual Environment) to evaluate vehicle-to-pedestrian (V2P) interactions, improving occlusion warning effectiveness. Samak et al. (2024b) and Shahriar et al. (2024) introduced the AutoDRIVE system, an open-source DT platform that enables mixed-reality and sim2real validation for autonomous vehicles (AVs). It supports human-in-the-loop experiments and cross-scale vehicle testing, bridging the gap between simulation and real-world deployment.

Recent studies increasingly leverage machine learning (ML) and deep learning (DL) techniques to enhance DT capabilities. Ali et al. (2023) developed a DT-based security framework for vehicle-to-grid (V2G) systems that integrates LSTM-based state estimation with DRL. This combination enables real-time detection and mitigation of coordinated cyberattacks, positioning the DT as a cyber-physical guardian. Roopini et al. (2024) introduced a cloud-integrated DT using CNN (Convolutional Neural Networks)-LSTM models for real-time vehicle monitoring and accident detection. Kamal et al. (2024) implemented a multi-agent DRL within a DT of an urban traffic network to optimise traffic signal timing, significantly reducing $CO_2$ emissions and fuel consumption. Similarly, Baluprithviraj et al. (2023) integrated NodeMCU-based emission sensing into a DT for urban pollution forecasting and mitigation, contributing to decarbonisation strategies. In more recent studies, Cheng et al. (2024) combined Vision Large Language Models with DTs to perform urban safety assessments from street-view imagery, validated with crowdsourced data. Barroso et al. (2024) employed particle filters within a DT integrating CARLA simulation and the CORTEX cognitive architecture to predict pedestrian collisions in AV contexts.

Several studies emphasise modularity, semantic modelling, and architectural layering to ensure interoperability and scalability in DTs for transport and logistics. Marinkovic et al. (2023) proposed a layered modular DT architecture for internal factory logistics, categorising functionalities for smart transport and real-time adaptability. Bertolini et al. (2024) developed a semantic DT for pavement distress management using 2D grids and 3D voxel representations, enabling predictive maintenance and improved decision-making. Heise et al. (2024) extended this approach with a comprehensive DT architecture for road infrastructure, explicitly linking physical assets, environmental conditions, and user behaviours to DT data and application layers. Recently, Xie et al. (2026) proposed a digital twin-based EV routing and charging framework (DT-EVRC) for dynamic urban traffic environments, integrating real-time traffic data, charging-station status, predictive analytics, and adaptive optimisation. Campolo et al. (2024) introduced an edge-computing DT framework for connected and autonomous vehicles (CAVs). This low-overhead semantic framework enables efficient data collection, sharing, and real-time multi-stakeholder decision-making. In a recent study, Xu et al. (2025) implemented a multi-agent DT framework to enhance collaborative logistics, enabling loosely coupled system integration and information sharing across carriers.

Since 2020, DT technologies have been applied across various areas within marine and maritime transportation systems. Yang et al. (2020) promoted a parallel network model for maritime IoT, describing the DT as an autonomous, learning-enabled proxy of physical marine systems. Cheng et al. (2020) extended DT applications to shipyard manufacturing by proposing a DT-driven approach for real-time quality control of marine diesel engine components. Similarly, Pang et al. (2021) proposed a DT-thread architecture with the capacity of continuity of data and behaviour streaming from design to operation, optimising lifecycle workflows in the production systems. Giering and Dyck (2021) proposed the Maritime Digital Twin Architecture (MDTA) as a holistic design spanning the full lifecycle of shipbuilding and shipping. Their proposed MDTA aligned closely with global regulatory and decarbonisation pressures, positioning DTs as operational engines in sustainable shipping. Several studies on DT have investigated the development of innovative and intelligent support systems. Wang and Lin (2022) presented a DT-enabled smart ocean networking architecture. This study demonstrated how DT in B5G/6G oceanic environments can lead to intelligent network slicing and maritime mobility adaptation. Kinaci (2023) introduced a ship DT architecture designed to optimise autonomous sailing by monitoring real-time ship responses to dynamic environmental conditions. Wang, Peng, et al. (2024) focused on deterministic scheduling and a double deep Q-network routing system, making maritime traffic routing both intelligent and reliable under harsh oceanic conditions. Considering interoperability in the DT architecture, Fonseca et al. (2023) proposed an open, web-driven framework for ship DTs that enables standardised handling of ships, sensors, and operational data. In addition, several studies explored the application of DT frameworks in marine engine health assessment (Tsitsilonis et al., 2023), expressway traffic crash detection (Qu et al., 2024), and a DT-driven safety management and decision support system for port operations (Wang, Xu, et al., 2024). Yang, Liu, et al. (2024) proposed a DT architecture for simulating ship manoeuvrability using the Functional Mock-up Interface standard.

In the rail transport system, Kampczyk and Dybeł (2021) proposed a DT framework for monitoring railway turnouts using environmental sensors. Zhou et al. (2022) developed an R4F DT Platform that consolidates data from disparate subsystems, such as bridges, tunnels, and turnouts, into a layered architecture aligned with RAMI 4.0 for railway infrastructure monitoring. Ferdousi et al. (2022) introduced RailTwin, a conceptual DT framework for intelligent railway management. Their model combines current insights, predicted future states, and decision-making capabilities using advanced AI techniques. Sanjana et al. (2024) designed a DT framework that combines edge analytics and sensor-actuator interactions for railway loop detection and obstacle avoidance. Tang et al. (2024) proposed a cloud-based DT framework to simulate railway vehicle dynamics in real time. Salierno et al. (2024) proposed a big data architecture for railway signals that integrates synthetic and real data to simulate switch-point performance. Recently, Aburasain (2025) proposed a digital DT-DRL framework for railway operation and maintenance, with emphasis on deterministic scheduling of mixed traffic flows across communication domains. In the air transport system, Kosova and Unver (2023) presented a DT-based framework

for early-stage failure detection in aircraft hydraulic systems using ML techniques. Zhang et al. (2024) developed FlightTwin, a DT framework for fixed-wing aircraft accompanying flight, integrating physical, virtual, data, and service layers. Overall, DT research has moved from asset-level monitoring toward simulation, predictive analytics, and decision support. However, most transport DTs remain mode-specific and are rarely aligned with a standardised reference architecture.

### 3.4. Hybrid systems

Several studies focus on CPS integration and IoT-enabled architectures to establish real-time connectivity between the physical and digital layers in transport systems. Back in 2005, Hsu and Chen (2005) presented practical embedded DT architecture for in-vehicle telematics and infotainment, integrating GPS, wireless, and emergency interfaces. Feng et al. (2018) extended DTs to CAVs using a distributed CPS for fleet formation control. By leveraging graph topology and edge computation, they achieved decentralised, synchronised coordination of movement across multiple vehicles. Lee et al. (2018) created an IoT-enhanced warehouse management system serving as a precursor to logistics DTs, employing RFID and barcode networks for real-time location tracking. Ahmed and Rani (2018) introduced a hybrid IoT-based DT for urban routing, incorporating AODV-SPEED protocols to virtualise street infrastructure and simulate urban mobility dynamics. In more recent studies, Mejjaouli and Alnourani (2024) developed a hybrid IoT-integrated DT system for dynamic EV charging scheduling. Moreover, Yu et al. (2024) presented an agent-based DT framework tailored for EV grid integration with the focus on demand response programs and incentive mechanisms. Tasgaonkar et al. (2024) implemented a lightweight IoT-cloud DT for urban accident detection, integrating GPS and ultrasonic sensors for low-latency safety alerts.

Several DT studies combine simulation platforms, GIS, and MCDM (multi-criteria decision-making) methods for urban mobility and infrastructure planning. Sun, Chen, et al. (2022) applied DTs for energy-efficient lighting control, using NB-IoT-WEBGIS in urban settings and DL in rural contexts, achieving context-aware illumination and load optimisation. Al-Turjman (2018) explored an information-centric IoT-DT leveraging Content Demand Ellipses to optimise content flows in dense urban networks, reducing infrastructure congestion and energy usage. Jiang et al. (2024) introduced a DT-MCDM-GIS framework for sustainable road planning, integrating spatial analytics and decision models to optimise road plans in a London case study.

In more recent studies, DTs leverage AI, ML, and DL to provide predictive analytics, optimisation, and decision-making in transport-energy systems. Ramal and Anbalagan (2024) introduced a Cyber-Physical DT for smart city traffic management, combining IoT data, AI-based prediction, and optimisation algorithms. Puri et al. (2024) employed a hybrid ML-DT ensemble to optimise urban traffic, enhancing route prediction and congestion management. Aloupogianni et al. (2024) developed an AI-driven DT that fuses sensor, weather, and image data for adaptive and predictive traffic flow control in data-dense urban environments. Bezrodniy et al. (2024) proposed a causal cyber-physical DT framework to coordinate energy and transport flows at the national infrastructure scale, employing cause-effect modelling and integrated control functions to support sustainable resource management. In Karnehm et al. (2024), a five-layer IoT-fog-cloud DT architecture is designed for lithium-ion battery management in e-transport, enabling bidirectional communication, low latency, and high fault tolerance in hybrid cloud-fog settings.

Recently, DT studies have focused on logistics optimisation and last-mile delivery using IoT, simulation, AI integration, and a federated DT platform (Estil-Les et al., 2026; Liu et al., 2025). Fatorachian et al. (2025) designed a cybernetic IoT-AI DT for last-mile logistics to improve real-time demand forecasting and adaptive routing to accelerate emission reduction. GhanavatiNejad et al. (2025) implemented a smart logistics DT for fast-moving consumer goods using IoT and RFID technologies to enhance delivery accuracy and customer satisfaction in time-sensitive supply chains. Since DT systems have become increasingly data-intensive, privacy and security have become critical. Salin (2025) introduced a privacy-enhanced DT architecture for cooperative ITS, using cryptographic accumulators and anonymous credentials to secure real-time V2X (Vehicle-to-Everything) interactions. Yigit et al. (2024) developed a 6G IoV (Internet of Vehicles) cyber-resilient DT framework using feature-optimised distributed twins to enhance attack detection and resource efficiency for AVs and V2X infrastructures.

IoT-driven DTs increasingly support environmental sustainability in maritime transport for real-time sensing and predictive analytics. Aguiar et al. (2022) present an operational DT-enabled eco-routing framework that integrates IoT data, microservice interoperability, simulation, and visual analytics to support traffic and emissions-aware routing decisions. By contrast, Jiang et al. (2022) situate the DT more explicitly within the planning domain by integrating DT, MCDM, and GIS to support sustainable urban road-planning decisions, such as route alignment and road widening. Huang (2023) developed a broadband IoT-based DT for marine pollution detection that captures pH, salinity, and dissolved oxygen measurements. In their design, data are fed through a ZigBee-enabled feedback loop to a real-time cluster analysis engine, enabling predictive alerting for marine conservation and decarbonisation efforts. Nguyen et al. (2025) designed an integrated IoT-DT to collect real-time ship telemetry (engine torque, shaft power) and applied explainable machine learning (XAI) using XGBoost with SHAP values to optimise fuel consumption. This approach provides interpretable insights to help operators reduce emissions and operational costs.

Cybersecurity and trustworthy data exchange are emerging as critical for maritime digitalisation. Kumar and Ali (2024) introduced the blockchain authentication framework for maritime, integrating 6G-IoT networks with decentralised validation mechanisms. ML and computer vision are increasingly embedded into maritime DTs for vessel detection, tracking, and predictive operations. Gupta and Rahmani (2024) introduced an IoT-based, multi-scale ship identification DT, integrating a CNN-Kalman filter hybrid with YOLOv3 detection for high-accuracy small-vessel tracking. Vasilikis et al. (2023) created a hybrid DT for naval carbon modelling, combining first-principles physical modelling with ML to account for operational and environmental uncertainties.

IoT-driven DTs are widely used in railway systems to monitor physical components and enable real-time safety loops. Errandonea et al. (2021) developed an IoT-enabled DT framework, integrating real-time sensor data from pantographs and catenaries into digital models. Naik et al. (2024) implemented an IoT-based automated railway gate system using ESP32 boards and IR sensors. The system creates a cyber-physical DT loop for real-time gate control and SMS alerts, minimising human error and enhancing operational safety. De Donato et al. (2023) introduced an AI-integrated DT reference architecture for railway asset monitoring. Chartrain et al. (2024) proposed a model-driven engineering DT framework supported by semantic ontologies for railway infrastructure. Their system design enables reasoning, validation, and traceability at a system-of-systems level to ensure interoperability and alignment with national railway innovation agendas. Overall, hybrid systems represent the most mature direction for transport DT development because they combine sensing, control, simulation, AI, and data architectures. Nevertheless, they often remain application-specific and do not yet provide a unified cross-modal architecture for decarbonisation. Road transport dominates the reviewed literature, accounting for ~59%, followed by maritime/marine transport with 17.0%, rail, smart city/urban transport accounts for approximately 11% and 9% respectively, while air and warehouse/internal logistics together account for 4%, as illustrated in Fig. 2(a). Moreover, the publication trend between 2005 and 2026 shows that there was limited publication activity before 2018, followed by a clear increase from 2021, reaching a peak in 2024. Road transport remains the dominant mode across most years, while maritime, rail, and urban/smart city transport become more visible after 2021, indicating a growing diversification of research focus,

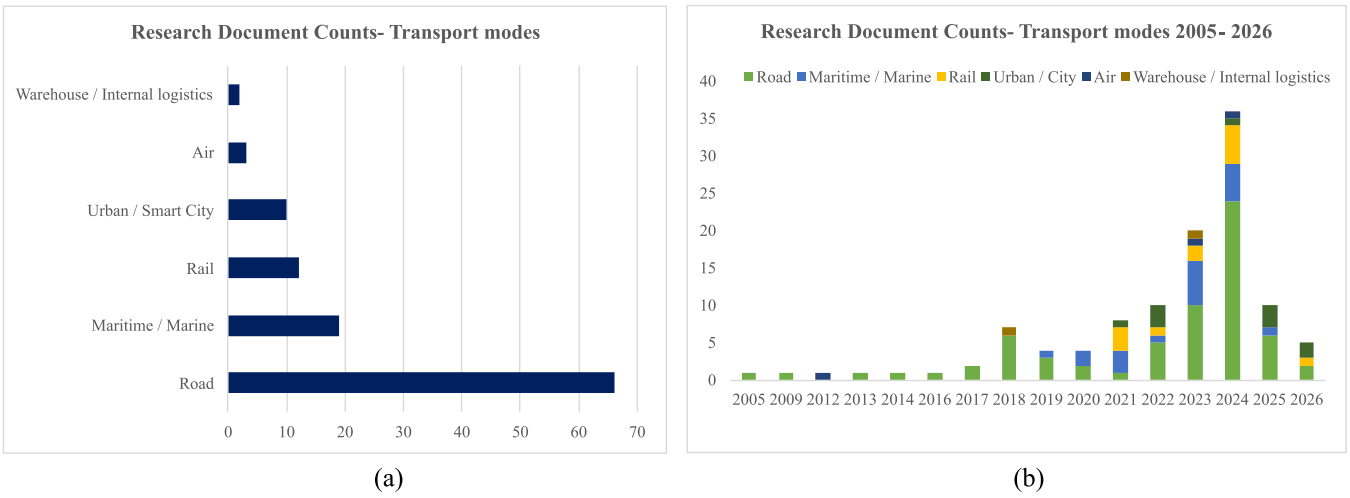



**Fig. 2.** Research documents count from SLR for (a) transport modes and (b) transport mode research trend between 2005 and 2026.

as presented in Fig. 2(b).

