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Digital Road Operator Information and Data Strategy (DROIDS)

State of the Art of Digital Twins for Road Infrastructure

Deliverables D2.1 and D3.1 Version 1.1

19th of February 2025

DRAFT deliverable

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CEDR Call 2022 Data: Maintaining and sharing the digital road infrastructure

Digital Road Operator Information and Data Strategy (DROIDS)

D2.1 State of the Art of Digital Twins for Road Infrastructure
D3.1 Digital Twin State of the Art – Technical Aspects

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Executive summary

The deliverable describes the state of the art of road operation related digital twins from both technical, operational and organisational points of view. The findings are based on desktop analyses, road operator and other stakeholder expert interviews, and a workshop targeting especially the road operators.

Due to the ambiguities related to terminology, the deliverable first sets the scene by defining the term digital twin for road operators as well as the digital model and digital shadow as specific less mature versions of the digital twin.

Next, the deliverable reviews the digital twins' technological maturity and stage of development covering the data, the digital twin architecture, services, software, and other technologies.

The review lays the groundwork for understanding Digital Twins (DTs) by exploring the core technologies that bring them to life. It highlights the integration of Internet of Things (IoT) sensors, Artificial Intelligence (AI) and machine learning, cloud platforms, and 3D modeling. These enabling technologies play a crucial role in the creation of virtual counterparts for physical systems, facilitating real-time monitoring, optimization, and predictive maintenance capabilities.

The review goes beyond technology to emphasize the critical role of high-quality data in maximizing DT value. Early data acquisition methods were manual and limited, hindering the effectiveness of DTs. Fortunately, advancements like sensor technology have revolutionized data collection, enabling comprehensive and real-time data streams. This review details the key data requirements for DTs, emphasizing the importance of complete, up-to-date, and adaptable data. It introduces the concept of DTD, encompassing data from both the physical world (sensor readings) and the virtual world (simulations). Additionally, it outlines seven key principles for effective DTD management, ensuring optimal data utilization.

To leverage this valuable data, however, a robust Digital Twin architecture is required. Digital Twin architecture lacks a universal standard, with specific components and arrangements depending on the use case. However, common elements exist across all architectures:

- Physical Layer: The real-world entity and its data collection sensors.
- Communication Layer: Bridges the physical and digital worlds, transmitting data.
- Digital Twin Layer: A virtual replica enabling monitoring, analysis, and optimization.

The maturity of Digital Twins also varies. Most reside in the lower levels (0-3), focusing on static data and design optimization. Integration with real-time data streams remains a challenge due to data management complexities and potential issues like sensor malfunctions. Future advancements are expected to push Digital Twins towards higher maturity levels with features like two-way data interaction and even autonomous operations.

As Digital Twins evolve and integrate real-time data streams, the importance of standardized practices for DT functionality becomes even more critical. While no road infrastructure specific DT standards exist, various existing standards related to interoperability, data management, communication, asset management, IoT, and 3D modeling can be leveraged. Examples include ISO/IEC standards for data interchange, communication protocols, and cloud computing. A more detailed discussion of standards and specifications is provided in a separate deliverable (D3.2).

Finally, the analysis explores the diverse data types employed in DTs. The specific data selection is crucial and depends on the DT's intended purpose. This highlights the need for a tailored approach to DTD management based on the specific goals of each DT application

Specific attention is given to Building Information Modelling (BIM) and Asset Information Modelling (AIM) currently widely used by road operators and their contractors. Building Information Modeling (BIM) and Asset Information Modeling (AIM) as foundational technologies for Digital Twins (DTs). A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition. Project Information Model (PIM) is the information model developed during the design and construction phase of a project. Upon project completion, the PIM transitions into an Asset Information Model (AIM) for ongoing asset management. AIM extends BIM principles beyond construction, providing a comprehensive digital representation of an asset throughout its lifecycle. This includes design data, construction details, operational parameters, maintenance schedules, and other relevant information. The successful creation of an AIM requires careful consideration of factors like Level of Development (LOD), Level of Information (LOI), and Level of Accuracy (LOA) of model elements. To further clarify the distinctions between DTs and related technologies, the report includes a comparison of key features for BIM, AIM, and DTs.

The road operator applications of digital twins are discussed starting with their use in the provision of road operator decision support. Real-time accurate data on road, traffic and environmental conditions provide for appropriate road operator decisions in planning, construction, maintenance, network operation and management as well as for serving the road users and various stakeholders' mobility and other services. Road operators two main responsibilities of road infrastructure and traffic management were reviewed more closely. For road infrastructure, especially pavement, bridges and tunnels have been for interest when developing digital twins to support operational lifecycle of the infrastructure. For traffic management, digital twins could contain exchange of data such as road transport network, road transport, public transport and influencing factors (such as weather).

The analyses also address the current status of road operators' digital models, shadows and twins with regard to road infrastructure, its assets, and traffic conditions for traffic management by selected road operators. Road operators are currently in the early stages of adopting digital twins. They're using existing systems like asset management and Geographic Information Systems (GIS) to build a foundation. However, their digital representations are still basic and lack real-time data integration.

The desired future state involves using digital twins for various tasks like predictive