The reviewed studies reveal several recurring architectural trends and limitations. Most transport DTs remain mode-specific or asset-specific, focusing on applications such as EV charging, traffic control, rail infrastructure monitoring, maritime routing, aviation maintenance, or urban logistics, with limited cross-modal integration across road, rail, maritime, and air systems. IoT-enabled observability is the dominant capability in literature, supporting GPS tracking, emissions sensing, vehicle telemetry, smart lighting, and infrastructure monitoring (Giering and Dyck, 2021; Kosova and Unver, 2023; Zhang et al., 2024; Zhou et al., 2022). However, these implementations often prioritise data collection over system-level integration (Baluprithviraj et al., 2023; Jan et al., 2019; Luo et al., 2019; Sun, Guo, et al., 2022). CPS and adaptive control functions appear in selected applications, including EV-grid scheduling, connected vehicle coordination, and traffic signal optimisation, but these capabilities are typically isolated and not standardised across DT architectures (Feng et al., 2018; Jin et al., 2013; Kamal et al., 2024; Zhao et al., 2025). Cloud, edge, semantic, and federated data architectures are emerging, particularly in CAVs, logistics, railway infrastructure, and ship DTs (Campolo et al., 2024; Chartrain et al., 2024; Fonseca et al., 2023; Liu et al., 2025). Nonetheless, semantic interoperability, plug-and-play integration, and cross-system governance remain underdeveloped. Although several studies address emissions reduction, energy optimisation, eco-routing, carbon-aware logistics, or maritime fuel efficiency, decarbonisation is generally treated as an application outcome rather than as a structural design requirement (Aguiar et al., 2022; Kamal et al., 2024; Liu et al., 2026; Nguyen et al., 2025). Finally, while recent research increasingly recognises cybersecurity, data assurance, access control, dashboards, HMI, AR/VR, and user-facing simulation tools (Liao et al., 2022; Salin, 2025; Samak et al., 2024b; Yigit et al., 2024), these elements are rarely integrated into a unified reference architecture. These limitations justify the need for an ISO-23247-aligned transport DT framework that embeds observable, device communication, core, user, and cross-system entities within a standardised architecture for interoperable and climate-aligned transport decarbonisation.

## 4. Digital twin design framework

### 4.1. Methodological mapping (RO1)

This study systematically reviewed relevant documents to identify and map existing digital methodologies for developing DTs in transport systems, including IoT, CPS, embedded systems, hybrid systems, and data architectures. Each document and academic paper was qualitatively categorised based on its primary digital methodology. The categories and their descriptions are summarised in Table 2.

The number of identified documents for each digital methodology category is illustrated in Fig. 3(a). The evolution of DT methodologies in transport systems mirrors the broader technological shifts in intelligent systems, as shown in Fig. 3(b). The dataset spans from 2005 to 2026, illustrating the temporal evolution of research interest. The results show that IoT is the most widely used primary method family, followed by digital twins; both are especially concentrated in road transport, indicating that road-based studies dominate technological applications. Other approaches, such as CPS, hybrid systems, data architecture, and embedded systems, are less frequent in comparison but show broader use across rail, maritime, and urban/smart city contexts, while air and warehouse/internal logistics remain minimally represented.

In road transport systems, IoT technologies have been rapidly adopted since 2016, mainly due to advancements in wireless communication protocols, the spread of low-cost sensors, and the growth of edge computing capabilities. The IoT-focused studies between 2016 and 2020 highlight the importance of such technological readiness and growing institutional and governmental interest in smart city infrastructure and ITS. On the other hand, CPS has maintained a moderate but consistent presence in research over the past two decades. Overall, CPS adoption is less frequent than IoT adoption. Nevertheless, CPS appears as a complementary framework within hybrid solutions. This observation suggests that CPS is often applied to bridge the gap between digital decision-making applications and physical actuation, such as in AV coordination, energy-efficient routing, or adaptive traffic signal control. In terms of the sector's specific applications, the development of DT systems in aviation has progressed relatively more slowly compared to other transport sectors. However, the research trajectory shows a clear shift from early CPS architectures toward real-time, predictive, and AI-enhanced DT implementations. The marine sector has experienced

**Table 2**
Digital methodology categories used for classifying transport DT studies.

| Methodology | Description |
|---|---|
| IoT | IoT, including wireless sensor networks, vehicle connectivity, and real-time monitoring |
| CPS | CPS with the integration of computational and physical processes |
| Embedded Systems | Hardware-level control and sensing mechanisms form the basis for DTs |
| Hybrid Systems | Combinations of IoT, CPS, and embedded systems in DT frameworks |
| Data Architectures | Cloud computing, edge computing, and data frameworks that enable system-level intelligence |

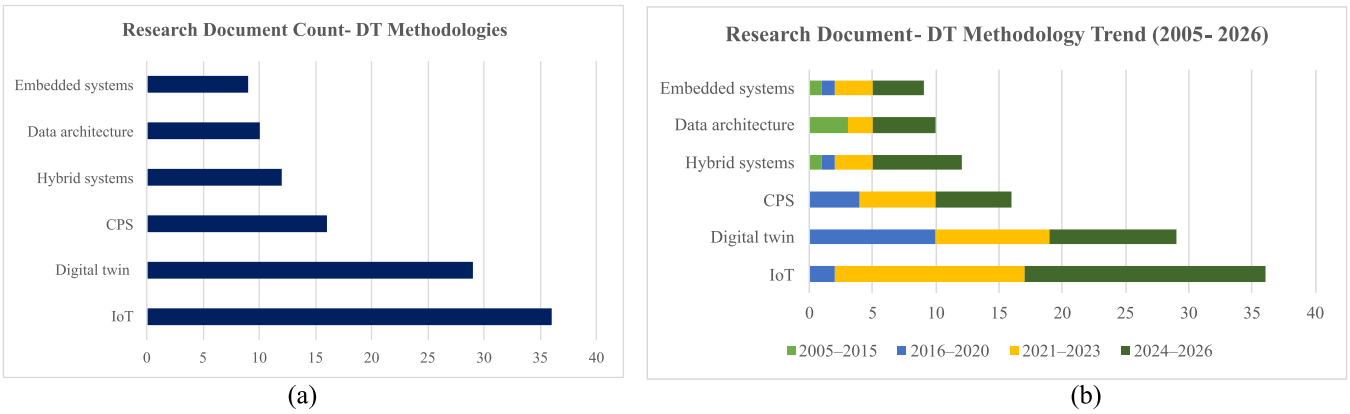



**Fig. 3.** Article count and trend over time for different DT methodologies.

rapid DT adoption since 2019, with publication peaks in 2023 and then again in 2024. This growth could be due to the emerging advances in maritime logistics, port automation, and environmental compliance. Applications span ship-level monitoring, predictive maintenance, port optimisation, and carbon footprint modelling. This shows that the sector is broadening its digital ecosystem. The core methodologies are often supported by edge (or fog) computing, AI (or ML), and data architecture platforms. In rail systems, DT deployment has accelerated since 2021 with a peak in 2024. The literature reveals an evolution from sensor-driven monitoring to cloud-based, simulation-integrated DTs.

### 4.2. Digital twin functional elements (RO2)

This Section presents the relevant DT Functional Element (FE) essential in the design of a DT framework for transport decarbonisation, grounded in ISO-23247, as illustrated in Fig. 4. In this study, the ISO-23247 structure is tailored to transport systems following a comprehensive literature review and Delphi workshops with practitioners across the logistics, automotive, maritime, rail, and aviation sectors. The goal was to extend the applicability of ISO FE categories, given the emerging transport ecosystem. Building on the structured classification of framework FEs identified from the literature, the expert workshop introduced notable expansions. These insights demonstrate that effective DT implementations in transport require not only technical observability but also an understanding of operational and sustainability-related elements.

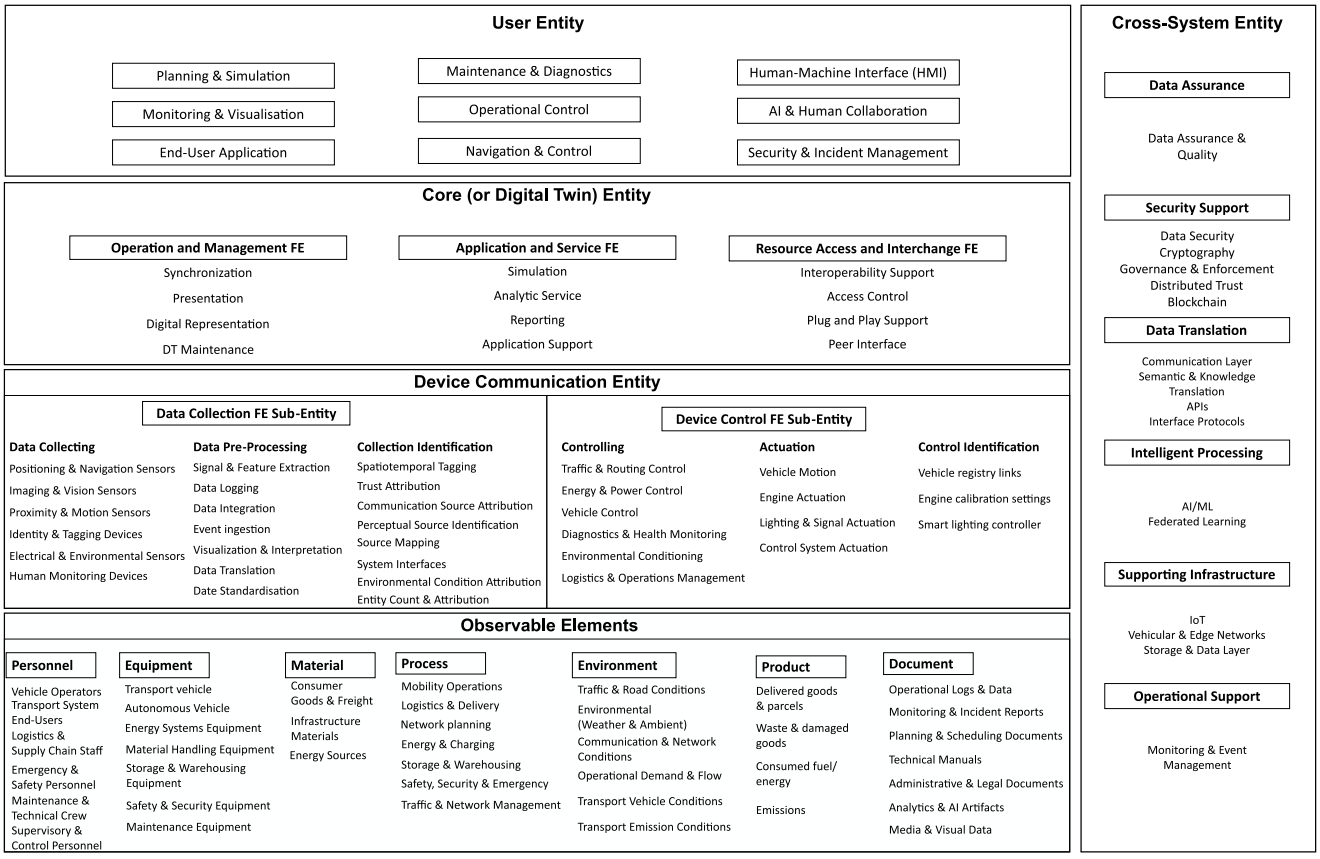



**Fig. 4.** Proposed ISO-23247-aligned Digital Twin framework for transport decarbonisation, presented as a reference architecture showing the main functional elements and their interaction structure.

#### 4.2.1. Observable elements

From ISO/IEC 23247, observable elements are defined as entities with identifiable characteristics, measurable states, and detectable behaviours that participate in physical or logical processes. These include personnel, equipment, material, process, facility, environment, product and document categories. In transport systems, observable elements provide dynamic visibility into operations, enabling real-time monitoring, decision-making, and system-wide optimisation. Adapting the ISO/IEC 23247 category definitions to transport systems, in this study, 'personnel' refers to people who are involved and interacting with the transport system, 'equipment' are tangible assets carried out transport system processes across the value chain, 'material' represents physical entities that move or are consumed within transport processes, 'process' describes a sequence of events or activities occurring within the transport system, 'facility' refers to the transport infrastructure across the value chain, 'environment' denotes the operational conditions under which transport system elements function, 'product' in an output generated by transport system processes, and 'document' refers to analog and digital records used or generated within the transport system. A summary of the identified observable elements is provided in Table 3.

The literature primarily emphasised equipment, infrastructure, and environmental elements, while expert input provided greater specificity to personnel, processes, and document categories. The outcomes expand the 'material' category to include fuel and sustainable fuels e.g., hydrogen, SAF and biofuels, to align DTs with decarbonisation purposes. The workshop also identified additional 'facility' elements such as 'green energy infrastructure', battery swapping stations', and 'SAF blending facilities', highlighting the growing importance of energy system observability. For the 'process' category, experts identified additional logistical operations such as 'order routing', 'fuel refilling (or charging)', and 'intermodal transitions', illustrating the need to model transport system flows in greater operational detail. Similarly, 'product' (e.g., specialised cargo, palletised freight) and 'document' categories (e.g., shipment passports, commercial invoices, export lists) were expanded to ensure both transport and decarbonisation-related elements.

**Table 3**
Observable elements entity categorisation with examples.

| Main Category | Short Description | Key Examples |
|---|---|---|
| Personnel | People involved in operations | drivers, pilots, logistics coordinators, maintenance technicians, warehouse staff, traffic controllers, all contributing to vehicle operation, monitoring, dispatch, and emergency handling. |
| Equipment | Tangible assets used in transport | vehicles (e.g. cars, vans, trucks, ships, trains, etc.), autonomous vehicles, onboard units, UAVs, forklifts, EV chargers. |
| Material | Transported or used goods | parcels, fuel (e.g., electricity, hydrogen, SAF), palletised freight, hazardous goods, and consumer products used or moved in transport operations. |
| Process | Flow of operations | network planning, vehicle-to-grid scheduling, order dispatch, charging coordination, emergency response, map-based navigation, maintenance planning and interventions. |
| Facility | Physical infrastructure | road segments, intersections, depots, EV charging stations, shipyards, urban logistics centres, airports. |
| Environment | Operating and ambient conditions | sea conditions, weather, $CO_2$ levels, road surface state, dynamic inter-vehicle spacing, sunlight intensity, and energy grid load fluctuations. |
| Product | Outputs of processes | delivered goods & parcels, waste, damaged goods, consumed fuel/energy, emissions |
| Document | Data and records generated | accident reports, charging schedules, routing manifests, maintenance records, environmental monitoring data (e.g., GIS logs or emission reports). |
| Key References | (Saini et al., 2024), (Wang et al., 2023), (Adil Khan et al., 2023), (Hsu and Chen, 2005), (Kosova and Unver, 2023), (Zhang et al., 2024), (Salin, 2025), (Xiong et al., 2022), (Divyapriya et al., 2018), (Karnehm et al., 2024), (Han et al., 2024), (Sun, Chen, et al., 2022), (Zhao et al., 2025), (Yu et al., 2024), (Belfadel et al., 2021), (Nguyen et al., 2025), (GhanavatiNejad et al., 2025), (Huang, 2023), (Shariatpour et al., 2025) | |

#### 4.2.2. Device communication – data collection & device control entity

In ISO-23247, the Device Communication Entity (DCE) serves as the interface between observable physical elements and their DT representations. It is divided into 'Data Collection Sub-Entities' and 'Device Control Sub-Entities', which are further categorised into 'Data Collecting', Data Pre-processing', 'Collection Identification', 'Controlling', 'Actuation', and 'Control Identification' FEs. These sub-entities support right-time data exchange to enable DT to sense, interpret, and respond to changes in the physical transport environment. The outcomes reveal that the 'Data Collecting' function is by far the most frequent, with widespread use of IoT sensors, vehicle telemetry, environmental monitors, and user tracking systems. The 'Controlling' function is the next most common sub-entity, e.g., embedded controllers, microprocessors, and network elements, to emerge structured commands to observable elements such as vehicles, lights, or chargers. The 'Data Pre-processing' entities are typically implemented through local microcontrollers or edge entities. Several use cases are defined by experts, including context-aware actuation (e.g., switching hybrid energy sources based on right-time load and emissions) and sensor-driven comfort control (e.g., minimising vehicle idling or adjusting cargo temperature). These functions indicate a deeper evolution of DCE toward predictive, distributed, and sustainability-focused architectures. The results are summarised in Table 4.

#### 4.2.3. Core (or Digital twin) entity

In the ISO-23247 architecture, the Core Entity refers to the Digital Twin Entity, which is the vital component of the DT framework,

**Table 4**
Device communication entity categorisation with examples.

| Main Category | Sub-Category | Key Examples |
|---|---|---|
| Data Collection Sub-Entity | *Data Collecting* | Radar sensors, IoT devices, environmental monitors, GPS receivers, cameras, RFID tags, sensors (LiDAR, IMU, $CO_2$, etc.), CAN bus loggers, Raspberry Pi units, smart meters, IoT nodes, and edge gateways are collecting vehicle or infrastructure data. |
| | *Data Pre-Processing* | Edge-based CNN processors to analyse camera input, Raspberry Pi units, signal smoothing on GPS feeds, and aggregators to filter vehicle telemetry streams. |
| | *Collection Identification* | Systems to detect and select required sensor feeds, route planners to identify traffic data needs, and modules to determine emission sources to monitor. |
| Device Control Sub-Entity | *Controlling* | IoT controllers adjusting traffic lights, embedded systems sending routing updates to vehicles, and smart grid agents modulating energy dispatch. |
| | *Actuation* | Embedded systems trigger lighting adjustments, braking mechanisms, or engine mode changes based on real-time input. |
| | *Control Identification* | Asset registries map control commands to specific vehicles, and interfaces uniquely address actuators in smart infrastructure networks. |
| Key References | (Nasr et al., 2016), (Chowdhury et al., 2018), (Hwang and Joe, 2023), (Naik et al., 2024), (Yigit et al., 2024), (Al-Turjman, 2018), (Gupta and Rahmani, 2024), (Ahmed and Rani, 2018), (Aguiar et al., 2022) | |

responsible for hosting the virtual representation of observable physical elements. It provides a structural and functional basis for modelling, simulating, analysing, and interacting with physical systems in a synchronised and interoperable manner. The Core Entity is logically divided into three key sub-entities: (i) 'Operation and Management', which maintains up-to-date digital models and synchronises state with observable elements, (ii) 'Application and Service', which delivers value-added functionalities such as simulation, analytics, and decision support, and (iii) 'Resource Access and Interchange', which facilitates controlled interaction between the DT and external users platforms through standardised interfaces. The outcome shows a strong emphasis on the 'Application and Service sub-entity', reflecting transport systems' increasing reliance on simulation, data analytics, and real-time decision-making. Furthermore, the role of the 'Resource Access and Interchange sub-entity' has become increasingly prominent, especially through technologies such as microservices, semantic APIs, and data streaming platforms that support modularity and interoperability. Together, these developments illustrate how DTs in transport are evolving from isolated monitoring tools into integrated and intelligent platforms which can support complex cyber-physical operations across scales and domains. The results are summarised in Table 5.

#### 4.2.4. User entity

In ISO-23247, the 'User Entity' is key to ensuring accessibility, usability, and operational relevance of DT in transport systems. It defines how the end users, such as operators, technicians, planners, passengers, and regulators, interact with DT through user interfaces, applications, and services. This entity can include visual dashboards, HMIs, AR/VR tools, mobile devices, and APIs that provide both right-time visibility and control. It is important that DT architecture reflects a human-centred design orientation to promote intuitive, responsive, and role-based tools. In transport safety, timely interactions are critical; thus, such interfaces provide essential system intelligence directly to field or control rooms. Importantly, the User Entity serves as an intermediary between DT and broader enterprise ecosystems via ERP systems, logistics platforms, or data service APIs. This ensures that transport DTs are not siloed applications but interoperable components of complex operational workflows. Nonetheless, as the analysis and expert workshop reveal, the User Entity should evolve further, moving from static visualisation toward adaptive, task-specific, and ethically governed interfaces that support distributed intelligence and human-AI collaboration. As a result, a series of User Entity types are identified and summarised in Table 6.

#### 4.2.5. Cross-system entity

In the ISO-23247 architecture, the Cross-System Entity (CSE) plays a foundational role in providing secure, reliable, and interoperable DT ecosystems, especially in complex, multi-modal transport systems. The CSE is responsible for three core capabilities: data translation, data assurance, and security support. These are critical not only for connecting disparate systems and communication protocols, but also for safeguarding the integrity and trustworthiness of data that drives DT analytics and control actions. Cross-modal interoperability within the proposed framework is enabled through the combined action of semantic translation, API and protocol mediation, data assurance, and secure peer interfaces. This allows heterogeneous transport systems to exchange and interpret relevant DT information while preserving mode-specific operational detail at the source-system level. This entity becomes particularly important when DTs are federated across domains,

**Table 5**
Core (or Digital Twin) entity categorisation with examples.

| Main Category | Sub-Category | Examples |
|---|---|---|
| Operation and Management | *Synchronisation* | Unity3D-based DT engines synchronise AV states in real time, ensuring consistent mirroring of the physical and virtual systems. |
| | *Presentation* | Cloud dashboards visualise real-time emissions and traffic metrics for planners and vehicle operators. |
| | *Digital Representation* | DTs model vehicle dynamics and road networks using simulation tools and CAD integration. |
| | *DT Maintenance* | Monitoring engines to track anomalies, issue alerts, and support predictive maintenance |
| Application and Service | *Simulation* | RL engines for simulating traffic flow and system behaviours to optimise signal timing. |
| | *Analytic Service* | AI engines to analyse accident data, sensor streams and to predict events and inform control decisions. |
| | *Reporting* | Generate reports on energy consumption, mobility behaviour, and maintenance outcomes. |
| | *Application Support* | Support smart contracts and predictive logistics in EV coordination platforms. |
| Resource Access and Interchange | *Interoperability Support* | Neo4j-backed DTs and ERP-integrated engines enable system-wide data exchange and model alignment. |
| | *Access Control* | Blockchain-enabled access control ensures secure interaction between users and system components. |
| | *Plug and Play Support* | Modular DT platforms enable real-to-sim and sim-to-real connections, allowing for dynamic OME linkages. |
| | *Peer Interface* | APIs to run simulation with synchronisation capabilities to coordinate with other DTs. |
| Key References | (Zhang et al., 2023), (Chitra et al., 2024), (Tsitsilonis et al., 2023), (Errandonea et al., 2021), (Tiwari et al., 2021), (Sampigethaya and Poovendran, 2012), (Tang et al., 2024), (Feng et al., 2018), (Campolo et al., 2024), (Samak et al., 2024b), (Kamal et al., 2024), (Roopini et al., 2024), (Barroso et al., 2024), (Lopez-Martin et al., 2019), (Jan et al., 2019), (Xiong et al., 2024), (Bhaskar et al., 2022), (Ali et al., 2023), (Hosseini et al., 2025), | |

**Table 6**
User entity categorisation with examples.

| Category | Examples |
|---|---|
| *Monitoring & Visualisation* | Fleet dashboards, emissions dashboards, monitoring traffic flow, KPIs, and system health. |
| *Operational Control* | book charging slots and assign routes, warehouse staff track inventory and tasks via dashboards, and city operators manage lighting and road repairs through web-based control panels. |
| *Human-Machine Interface (HMI)* | In-cab displays with alerts, vehicle touchscreens for adjusting energy recovery settings, AR headsets guiding repair processes, and cockpit controls for aircraft or simulation environments. |
| *End-User Application* | EV charging schedules, driver alerts or navigation assistance, and citizen reporting of issues or viewing solar station availability. |
| *Planning & Simulation* | Scenario analysis, urban planners use GIS dashboards, simulation tools for lifecycle assessments, and VR simulators for training |
| *Maintenance & Diagnostics* | Predictive maintenance dashboards, AR overlays, guide, track fleet or equipment health, including emission metrics and performance issues. |
| *Security & Incident Management* | Visual analytics tools to highlight anomalies and real-time alert systems to detect and respond to network intrusions. |
| *Navigation & Control* | Dashboard-mounted systems, ship navigation monitors, signal optimisation strategies in intelligent transport systems. |
| *AI & Human Collaboration* | optimal charging routes, battery swapping. |
| Key References | (Vanitha et al., 2023), (Hassain et al., 2024), (Tasgaonkar et al., 2024), (Aloupogianni et al., 2024), (Jiménez et al., 2017), (De Donato et al., 2023), (Chavan et al., 2009), (Godavarthi et al., 2017), (Sanjana et al., 2024), (Sahay et al., 2019), (Yue et al., 2021), (Liao et al., 2022) |

for instance, connecting rail traffic models to logistics platforms or synchronising EV twins with smart grid infrastructure. In such settings, data must be exchanged between heterogeneous systems that use different protocols (e.g., RF, LoRa, GSM, CAN bus), data models, and governance structures. By enabling semantic mapping, protocol bridging, and security-layer alignment, the CSE allows DTs to function as reliable, policy-compliant participants in broader cyber-physical systems. The refined classification in this study reflects an increased representation of CSE, alongside emerging practices in semantic translation and lifecycle-based data assurance. The results are summarised in Table 7.

### 4.3. Digital twin framework for transport decarbonisation

This section presents the proposed ISO-23247-aligned DT framework for transport decarbonisation, developed from the functional elements identified in Section 4.2. This framework is explicitly tailored to the decarbonisation of transport. Although the proposed framework does not prescribe a single universal emissions quantification methodology applicable to all transport modes, it embeds decarbonisation-related capability within the reference architecture through the interaction of multiple functional entities. At the level of Observable Elements, the framework provides a measurable basis for representing energy use, fuel transitions, infrastructure-carbon interactions, operational activity, route conditions, energy demand, and emissions-related records. These may include, for example, electricity, hydrogen, SAF, EV charging infrastructure, battery-swapping stations, SAF-blending facilities, vehicle telemetry, smart energy systems, environmental sensors, and operational documentation. Through the Device Communication Entity, such data can be captured, pre-processed, and transmitted from physical assets, infrastructure, meters, sensors, and records into the digital environment. Within the Core or Digital Twin Entity, these inputs can then be transformed into higher-level outputs, including emissions estimates, energy-efficiency indicators, lifecycle carbon accounting, carbon-aware scenario comparisons, simulation outputs, and reporting artefacts. The User Entity links these outputs to practical decision-making through emissions dashboards, energy-consumption views, carbon-threshold alerts, planning interfaces, and scenario-comparison tools for planners, operators, technicians, regulators, and decision-makers. In this way, the framework connects emissions-related information to operational interventions such as route adjustment, charging or fuelling coordination, scheduling changes, maintenance prioritisation, infrastructure utilisation, and consignment-level comparison of alternative dispatch strategies. These examples are intended to demonstrate how carbon-aware monitoring and decision support are structurally accommodated within the proposed architecture, while remaining illustrative rather than exhaustive. The proposed framework is presented in Fig. 4.

**Table 7**
Cross-system entity categorisation with examples.

| | | |
|---|---|---|
| Data Assurance | Sub-categories: | *Data Assurance & Quality* |
| | **Examples:** | Data validation, accuracy, redundancy checks, and tolerance logic; Log Level (indirectly, via monitoring fidelity) |
| Security Support | **Sub-categories:** | *Data Security & Cryptography, Governance & Enforcement, Distributed Trust, Blockchain* |
| | **Examples:** | Encryption, authentication, integrity, PKI, access control; Policy engines, enforcement modules, verification subsystems; Blockchain networks, smart contracts, decentralised trust; TLS, PKI, E2EE, VPN, GDPR, ICO, CAA, DfT, ISO 27001, CIA Triad, Access Control, NIST CSF, NCSC CAF, NCSC, UK DT Centre, Standards, Threat Models, ITGov.uk, Organisation context |
| Data Translation | **Sub-categories:** | *Communication Layer, Semantic & Knowledge Translation, APIs & Interface protocol mediations,* |
| | **Examples:** | Middleware, protocol translation, interoperability components, Ontology mapping, semantic layers, translation logic, REST APIs, WebSocket, MQTT, socket protocols. |
| Intelligent Processing | **Sub-categories:** | *AI/ML, Federated Learning* |
| | **Examples:** | Federated learning, ML pipelines, model orchestration, |
| Supporting Infrastructure | **Sub-categories:** | *IoT, Vehicular & Edge Networks, Storage & Data Layer* |
| | **Examples:** | IoT gateways, sensors, edge-cloud synchronizing systems, SQL, Redis, Oracle, Parquet conversion, data storage engines, V2X/V2V communications, RSU integration. |
| Operational Support | **Sub-categories:** | *Monitoring & Event Management* |
| | **Examples:** | Logging, alerting, real-time sync, and monitoring pipelines. |
| Key References | (Ramal and Anbalagan, 2024), (Marinkovic et al., 2023), ( Samak et al., 2024a), (Tang et al., 2018), (Liu et al., 2026), (Liu et al., 2025) | |

To clarify the alignment between the proposed framework and ISO-23247, Table 8 presents an alignment matrix that maps the main framework entities, sub-entities, and FEs against the corresponding ISO-23247-2 clauses. The matrix distinguishes among FEs that are fully aligned with ISO-23247-2, those tailored to the transport domain, and those extended to address transport decarbonisation requirements. In this study, "aligned" refers to FEs adopted directly from ISO-23247-2, "tailored" refers to ISO-defined entities adapted to transport-specific contexts, and "extended" refers to additional FEs introduced through the literature review and Delphi consultation. The matrix shows that the Device Communication Entity and Core Digital Twin Entity are largely retained from ISO-23247-2, while the Observable Elements and User Entity are tailored to transport operations. The Cross-System Entity is further extended to include intelligent processing, supporting infrastructure, and operational support, reflecting the need for interoperability, governance, cybersecurity, and decarbonisation-oriented decision-making across multi-modal transport systems.

### 4.4. Illustrative use case: air-road interface for transport decarbonisation

To clarify the functional boundaries and interactions among the architectural entities, an illustrative use case is presented that focuses on the air-road interface, considering EV-based ground operations, electric HGVs (eHGVs), and SAF-enabled aviation systems. This scenario reflects a multi-modal transport context in which airport ground vehicles, charging infrastructure, fuel supply systems, road freight logistics, and flight operations are interconnected within a decarbonisation-oriented DT framework. The purpose of the use case is not to provide empirical validation of a deployed DT system, but to demonstrate how the proposed ISO-23247-aligned FEs can be interpreted and connected in a practical cross-modal decarbonisation setting. In this use case, two tightly coupled decarbonisation challenges dominate the air-road interface. The first concerns the allocation of SAF for departing aircraft under the requirements of ASTM D7566 and DEF STAN 91-091. The second concerns the integration of electric freight logistics systems, particularly eHGVs operating across airport landside areas, logistics hubs, depots, and regional supply chains. Limited SAF availability, hydrant scheduling constraints, variable freight arrival patterns, peak charging demand, and depot capacity limitations create operational interdependencies that can disrupt both aircraft turnaround performance and freight delivery reliability. The DT, therefore, acts as a coordination layer between aviation fuel operations, airport turnaround processes, electric freight movements, and energy infrastructure. The proposed use case demonstrates how a DT framework can support the joint optimisation of SAF blending, hydrant scheduling, eGSE (electric Ground Support Equipment) assignment, and road freight logistics

**Table 8**
ISO-23247-2 alignment matrix for the proposed Digital Twin framework for transport decarbonisation.

| Entity | Sub-Entity | Functional Elements (FE) | ISO-23247-2 Clause | Mandatory | Status |
|---|---|---|---|---|---|
| Observable Elements | | | 5.2.2 | Yes | Tailored |
| Device Communication | | | 5.2.3 | Yes | Aligned |
| | Data Collection | | 6.2.1 | Yes | Aligned |
| | | Data Collecting | 6.2.1.1 | Yes | Aligned |
| | | Data Pre-processing | 6.2.1.2 | Yes | Aligned |
| | | Collection Identification | 6.2.1.3 | Yes | Aligned |
| | Device Control | | 6.2.2 | Yes | Aligned |
| | | Controlling | 6.2.2.1 | Yes | Aligned |
| | | Actuation | 6.2.2.2 | Yes | Aligned |
| | | Control Identification | 6.2.2.3 | Yes | Aligned |
| Core (or DT) | | | 5.3.3 | Yes | Aligned |
| | Operation and Management | | 6.3.1 | Yes | Aligned |
| | | Synchronization | 6.3.1.1 | Yes | Aligned |
| | | Presentation | 6.3.1.2 | Yes | Aligned |
| | | Digital Representation | 6.3.1.3 | Yes | Aligned |
| | | DT Maintenance | 6.3.1.4 | Yes | Aligned |
| | Application and Service | | 6.3.2 | Yes | Aligned |
| | | Simulation | 6.3.2.1 | Yes | Aligned |
| | | Analytic Service | 6.3.2.2 | Yes | Aligned |
| | | Reporting | 6.3.2.3 | Yes | Aligned |
| | | Application Support | 6.3.2.4 | Yes | Aligned |
| | Resource Access and Interchange | | 6.3.3 | Yes | Aligned |
| | | Interoperability Support | 6.3.3.1 | Yes | Aligned |
| | | Access Control | 6.3.3.2 | Yes | Aligned |
| | | Plug and Play Support | 6.3.3.3 | Yes | Aligned |
| | | Peer Interface | 6.3.3.4 | Yes | Aligned |
| User | | | 5.3.4 | Yes | Tailored |
| | | Planning & Simulation | (new) | No | Extended |
| | | Monitoring & Visualisation | (new) | No | Extended |
| | | End-User Application | (new) | No | Extended |
| | | Maintenance & Diagnostics | (new) | No | Extended |
| | | Operational Control | (new) | No | Extended |
| | | Navigation & Control | (new) | No | Extended |
| | | Human-Machine Interface (HMI) | (new) | No | Extended |
| | | AI & Human Collaboration | (new) | No | Extended |
| | | Security & Incident Management | (new) | No | Extended |
| Cross-System | | | 5.3.5 | Yes | Extended |
| | Data Assurance | | 6.5.1 | Yes | Aligned |
| | Security Support | | 6.5.2 | Yes | Aligned |
| | Data Translation | | 6.5.3 | Yes | Aligned |
| | Intelligent Processing | | (new) | No | Extended |
| | Supporting Infrastructure | | (new) | No | Extended |
| | Operational Support | | (new) | No | Extended |

coordination, including eHGV routing, scheduling, and charging operations. The objective is to reduce GHG emissions, expressed in grams of carbon dioxide equivalent ($gCO_2e$) per Air Transport Movement (ATM) and Revenue Tonne Kilometre (RTK), while respecting Airport Collaborative Decision Making (A-CDM) milestones. The framework also supports alignment with CORSIA, the UK Jet Zero Strategy, SECR, and ESOS by linking operational data, fuel certification, energy use, and emissions reporting within a single DT structure. The ISO-23247-aligned use-case framework is illustrated in Fig. 5.

#### 4.4.1. *Use case alignment to ISO-23247 fes*

The use case is structured around the five main ISO-23247-aligned entities: Observable Elements, Device Communication Entity, Core Digital Twin Entity, User Entity, and Cross-System Entity. Together, these entities describe how physical transport operations are observed, connected, analysed, controlled, visualised, and governed within the air-road decarbonisation scenario.

The Observable Elements represent the real-world entities involved in aviation fuel systems, airport ground operations, and road freight logistics. Personnel include pilots, turnaround crews, refuellers, fuel-farm operators, eGSE operators, eHGV drivers, fleet managers, warehouse operators, and freight coordinators. Equipment includes aircraft, fuel hydrants, SAF blending units, eGSE, eHGV fleets, depot chargers, logistics hubs, consolidation centres, and loading or unloading infrastructure. Material flows include SAF, Jet A-1, electricity, batteries, cargo containers, palletised freight, and time-sensitive goods moving between warehouses, airport terminals, and aircraft. Processes include SAF blending and uplift, aircraft turnaround, A-CDM (airport collaborative decision making) milestone management, eGSE assignment, freight scheduling, warehouse handling, gate allocation, and last-mile delivery coordination. The environment includes weather conditions, grid carbon intensity, substation load, road congestion, travel-time variability, and freight corridor utilisation. In this way, the Observable Elements provide the physical and operational basis for carbon-aware monitoring across both air and road activities.

The Device Communication Entity provides the cyber-physical interface for right-time data acquisition and control between these observable elements and the DT. Aircraft and fuel data can be obtained through ACARS, FQIS, hydrant metering, SAF batch records, and fuel-farm systems, while eGSE and eHGV telemetry can be captured through CAN-bus, fleet telematics, smart meters, and charging systems. Charger communication is managed through OCPP, and smart metering through DLMS/COSEM. Positioning and movement data can be obtained through GNSS, RTLS, and logistics tracking platforms. Additional data streams are provided by WMS (warehouse management systems), TMS (transport management systems), A-CDM platforms, airline OCC (operations control centre) systems, and airport cargo systems. Edge processing supports SAF mass-balance reconciliation, anomaly detection, battery SoC (state of charge) monitoring, route-deviation detection, and predictive monitoring of eHGV charging demand. The control

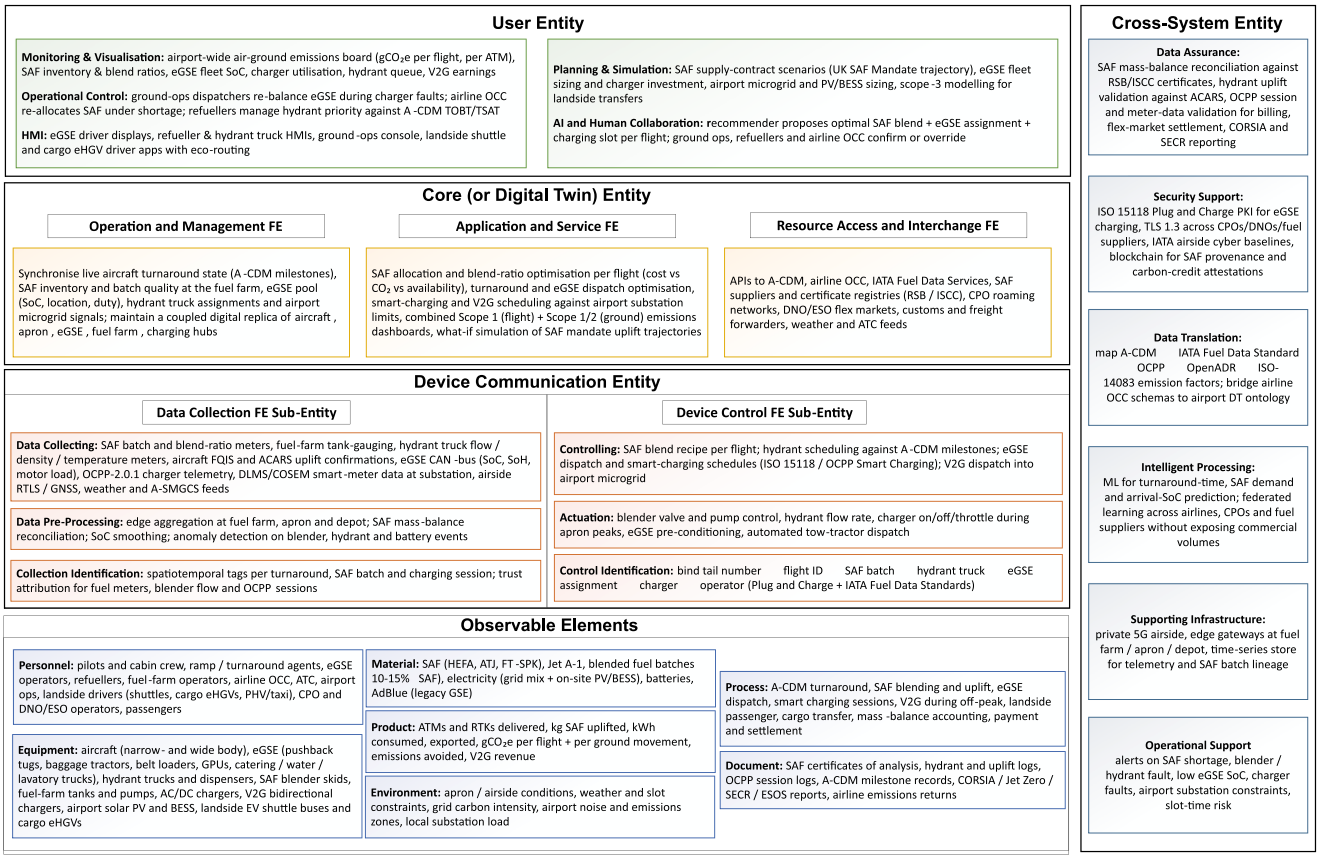



**Fig. 5.** ISO-23247-aligned framework as a reference architecture for a use case in Air-Road Interface for Transport Decarbonisation.

functions then translate DT outputs into operational actions, such as hydrant scheduling, smart charging, eGSE assignment, and dynamic re-routing or rescheduling of eHGV fleets.

The Core Entity forms the intelligence layer of the use case. It maintains a synchronised digital representation of aircraft turnaround operations, SAF supply, fuel infrastructure, eGSE deployment, eHGV movements, depot charging, and cargo flows. The Core integrates these data streams into a unified model that supports simulation, prediction, optimisation, and reporting. Advanced optimisation and ML techniques can be used to evaluate SAF allocation per flight, hydrant scheduling, eGSE utilisation, eHGV routing, charging coordination, fleet utilisation, and freight dispatch decisions. The DT can also simulate disruptions such as SAF shortages, charging bottlenecks, grid constraints, traffic congestion, delayed freight arrivals, or warehouse capacity limitations. By linking freight arrival times and fuel operations to A-CDM milestones, the Core DT supports coordinated decision-making that reduces idle time, improves turnaround reliability, and minimises emissions across both ATM- and RTK-based indicators.

The User Entity enables different stakeholders to interact with DT through dashboards, HMI, alerts, and decision-support tools. Users include airport operators, fuel suppliers, refuellers, airline operations teams, eGSE managers, logistics managers, eHGV fleet operators, cargo terminal coordinators, energy operators, and supply chain planners. The interface provides visibility of SAF inventory, hydrant utilisation, aircraft readiness, eGSE availability, eHGV fleet status, delivery schedules, charger utilisation, warehouse throughput, logistics delays, and emissions performance. Decision-support functions allow users to adjust SAF allocation, prioritise freight movements, allocate charging slots, reschedule eGSE or eHGV operations, and assess alternative dispatch strategies. The User Entity, therefore, translates DT intelligence into human-in-the-loop operational decisions, allowing operators to validate, adjust, or override AI-generated recommendations where necessary.

The Cross-System Entity ensures that data exchange across aviation, freight, energy, and regulatory systems is interoperable, secure, and trustworthy. It connects A-CDM platforms, airline OCC systems, fuel management systems, SAF certification data, WMS, TMS, charger management systems, and emissions reporting platforms. Data assurance functions support SAF mass-balance verification, RSB/ISCC certificate checking, chain-of-custody tracking, telemetry validation, and emissions reporting. Security support is provided through mechanisms such as TLS, PKI, authentication, access control, and secure stakeholder interfaces. Data translation is achieved through API mediation, semantic mapping, and a unified DT ontology that connects data models for aviation, fuel, freight, vehicles, infrastructure, and energy. The Cross-System Entity is therefore central to the use case because it allows independently operated systems to contribute to a shared decarbonisation objective without removing the need for mode-specific governance, commercial confidentiality, or regulatory compliance.

Overall, the use case demonstrates how the proposed framework can organise air-road decarbonisation around ISO-23247-aligned FEs. Observable Elements define what must be monitored; the Device Communication Entity captures and controls operational data; the Core Digital Twin Entity analyses and optimises system behaviour; the User Entity supports decision-making; and the Cross-System Entity enables secure interoperability, assurance, and governance. This shows how the proposed framework can move beyond isolated aviation or road-freight applications towards a coordinated, cross-modal DT structure for transport decarbonisation.

## 5. Critical discussion

This study addressed two research objectives: (RO1) the systematic identification of existing digital methodologies used in transport DT

design, and (RO2) the proposal of a standardised DT framework aligned with ISO-23247. The findings show that transport DT research has expanded rapidly across road, rail, maritime, and air systems, but existing architectures remain largely fragmented, mode-specific, and weakly connected to standardised reference models (Campolo et al., 2024; Fonseca et al., 2023; Giering and Dyck, 2021; Zhang et al., 2024; Zhou et al., 2022). This fragmentation is not only a technical limitation, but also a barrier to coordinated transport decarbonisation, because emissions reduction requires data, control, governance, and decision-making to operate across multiple transport modes and organisational boundaries (Aguiar et al., 2022; Ali et al., 2023; Chartrain et al., 2024; Kamal et al., 2024; Nguyen et al., 2025; Salin, 2025). In response, the proposed framework adapts ISO-23247 to the transport domain by extending its functional entities to reflect multi-modal observability, cross-system integration, user-centred interaction, and climate-relevant operational analytics. In addition, the Delphi process played an important role in refining the proposed framework beyond the initial literature-derived architecture. While the SLR primarily identified technical DT elements related to sensing, communication, simulation, analytics, and digital representation, expert feedback helped adapt these elements to the operational realities of transport systems. This was particularly important because the literature tended to emphasise technical components, whereas the experts highlighted organisational, user-facing, and governance-related requirements. The Delphi consultation, therefore, strengthened the representation of personnel, operational processes, documents, alternative fuels, EV charging infrastructure, user roles, semantic interoperability, cybersecurity, and trusted data exchange.

### 5.1. *Digital methodologies and insights (RO1)*

A systematic review and analysis of over one hundred peer-reviewed publications and policy documents reveals that DT development across transport domains remains siloed, domain-specific, and unaligned with international standards such as ISO-23247. The literature review shows that IoT technologies are the most widely adopted digital methodology across all transport modes. IoT enables sensor integration, vehicle monitoring, and environmental feedback loops (Jabbar et al., 2020; Luo et al., 2019; Ren et al., 2019). These implementations have matured significantly in road and marine domains, driven by low-cost hardware, improved wireless protocols, and smart city initiatives (Chitra et al., 2024; Sahay et al., 2019). However, while IoT has enabled right-time data acquisition, it often lacks semantic coherence and interoperability, particularly when deployed without structured ontologies or control abstractions (Fonseca, de Oliveira and Gaspar, 2023; Heise, Esser and Borrmann, 2024). CPS, though theoretically well-positioned to enable intelligent control, are less prevalent in transport DTs and frequently embedded within broader hybrid systems (Levshun et al., 2021; Yang et al., 2023). These insights reflect on the importance of technical complexity and digital risks associated with right-time control in dynamic, multi-agent environments (Jin et al., 2013; Sampigethaya and Poovendran, 2012). Moreover, CPS have proven effective in secure scheduling (e.g., EV charging) and transport-grid interactions, yet these remain isolated applications with limited generalisability (Ahmed and Rani, 2018; Mejjaouli and Alnourani, 2024). Embedded systems dominated early DT research up until 2010, focusing on vehicle telemetry and control (Johnson et al., 2014; Nasr, Kfoury and Khoury, 2016). While foundational, these approaches have been superseded by data-centric, networked architectures that integrate edge computing and AI (Kamal et al., 2024; Wang et al., 2023). However, their legacy persists in constrained environments (e.g., in-vehicle systems) where resource optimisation and latency remain critical. Data architecture has been emerging since 2015, so the studies increasingly emphasise cloud-edge integration, big data analytics, and semantic platforms (Bertolini et al., 2024; Vanitha et al., 2023). However, despite its growth, architectural alignment with standards is rarely achieved, and few systems support modular plug-and-play integration, hindering scale (Campolo et al., 2024; Xu et al., 2025). Transport mode-specific trends also highlight research imbalance. Road and rail domains demonstrate methodological maturity with extensive IoT deployments and growing ML integration (Chartrain et al., 2024; Shahriar et al., 2024). In contrast, aviation DTs remain scarce, with a few studies targeting predictive maintenance and simulation-enhanced design (Kosova and Unver, 2023; Zhang et al., 2024). The maritime sector lacks agreement around data standards, cybersecurity, and semantic modelling (Giering and Dyck, 2021; Kinaci, 2023; Kumar and Ali, 2024).

### 5.2. *Standardised framework development (RO2)*

A comparative analysis of the literature found several key contributions and gaps in developing a standardised DT design framework. The methodological mapping shows that IoT remains the dominant enabling methodology in transport DT development. This dominance reflects the maturity of sensor networks, vehicle connectivity, wireless communication, and smart-city infrastructure. However, the findings also show that IoT-based DTs mainly strengthen observability rather than system-level intelligence. In other words, many studies collect transport data, but fewer provide the architectural mechanisms needed to translate this data into coordinated control, governance, and decarbonisation decisions. In the existing literature, observable elements, such as equipment and environment, are prominently represented in current DTs (Aldeen et al., 2024; Yang et al., 2020). However, other elements, such as documents, personnel, and processes, remain underdeveloped despite their critical role in real-world operations (Tang et al., 2024; Tsitsilonis et al., 2023). Moreover, the ‘Data Collection’ function is well-developed within the existing frameworks (Hassain et al., 2024; Jan et al., 2019). However, ‘Control identification’ with adaptive actuation is notably lacking. These limitations restrict DTs' ability to operate as intelligent CPS capable of autonomously responding to context shifts, which are essential for future smart transport. Most recent DT designs include advanced analytics, simulation, and ML capabilities (Ali et al., 2023; Barroso et al., 2024). However, this research often fails to maintain sub-entities. This constraint causes a disconnect between analytical prowess and long-term system resilience (Baluprithviraj et al., 2023). Despite the widespread deployment of DT technologies in transport systems since 2021, only a few designs adapt interfaces to user context or role-specificity (Adil Khan et al., 2023; Yue et al., 2021). It is worth noting that recent literature has addressed cognitive ergonomics, AR/VR-assisted interaction, and AI-human collaboration (Aloupogianni et al., 2024; Puri et al., 2024). Protocol translation and data security are routinely acknowledged in the literature (Gupta and Rahmani, 2024; Salin, 2025). However, the architectural considerations for alignment with standards such as NCSC CAF or ISO 27001 were not considered. Moreover, ‘Trust negotiation’, ‘semantic data translation’, and ‘plug-and-play integration’ remain emerging, thereby limiting real-time interoperability in federated systems (Bezrodniy et al., 2024; Fonseca et al., 2023).

Although the framework provides a standardised architectural structure, its translation into operational settings would require careful attention to data interoperability, governance, scalability, assurance, and implementation cost. Data interoperability remains challenging because transport systems rely on legacy infrastructures, proprietary platforms, incompatible interfaces, and inconsistent semantic models across organisations and modes. This reinforces the importance of semantic modelling, ontology-based representation, and standardised interfaces to ensure traceability and coherent DT behaviour (Chartrain et al., 2024; Fonseca et al., 2023; Heise et al., 2024). Governance is equally important because DT-supported decisions may affect safety-critical operations, requiring clear arrangements for data ownership, access control, accountability, cybersecurity responsibilities, and human oversight. Existing studies on secure CPS, V2G systems, cooperative ITS, maritime authentication, and cyber-resilient vehicular

DTs further show that authentication, anomaly detection, data assurance, and access control are central to trustworthy DT operation (Ali et al., 2023; Kumar and Ali, 2024; Levshun et al., 2021; Salin, 2025; Yigit et al., 2024). In addition, scalability and cost are likely to differ across transport modes due to variations in sensing requirements, retrofit needs, certification environments, asset life cycles, and digital maturity. These issues do not undermine the proposed framework as a reference architecture, but they highlight key considerations for future application, pilot-based evaluation, and mode-specific adaptation. Compared with recent layered and modular DT frameworks, the proposed framework provides a distinct conceptual contribution. Existing DT architectures in transport are often designed for specific applications, such as EV charging, traffic optimisation, infrastructure monitoring, or logistics coordination, and are typically developed independently of an overarching reference model (Campolo et al., 2024; Chartrain et al., 2024; Fonseca et al., 2023; Zhou et al., 2022). As a result, they tend to exhibit limited interoperability, weak alignment across transport modes, and inconsistent treatment of governance and lifecycle considerations. In contrast, this study adapts ISO-23247 as a unifying reference architecture and translates its domains, entities, and FE into the context of transport decarbonisation. The proposed framework embeds decarbonisation-related observables, interoperability mechanisms, governance considerations, user roles, and cross-system entities within a single architectural structure. This enables a shift from application-specific DT designs toward a more consistent and standardised approach to structuring transport DTs at the system level, without implying functional implementation.

### 5.3. *Implementation considerations and limitations*

The proposed framework can support policymakers, industry stakeholders, and researchers by providing a common structure for organising the development of transport DT. For policymakers, the framework can support more consistent emissions monitoring and reporting, as well as climate-aligned decision-making. For industry stakeholders, it clarifies how sensing, control, analytics, user interfaces, and cross-system functions can be integrated across operational systems. For researchers, it provides a standards-aligned basis for future pilot studies, interoperability testing, quantitative performance assessment, and mode-specific DT development.

The proposed framework provides standardised ISO 23247-aligned reference architecture for transport decarbonisation. However, several limitations should be acknowledged. First, the framework remains conceptual and requires empirical validation through pilot deployments, simulations, interoperability testing, or quantitative performance assessment. Second, although the framework identifies the need for data translation, semantic alignment, access control, security support, and peer interfaces, it does not provide a fully specified ontology, message standard, or technical protocol for cross-modal data exchange. Third, the validation process is expert-informed and scenario-supported rather than based on a deployed DT system. Governance and decarbonisation constraints further define the study's limits. Finally, practical deployment and emissions-accounting assessments require clear arrangements for data ownership, access rights, privacy, cybersecurity, liability, accountability, regulatory compliance, and decision-making authority.

## 6. Concluding remarks

This study addressed a critical gap in the digitalisation of transport systems by developing a standardised Digital Twin Design Framework aligned with the ISO-23247 architecture, tailored to system-level decarbonisation across road, rail, maritime, and air modes. This research employed a twofold methodology, including a systematic literature review of more than 100 peer-reviewed sources covering all major transport modes and a Delphi-based expert consultation involving digital engineering and sustainability specialists from three higher education institutions in the UK. The research methodology provides a practical approach for adapting and implementing the existing international standard for transport decarbonisation across multiple modes. The literature review confirmed substantial advancements in IoT adoption and CPS integration in DT designs. However, existing transport designs are mostly fragmented, domain-specific, and often ad hoc, with limited interoperability and minimal integration of decarbonisation metrics. To address these limitations, this research developed a multi-layered, cross-modal DT framework that expands upon ISO-23247's core entities. It incorporates granular observability, intelligent data collection and control, semantic interoperability, adaptive user interfaces, and context-aware governance structures. The framework includes decarbonisation-relevant observables, such as EV charging infrastructure, fuel systems, emissions tracking, and grid-integrated transport devices, while also modelling human actors, policy documents, and lifecycle operations that are typically excluded from current implementations. These additions were validated and refined through three iterative rounds of Delphi workshops, which brought insights on modularity, plug-and-play architectures, and cybersecurity alignment with national standards. This research contributes to the body of knowledge on DT design by (i) providing a comprehensive analysis of digital methodologies, including IoT, CPS, hybrid systems, and data architectures, used in transport DT design. (ii) extending the ISO-23247 to transport decarbonisation metrics, to the best knowledge of the authors, for the first time.

In addition, this research highlights the following key takeaways: (i) the ISO-23247 standard is an effective approach in DT design by providing a standardised structure that ensures interoperability and scalability across different transport modes, (ii) this research emphasises the consideration of emission modelling, energy efficiency optimisation, and carbon accounting as core analytical functions for transport decarbonisation. (iii) it is crucial in any DT design that cyber-physical integration strengthened through right-time data synchronisation between physical and digital models, supported by IoT sensor networks and CPS orchestration, (iv) cross-sector data architectures should be developed to bridge modal silos to federated designs that enable system-wide decision-making, (v) successful implementation demands multidisciplinary collaboration, engaging engineers, data scientists, sustainability experts, and policy specialists to ensure robustness and real-world relevance, and finally (vi) the proposed framework should be treated as a living artefact, evolving alongside technological advances and emerging standards to remain fit for purpose. Future work should be conducted with the focus on deploying the framework in live pilot environments, particularly in EV or autonomous logistics with more established basis. Additional research is also required to operationalise semantic interoperability, lifecycle carbon accounting, and ethical human-AI collaboration in right-time DT contexts. The integration of machine-readable governance models, adaptive user interfaces, and context-sensitive security protocols will be critical for supporting the next generation of federated, trustworthy, and ethically aligned DT systems. As the transport sector accelerates its digital transformation, standardisation, transparency, and decarbonisation must be treated as inevitable design imperatives. This study offers a fundamental step toward that goal, where digital intelligence and environmental considerations are co-designed into the DTs that will shape the future of sustainable mobility.

Future work should focus on pilot-based deployment, simulation experiments, interoperability testing, quantitative performance assessment, and comparison with alternative DT architectures across different transport modes. The research should involve a wider range of stakeholders assessing practical relevance, governance requirements, organisational readiness, and applicability beyond the current expert-informed validation. Future studies should also develop the technical and governance mechanisms needed for implementation, carbon-aware monitoring, and decision-making across different transport modes and

organisational settings.

## CRediT authorship contribution statement

**Maryam Farsi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Bernadin Namoano:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Christina Latsou:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Mohammad Alquraan:** Writing – review & editing, Validation, Methodology. **Dhanan Utomo:** Writing – review & editing, Validation, Methodology. **Ahmad Taha:** Writing – review & editing, Validation, Methodology. **John Ahmet Erkoyuncu:** Writing – review & editing, Validation, Supervision, Funding acquisition. **David Flynn:** Validation, Supervision, Funding acquisition. **Phil Greening:** Validation, Supervision, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

## References

Aburasain, R. (2025). A digital twin-driven deep reinforcement learning framework for end-to-end mixed traffic scheduling. *IEEE Transactions on Consumer Electronics*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/TCE.2025.3645697

Adil Khan, M., Nawaz, T., Khan, U. S., Hamza, A., & Rashid, N. (2023). IoT-based non-intrusive automated driver drowsiness monitoring framework for logistics and public transport applications to enhance road safety. In *IEEE Access, 11* pp. 14385–14397). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ACCESS.2023.3244008

Aguiar, A., Fernandes, P., Guerreiro, A. P., Tomás, R., Agnelo, J., Santos, J. L., Araújo, F., et al. (2022). MobiWise: Eco-routing decision support leveraging the Internet of Things. In *Sustainable Cities and Society, 87*. Elsevier, Article 104180. https://doi.org/10.1016/J.SCS.2022.104180

Ahmed, S. H., & Rani, S. (2018). A hybrid approach, smart street use case and future aspects for internet of things in smart cities. In *, 79. Future Generation Computer Systems* (pp. 941–951). Elsevier B.V.. https://doi.org/10.1016/j.future.2017.08.054

Aldeen, Y. A. A. S., Jaber, M. M., Ali, M. H., Abd, S. K., Alkhayyat, A., & Malik, R. Q. (2024). Electric charging station management using IoT and cloud computing framework for sustainable green transportation. In *Multimedia Tools and Applications, 83* pp. 28705–28728). Springer. https://doi.org/10.1007/S11042-023-16630-0/FIGURES/12

Ali, M., Kaddoum, G., Li, W. T., Yuen, C., Tariq, M., & Poor, H. V. (2023). A smart digital twin enabled security framework for vehicle-to-grid cyber-physical systems. In *IEEE Transactions on Information Forensics and Security, 18* pp. 5258–5271). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/TIFS.2023.3305916

Aloupogianni, E., Doctor, F., Karyotis, C., Maniak, T., Tang, R., & Iqbal, R. (2024). An AI-based digital twin framework for intelligent traffic management in singapore. In *International Conference on Electrical, Computer, and Energy Technologies, ICECET 2024*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ICECET61485.2024.10698642

Al-Turjman, F. (2018). Information-centric framework for the internet of things (IoT): Traffic modeling & optimization. In *, 80. Future Generation Computer Systems* (pp. 63–75). https://doi.org/10.1016/J.FUTURE.2017.08.018

Andruccioli, M., Delnevo, G., Girau, R., & Salomoni, P. (2026). Digital twins in public bus transport: A systematic literature review of architectures, intelligence, and interaction. In *, 180. Future Generation Computer Systems*, Article 108379. https://doi.org/10.1016/J.FUTURE.2026.108379

Baluprithviraj, K. N., Dhanalakshmi, M., Dharanidharan, D., Gokulkrishnan, K., Kalavathi Devi, T., & Madhan Mohan, M. (2023). Design and development of a system to control and monitor the atmospheric CO and CO2 in traffic junctions using IoT. In *International Conference on Self Sustainable Artificial Intelligence Systems, ICSSAS 2023 - Proceedings* (pp. 1–6). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ICSSAS57918.2023.10331718

Barroso, S., Zapata, N., Pérez, G., Bustos, P., & Núñez, P. (2024). Real-time hazard prediction in connected autonomous vehicles: A digital twin approach. In *IEEE International Conference on Intelligent Robots and Systems* (pp. 3182–3188). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/IROS58592.2024.10802333

Belfadel, A., Horl, S., Tapia, R. J., & Puchinger, J. (2021). Towards a digital twin framework for adaptive last mile city logistics. In *2021 6th International Conference on Smart and Sustainable Technologies, SpliTech 2021*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.23919/SPLITECH52315.2021.9566324

Bertolini, L., Giorgadze, I. M., Vahdatikhaki, F., & D'Amico, F. (2024). A semantic digital twinning approach for the management of road distress data. In *, 10. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* (pp. 49–54). Copernicus Publications. https://doi.org/10.5194/ISPRS-ANNALS-X-4-W5-2024-49-2024.

Bezrodniy, A., Rezchikov, A., & Stepanovskaya, I. (2024). Cyber-physical system development to improve energy supply on transport by causal approach. In *Proceedings of 2024 17th International Conference on Management of Large-Scale System Development, MLSD 2024*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/MLSD61779.2024.10739548

Bhaskar, K. B. R., Prasanth, A., & Saranya, P. (2022). An energy-efficient blockchain approach for secure communication in IoT-enabled electric vehicles. *International Journal of Communication Systems, 35*(11), Article e5189. https://doi.org/10.1002/DAC.5189;JOURNAL:JOURNAL:10991131B;PAGE:STRING:ARTICLE/CHAPTER

Campolo, C., Genovese, G., Molinaro, A., Pizzimenti, B., Ruggeri, G., & Zappala, D. M. (2024). An edge-based digital twin framework for connected and autonomous vehicles: design and evaluation. In *IEEE Access, 12* pp. 46290–46303). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ACCESS.2024.3382001

Chartrain, A., Dessagne, G., Haddad, N., & Hill, D. R. C. (2024). Linking digital twin design and ontologies with model-driven engineering: application to railway infrastructure. In *International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management, IC3K - Proceedings, 2* pp. 265–276). Science and Technology Publications, Lda. https://doi.org/10.5220/0013090200003838

Chavan, S. S., Deshpande, R. S., & Rana, J. G. (2009). Design of intelligent traffic light controller using embedded system. In *2009 2nd International Conference on Emerging Trends in Engineering and Technology* (pp. 1086–1091). ICETET. https://doi.org/10.1109/ICETET.2009.76. *2009*.

Cheng, D. J., Zhang, J., Hu, Z. T., Xu, S. H., & Fang, X. F. (2020). A digital twin-driven approach for on-line controlling quality of marine diesel engine critical parts. *International Journal of Precision Engineering and Manufacturing, 21*(10), 1821–1841. https://doi.org/10.1007/S12541-020-00403-Y/FIGURES/20

Cheng, Y., Yin, Z., Li, D., & Li, Z. (2024). Assessing urban safety: A digital twin approach using streetview and large language models. In *IEEE Vehicular Technology Conference*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/VTC2024-FALL63153.2024.10757666

Chitra, K., Gnanasekar, A., Ravi, C. N., Jaisudha, J., Ramya, R., & Jithendar, P. (2024). A comprehensive evaluaion of solar powered electric vehicle charging station design using internet of things. In *Proceedings - 1st International Conference on Electronics, Communication and Signal Processing, ICECSP 2024*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ICECSP61809.2024.10698561

Chowdhury, D. N., Agarwal, N., Laha, A. B., & Mukherjee, A. (2018). A vehicle-to-vehicle communication system using Iot approach. In *Proceedings of the 2nd International Conference on Electronics, Communication and Aerospace Technology, ICECA 2018* (pp. 915–919). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ICECA.2018.8474909

Cui, Y., & Lei, D. (2023). Design of highway intelligent transportation system based on the internet of things and artificial intelligence. In *IEEE Access, 11* pp. 46653–46664). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ACCESS.2023.3275559

Debadarshini, J., & Saha, S. (2022). Efficient coordination among electrical vehicles: An IoT-assisted approach. In *INFOCOM WKSHPS 2022 - IEEE Conference on Computer Communications Workshops*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/INFOCOMWKSHPS54753.2022.9797944

Divyapriya, S., Amutha, & Vijayakumar, R. (2018). Design of residential plug-in electric vehicle charging station with time of use tariff and IoT technology. In *ICSNS 2018 - Proceedings of IEEE International Conference on Soft-Computing and Network Security*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ICSNS.2018.8573637

De Donato, L., Dirnfeld, R., Somma, A., De Benedictis, A., Flammini, F., Marrone, S., Saman Azari, M., et al. (2023). Towards AI-assisted digital twins for smart railways: Preliminary guideline and reference architecture. *Journal of Reliable Intelligent Environments, 9*(3), 303–317. https://doi.org/10.1007/S40860-023-00208-6/FIGURES/4

Errandonea, I., Goya, J., Alvarado, U., Beltron, S., & Arrizabalaga, S. (2021). IoT approach for intelligent data acquisition for enabling digital twins in the Railway

Sector. In *Proceedings - 2021 International Symposium on Computer Science and Intelligent Controls, ISCSIC 2021* (pp. 164–168). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ISCSIC54682.2021.00039

Estil-Les, M. A. D. C., Ali, W. A., Mangini, A. M., & Fanti, M. P. (2026). A digital twin approach for last-mile delivery. *IEEE Transactions on Automation Science and Engineering*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/TASE.2026.3672286

Fatorachian, H., Kazemi, H., & Pawar, K. (2025). Enhancing smart city logistics through IoT-enabled predictive analytics: A digital twin and cybernetic feedback approach. *Smart Cities 2025*, (2), 56. https://doi.org/10.3390/SMARTCITIES8020056, 8.

Feng, Y., Hu, B., Hao, H., Gao, Y., Li, Z., & Tan, J. (2018). Design of distributed cyber-physical systems for connected and automated vehicles with implementing methodologies. In *, 14. IEEE Transactions on Industrial Informatics* (pp. 4200–4211). IEEE Computer Society. https://doi.org/10.1109/TII.2018.2805910.

Ferdousi, R., Laamarti, F., Yang, C., & El Saddik, A. (2022). RailTwin: A digital twin framework for railway. In *, 2022. IEEE International Conference on Automation Science and Engineering* (pp. 1767–1772). IEEE Computer Society. https://doi.org/10.1109/CASE49997.2022.9926529.

Fonseca, A., de Oliveira, F. F., & Gaspar, H. M. (2023). Open framework for digital twin ship data: case studies on handling of multiple taxonomies and navigation simulation. In *Transactions of the Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering, 165* pp. A23–A42). University of Buckingham Press. https://doi.org/10.5750/IJME.V165IA1.813

GhanavatiNejad, M., Tavakoli, M., Sheikhalishahi, M., Aydın, N., & Aria, S. S. (2025). An integrated smart framework for fast-moving consumer goods online market logistics: A digital twin framework. *Journal of Industrial and Production Engineering*. https://doi.org/10.1080/21681015.2025.2470244;WGROUP:STRING:PUBLICATION

Giering, J. E., & Dyck, A. (2021). Maritime Digital twin architecture A concept for holistic Digital Twin application for shipbuilding and shipping. In *At-Automatisierungstechnik, 69* pp. 1081–1095). De Gruyter Oldenbourg. https://doi.org/10.1515/AUTO-2021-0082/ASSET/GRAPHIC/J_AUTO-2021-0082_FIG_002.JPG

Godavarthi, B., Nalajala, P., & Ganapuram, V. (2017). Design and implementation of vehicle navigation system in urban environments using internet of things (Iot). In *, 225. IOP Conference Series: Materials Science and Engineering*. IOP Publishing, Article 012262. https://doi.org/10.1088/1757-899X/225/1/012262.

Gupta, V., & Rahmani, M. K. I. (2024). IoT-based nano wireless sensor approach for detection of ships using mixed convolutional neural network approach. In *Signal, Image and Video Processing, 18* pp. 8185–8194). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/S11760-024-03460-2/FIGURES/4

Han, X., Lin, B., Wu, N., Wang, P., Na, Z., & Zhang, M. (2024). Design of a turbo-based deep semantic autoencoder for marine Internet of Things. In *Internet of Things, 28*. Elsevier, Article 101393. https://doi.org/10.1016/J.IOT.2024.101393

Hassain, M. M., Mazumder, M. F. U., Abdullah, K. M., Arefin, M. R., & Rahman, M. A. (2024). Design and implementation of road monitoring system using embedded system and IoT. In *Proceedings - International Conference on Advanced Computer Information Technologies, ACIT* (pp. 739–743). Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/ACIT62333.2024.10712498.

Heise, I., Esser, S., & Borrmann, A. (2024). In *Towards a Comprehensive Digital Twin of a Road Infrastructure System-Requirements Analysis and System Architecture*.

Hosseini, M. A., Roozbahani, M. H., & Sayyah, A. (2025). AI-driven digital twin architecture for urban bus fleet life-cycle cost analysis in a metaverse environment. In *Sustainable Cities and Society, 130*. Elsevier, Article 106611. https://doi.org/10.1016/J.SCS.2025.106611

House of Commons Transport Committee. (2023). Fuelling the future: motive power and connectivity: Government response to the Committee's third report. *Fourth Special Report of Session 2022–23. HC 1382*. London: The Stationery Office.

Hsu, R. C., & Chen, L. R. (2005). An integrated embedded system architecture for in-vehicle telematics and infotainment system. In *, IV. IEEE International Symposium on Industrial Electronics* (pp. 1409–1414). https://doi.org/10.1109/ISIE.2005.1529139

Huang, X. (2023). Design of intelligent collection system for marine pollution information based on broadband Internet of Things. In *Desalination and Water Treatment, 315* pp. 558–564). Elsevier. https://doi.org/10.5004/DWT.2023.30024

Hwang, H., & Joe, I. (2023). Enhancing IoT connectivity and services for worldwide ships through multi-region fog cloud architecture platforms. In *Electronics 2023, 12* p. 4250). Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/ELECTRONICS12204250

Jabbar, R., Krichen, M., Kharbeche, M., Fetais, N., & Barkaoui, K. (2020). A formal model-based testing framework for validating an IoT solution for blockchain-based vehicles communication. In *ENASE 2020 - Proceedings of the 15th International Conference on Evaluation of Novel Approaches to Software Engineering* (pp. 595–602). SciTePress. https://doi.org/10.5220/0009594305950602.

Jan, B., Farman, H., Khan, M., Talha, M., & Din, I. U. (2019). Designing a smart transportation system: An internet of things and big data approach. In *IEEE Wireless Communications, 26* pp. 73–79). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/MWC.2019.1800512

Jiang, F., Li, J., Ma, L., Dong, Z., Chen, W., Broyd, T., & Wang, G. (2024). Sustainable urban road planning under the digital twin-MCDM-GIS framework considering multidisciplinary factors. *Journal of Cleaner Production, 469*, Article 143097. https://doi.org/10.1016/J.JCLEPRO.2024.143097

Jiang, F., Ma, L., Broyd, T., Chen, W., & Luo, H. (2022). Digital twin enabled sustainable urban road planning. In *Sustainable Cities and Society, 78*. Elsevier, Article 103645. https://doi.org/10.1016/J.SCS.2021.103645

Jiménez, A., García-Díaz, V., & Anzola, J. (2017). Design of a system for vehicle trafiic estimation for applications on IoT. In *ACM International Conference Proceeding Series*. Association for Computing Machinery. https://doi.org/10.1145/3092090.3092103;TOPIC:TOPIC:CONFERENCE-COLLECTIONS>MISNC;PAGE:STRING:ARTICLE/CHAPTER. Part F129682.

Jin, R., Wang, B., Zhang, P., & Luh, P. B. (2013). Decentralised online charging scheduling for large populations of electric vehicles: A cyber-physical system approach. *International Journal of Parallel, Emergent and Distributed Systems, 28*(1), 29–45. https://doi.org/10.1080/17445760.2012.658803;WGROUP:STRING:PUBLICATION

Johnson, M., Fabregas, A., Wang, Z., Katkoori, S., & Lin, P. S. (2014). Embedded system design of an advanced illumination measurement system for highways. In *8th Annual IEEE International Systems Conference, SysCon 2014 - Proceedings* (pp. 579–586). IEEE Computer Society. https://doi.org/10.1109/SYSCON.2014.6819314.

Kamal, H., Yanez, W., Hassan, S., & Sobhy, D. (2024). Digital-twin-based deep reinforcement learning approach for adaptive traffic signal control. In *IEEE Internet of Things Journal, 11* pp. 21946–21953). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/JIOT.2024.3377600

Kampczyk, A., & Dybeł, K. (2021). The fundamental approach of the digital twin application in railway turnouts with innovative monitoring of weather conditions. In *Sensors 2021, 21* p. 5757). Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/S21175757. *Page*Vol. 21 No. 17, p. 5757.

Karnehm, D., Samanta, A., Neve, A., & Williamson, S. (2024). Five-layer iot and fog computing framework towards digital twinning of battery management systems for e-transportation. In *4th International Conference on Smart Grid and Renewable Energy, SGRE 2024 - Proceedings*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/SGRE59715.2024.10428786

Kinaci, O. K. (2023). Ship digital twin architecture for optimizing sailing automation. In *Ocean Engineering, 275*. Pergamon, Article 114128. https://doi.org/10.1016/J.OCEANENG.2023.114128

Kosova, F., & Unver, H. O. (2023). A digital twin framework for aircraft hydraulic systems failure detection using machine learning techniques. In *, 237. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* (pp. 1563–1580). SAGE Publications Ltd. https://doi.org/10.1177/09544062221132697/ASSET/934AD7DE-1FA7-4E8F-93AE-645D2DFD7072/ASSETS/IMAGES/LARGE/10.1177_09544062221132697-FIG15.JPG.

Kumar, N., & Ali, R. (2024). Blockchain-enabled authentication framework for maritime transportation system empowered by 6G-IoT. In *Computer Networks, 244*. Elsevier, Article 110353. https://doi.org/10.1016/J.COMNET.2024.110353

Lee, C. K. M., Lv, Y., Ng, K. K. H., Ho, W., & Choy, K. L. (2018). Design and application of internet of things-based warehouse management system for smart logistics. *International Journal of Production Research, 56*(8), 2753–2768. https://doi.org/10.1080/00207543.2017.1394592;PAGE:STRING:ARTICLE/CHAPTER

Levshun, D., Kotenko, I., & Chechulin, A. (2021). The application of the methodology for secure cyber–physical systems design to improve the semi-natural model of the railway infrastructure. *Microprocessors and Microsystems, 87*, Article 103482. https://doi.org/10.1016/J.MICPRO.2020.103482

Liao, X., Wang, Z., Zhao, X., Han, K., Tiwari, P., Barth, M. J., & Wu, G. (2022). Cooperative ramp merging design and field implementation: A digital twin approach based on vehicle-to-cloud communication. In *, 23. IEEE Transactions on Intelligent Transportation Systems* (pp. 4490–4500). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/TITS.2020.3045123

Liu, C., Liu, R., & Liu, X. (2026). A digital twin framework for intelligent electric vehicle charging optimization in smart manufacturing systems. In *Applied Energy, 406*. Elsevier, Article 127281. https://doi.org/10.1016/J.APENERGY.2025.127281

Liu, Y., Pan, S., & Ballot, E. (2025). Federated digital twins platform for smart city logistics: A knowledge-driven approach. *International Journal of Production Economics, 290*, Article 109772. https://doi.org/10.1016/J.IJPE.2025.109772

Lopez-Martin, M., Carro, B., & Sanchez-Esguevillas, A. (2019). Neural network architecture based on gradient boosting for IoT traffic prediction. In *, 100. Future Generation Computer Systems* (pp. 656–673). https://doi.org/10.1016/J.FUTURE.2019.05.060

Luo, X. G., Zhang, H. B., Zhang, Z. L., Yu, Y., & Li, K. (2019). A new framework of intelligent public transportation system based on the internet of things. In *IEEE Access, 7* pp. 55290–55304). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ACCESS.2019.2913288

Marinkovic, M., Galka, S. and Meißner, S. (2023), "Digital twins for internal transport systems: Use cases, functions, and system architecture", doi: 10.24251/HICSS.2023.147.

Marsden, G., & Docherty, I. (2021). Mega-disruptions and policy change: Lessons from the mobility sector in response to the Covid-19 pandemic in the UK. *Transport Policy, 110*, 86–97. https://doi.org/10.1016/J.TRANPOL.2021.05.015. Pergamon.

Mejjaouli, S., & Alnourani, S. (2024). Electric vehicles charging infrastructure framework using internet of things. *Journal of Cleaner Production, 480*, Article 144056. https://doi.org/10.1016/J.JCLEPRO.2024.144056

Naik, R., Naik, S., Salunke, M., Chavadi, C., & Jadhav, B. (2024). Design and implementation of IoT based automated railway gate crossing system. In *Proceedings of NKCon 2024 - 3rd Edition of IEEE NKSS's Flagship International Conference: Digital Transformation: Unleashing the Power of Information*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/NKCON62728.2024.10775209

Nasr, E., Kfoury, E., & Khoury, D. (2016). An IoT approach to vehicle accident detection, reporting, and navigation. In *2016 IEEE International Multidisciplinary Conference on Engineering Technology, IMCET 2016* (pp. 231–236). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/IMCET.2016.7777457

Nguyen, V. N., Chung, N., Balaji, G. N., Rudzki, K., & Hoang, A. T. (2025). Internet of things-driven approach integrated with explainable machine learning models for ship fuel consumption prediction. *Alexandria Engineering Journal, 118*, 664–680. https://doi.org/10.1016/J.AEJ.2025.01.067

Pang, T. Y., Pelaez Restrepo, J. D., Cheng, C. T., Yasin, A., Lim, H., & Miletic, M. (2021). Developing a digital twin and digital thread framework for an 'industry 4.0' shipyard. *Applied Sciences (Switzerland), 11*(3), 1–23. https://doi.org/10.3390/app11031097

Puri, B., Solanki, V. K., Kaur, M., & Puri, V. (2024). A hybrid ML-Digital Twin approach for urban traffic optimization. In *2024 IEEE Region 10 Symposium, TENSYMP 2024*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/TENSYMP61132.2024.10752187

Qu, Q., Shen, Y., Yang, M., & Zhang, R. (2024). Towards efficient traffic crash detection based on macro and micro data fusion on expressways: A digital twin framework. In *, 18*. *IET Intelligent Transport Systems* (pp. 2725–2743). John Wiley & Sons, Ltd. https://doi.org/10.1049/ITR2.12498.

Ramal, P. J., & Anbalagan, E. (2024). Cyber-physical digital twin for smart city transportation systems: A real-time simulation and optimization framework. In *International Conference on Distributed Systems, Computer Networks and Cybersecurity, ICDSCNC 2024*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ICDSCNC62492.2024.10941474

Ren, Q., Man, K. L., Li, M., Gao, B., & Ma, J. (2019). Intelligent design and implementation of blockchain and Internet of things–based traffic system. *International Journal of Distributed Sensor Networks, 15*(8). https://doi.org/10.1177/1550147719870653/ASSET/05A5C392-0869-4B57-ABF4-AFA0C83AD3E9/ASSETS/IMAGES/LARGE/10.1177_1550147719870653-FIG9.JPG

Roopini, G., Nagraj Rao, P. P., Dankan Gowda, V., Ingole, B. S., Pandey, S., & Chandra, S. H. (2024). AI-driven IoT framework for vehicle accident avoidance and detection with cloud integrated energy efficient solutions. In *2024 1st International Conference on Innovations in Communications, Electrical and Computer Engineering, ICICEC 2024*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ICICEC62498.2024.10808555

Sahay, R., Meng, W., Estay, D. A. S., Jensen, C. D., & Barfod, M. B. (2019). CyberShip-IoT: A dynamic and adaptive SDN-based security policy enforcement framework for ships. In *, 100*. *Future Generation Computer Systems* (pp. 736–750). https://doi.org/10.1016/J.FUTURE.2019.05.049

Saini, M., Adebayo, S. O., & Arora, V. (2024). IoT-Fog-based framework to prevent vehicle–road accidents caused by self-visual distracted drivers. In *Multimedia Tools and Applications, 83* pp. 90133–90151). Springer. https://doi.org/10.1007/S11042-024-19050-W/TABLES/2

Salierno, G., Leonardi, L., & Cabri, G. (2024). A big data architecture for digital twin creation of railway signals based on synthetic data. *IEEE Open Journal of Intelligent Transportation Systems, 5*, 342–359. https://doi.org/10.1109/OJITS.2024.3412820

Salin, H. (2025). A comparative analysis of anonymous and non-anonymous authorization architectures for iot environments in cooperative intelligent transport systems". *International Conference on Internet of Things, Big Data and Security, IoTBDS - Proceedings* (pp. 281–288). Science and Technology Publications, Lda. https://doi.org/10.5220/0013324700003944

Samak, T. V., Samak, C. V., & Krovi, V. N. (2024a). Metaverse for safer roadways: An immersive digital twin framework for exploring human-autonomy coexistence in urban transportation systems. In *2024 IEEE Conference on Telepresence* (pp. 160–165). IEEE. https://doi.org/10.1109/TELEPRESENCE63209.2024.10841549.

Samak, T. V., Samak, C. V., & Krovi, V. N. (2024b). Towards validation of autonomous vehicles across scales using an integrated digital twin framework. In *IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM* (pp. 1068–1075). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/AIM55361.2024.10637205.

Sampigethaya, K., & Poovendran, R. (2012). Cyber-physical system framework for future aircraft and air traffic control. In *IEEE Aerospace Conference Proceedings*. https://doi.org/10.1109/AERO.2012.6187151

Sanjana, D. N., Soumya, V., Sneha, L., Shama, G., & Pooja, M. R. (2024). An IoT framework for effective railway looping and obstacles detection. In *7th International Conference on Inventive Computation Technologies, ICICT 2024* (pp. 1814–1818). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ICICT60155.2024.10544410

Shahriar, M. S., Subramaniam, S., Matsuura, M., Hasegawa, H., & Lin, S. C. (2024). Digital twin enabled data-driven approach for traffic efficiency and software-defined vehicular network optimization. In *IEEE Vehicular Technology Conference*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/VTC2024-FALL63153.2024.10757450

Shariatpour, F., Behzadfar, M., & Jalilisadrabad, S. (2025). A socio-technical framework for urban digital twins: Tehran in a global comparison. *Sustainable Cities and Society, 134*, Article 106905. https://doi.org/10.1016/J.SCS.2025.106905

Shin, H., Oh, S., Isah, A., Aliyu, I., Park, J., & Kim, J. (2023). Network traffic prediction model in a data-driven Digital Twin network architecture. In *Electronics, 12* p. 3957). Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/ELECTRONICS12183957. *2023Page*Vol. 12 No. 18, p. 3957.

Sun, H., Chen, Y., Wang, L., Song, J., Sun, J., & Liu, X. (2022). Design of smart street light management system based on Internet of Things. In *, 2022*. *IEEE Advanced Information Technology, Electronic and Automation Control Conference (IAEAC)* (pp. 998–1003). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/IAEAC54830.2022.9930048.

Sun, P., Guo, Z., Sun, P., & Guo, Z. (2022). A design of high-speed railway internet of things security architecture. *SPIE, 12345*, Article 1234513. https://doi.org/10.1117/12.2650103

Tan, C., Li, X., Gao, L., Luan, T. H., Qu, Y., Xiang, Y., & Lu, R. (2023). Digital Twin Enabled Remote Data Sharing for Internet of Vehicles: System and Incentive Design. In *IEEE Transactions on Vehicular Technology, 72* pp. 13474–13489). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/TVT.2023.3275591

Tang, F., Fadlullah, Z. M., Mao, B., & Kato, N. (2018). An Intelligent traffic load prediction-based adaptive channel assignment algorithm in SDN-IoT: A deep learning approach. *IEEE Internet of Things Journal, 5*(6), 5141–5154. https://doi.org/10.1109/JIOT.2018.2838574

Tang, Z., Ling, L., Zhang, T., Hu, Y., Wang, K., & Zhai, W. (2024). Towards digital twin trains: Implementing a cloud-based framework for railway vehicle dynamics simulation. *International Journal of Rail Transportation*. https://doi.org/10.1080/23248378.2024.2355578;WEBSITE:WEBSITE:TFOPB;PAGEGROUP:STRING:PUBLICATION

Tasgaonkar, P. P., Dev, R., Pradeep, G., Garg, K., Dev Garg, R., & Garg, P. K. (2024). An IoT-based framework of vehicle accident detection for smart city. *IETE Journal of Research, 70*(5), 4744–4757. https://doi.org/10.1080/03772063.2023.2239757

Tiwari, D., Bhati, B. S., Nagpal, B., Sankhwar, S., & Al-Turjman, F. (2021). An enhanced intelligent model: To protect marine IoT sensor environment using ensemble machine learning approach. *Ocean Engineering, 242*, Article 110180. https://doi.org/10.1016/J.OCEANENG.2021.110180. Pergamon.

Tsitsilonis, K. M., Theotokatos, G., Patil, C., & Coraddu, A. (2023). Health assessment framework of marine engines enabled by digital twins. *International Journal of Engine Research, 24*(7), 3264–3281. https://doi.org/10.1177/14680874221146835/ASSET/A3505722-1E3E-4680-88CC-E32DA6978B89/ASSETS/IMAGES/LARGE/10.1177_14680874221146835-FIG10.JPG

Vanitha, U., Snegha, C., Gupta, S., & Sowmya, S. (2023). Design and implementation of IOT based real time traffic monitoring system. In *2023 International Conference on System, Computation, Automation and Networking, ICSCAN 2023*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ICSCAN58655.2023.10394760

Vasilikis, N., Geertsma, R., & Coraddu, A. (2023). A digital twin approach for maritime carbon intensity evaluation accounting for operational and environmental uncertainty. *Ocean Engineering, 288*, Article 115927. https://doi.org/10.1016/J.OCEANENG.2023.115927. Pergamon.

Wang, C., Peng, Y., Wu, J., Liu, L., Mumtaz, S., Dong, M., & Guizani, M. (2024). Deterministic scheduling and reliable routing for smart ocean services in maritime internet of things: A cross-layer approach. *IEEE Transactions on Services Computing*. https://doi.org/10.1109/TSC.2024.3442471

Wang, K., Xu, H., Wang, H., Qiu, R., Hu, Q., & Liu, X. (2024). Digital twin-driven safety management and decision support approach for port operations and logistics. *Frontiers in Marine Science, 11*, Article 1455522. https://doi.org/10.3389/FMARS.2024.1455522/BIBTEX. Frontiers Media SA.

Wang, Z., & Lin, B. (2022). A digital twin enabled maritime networking architecture. In *IEEE Vehicular Technology Conference*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/VTC2022-SPRING54318.2022.9860929. Vol. 2022-June.

Wang, Z., Zheng, O., Li, L., Abdel-Aty, M., Cruz-Neira, C., & Islam, Z. (2023). Towards next generation of pedestrian and connected vehicle in-the-loop research: A digital twin co-simulation framework. *IEEE Transactions on Intelligent Vehicles, 8*(4), 2674–2683. https://doi.org/10.1109/TIV.2023.3250353. No.

Xia, H., Liu, Z., Efremochkina, M., Liu, X., & Lin, C. (2022). Study on city digital twin technologies for sustainable smart city design: A review and bibliometric analysis of geographic information system and building information modeling integration. *Sustainable Cities and Society, 84*, Article 104009. https://doi.org/10.1016/J.SCS.2022.104009

Xie, Y., Li, S., Lu, L., Pan, Y., & Iida, F. (2026). A digital twin-based approach for dynamic traffic-aware routing and charging of electric vehicles. In *, 312*. *Expert Systems with Applications*, Article 131380. https://doi.org/10.1016/J.ESWA.2026.131380

Xiong, H., Wang, Z., Wu, G., & Pan, Y. (2022). Design and implementation of digital twin-assisted simulation method for autonomous vehicle in car-following scenario. *Journal of Sensors, 2022*(1), Article 4879490. https://doi.org/10.1155/2022/4879490

Xiong, Y., Dong, S., Shi, F., & Zhang, H. (2024). Advancing IoT anomalous traffic detection through arithmetic coding in transformer-based architectures. In *20th International Wireless Communications and Mobile Computing Conference, IWCMC 2024* (pp. 174–179). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/IWCMC61514.2024.10592532

Xu, L., Mak, S., Schoepf, S., Ostroumov, M., & Brintrup, A. (2025). Multi-agent digital twinning for collaborative logistics: Framework and implementation. *Journal of Industrial Information Integration, 45*, Article 100799. https://doi.org/10.1016/J.JII.2025.100799

Yang, B., Fan, F. C., Ni, R. R., Wang, H., Jafaripournimchahi, A., & Hu, H. Y. (2024). A multi-task learning network with a collision-aware graph transformer for traffic-agents trajectory prediction. *IEEE Transactions on Intelligent Transportation Systems, 25*(7), 6677–6690. https://doi.org/10.1109/TITS.2023.3345296

Yang, J., Zhang, J., & Wang, H. (2021). Urban traffic control in software defined internet of things via a multi-agent deep reinforcement learning approach. *IEEE Transactions on Intelligent Transportation Systems, 22*(6), 3742–3754. https://doi.org/10.1109/TITS.2020.3023788

Yang, T., Chen, J., & Zhang, N. (2020). AI-empowered maritime internet of things: A parallel-network-driven approach. In *IEEE Network, 34* pp. 54–59). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/MNET.011.2000020

Yang, T., Jiang, Z., Liu, P., Yang, Q., & Wang, W. (2023). A traffic anomaly detection approach based on unsupervised learning for industrial cyber–physical system. *Knowledge-Based Systems, 279*, Article 110949. https://doi.org/10.1016/J.KNOSYS.2023.110949

Yang, Y., Liu, X., Yin, W., Guo, Y., & Bao, J. (2024). Research on digital twin architecture of ship maneuverability simulation for system model. *Journal of Physics: Conference*

*Series, 2816*(1), Article 012021. https://doi.org/10.1088/1742-6596/2816/1/012021

Yigit, Y., Maglaras, L., Buchanan, W. J., Canberk, B., Shin, H., & Duong, T. Q. (2024). AI-enhanced digital twin framework for cyber-resilient 6G internet-of-vehicles networks. *IEEE Internet of Things Journal*. https://doi.org/10.1109/JIOT.2024.3455089, 1–1.

Yu, J. U., Cho, K. S., Park, S. W., & Son, S. Y. (2024). Digital twin system framework and implementation for grid-integrated electric vehicles. In *Energies 2024, 17* p. 6249). Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/EN17246249. *Page*.

Yue, Q., Jiang, K., & Liu, C. (2021). Design of obstacle avoidance path planning system for intelligent vehicles based on internet of things. In *Proceedings - 2021 International Conference of Social Computing and Digital Economy, ICSCDE 2021* (pp. 142–147). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ICSCDE54196.2021.00041

Zhang, H., Yue, X., Tian, K., Li, S., Wu, K., Li, Z., Lord, D., et al. (2025). Virtual roads, smarter safety: A digital twin framework for mixed autonomous traffic safety analysis. *IEEE Internet of Things Journal*. https://doi.org/10.1109/JIOT.2025.3637688

Zhang, W., Deng, J., Liu, X., & Lu, J. (2024). FlightTwin:A generalized digital twin accompanying flight framework for fixed-wing aircraft. *IEEE Access*. Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ACCESS.2024.3454197

Zhang, X., Han, D., Zhang, X., & Fang, L. (2023). Design and application of intelligent transportation multi-source data collaboration framework based on Digital Twins. In *Applied Sciences 2023, 13* p. 1923). Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/APP13031923. *Page*Vol. 13 No. 3, p. 1923.

Zhao, X., He, H., Li, J., Wei, Z., Huang, R., & Yue, H. (2025). Muti-physics constrained PEV charging management for solar PV penetrated energy-transportation Nexus: A novel DRL-based approach combining a cyber-physical system. *Journal of Energy Storage, 106*, Article 114732. https://doi.org/10.1016/J.EST.2024.114732

Zhou, S., Dumss, S., Nowak, R., Riegler, R., Kugu, O., Krammer, M., & Grafinger, M. (2022). A Conceptual Model-based Digital Twin platform for holistic large-scale railway infrastructure systems. In *, 109. Procedia CIRP* (pp. 362–367). Elsevier. https://doi.org/10.1016/J.PROCIR.2022.05.263.

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# A Standardised Digital Twin design framework for transport system decarbonisation

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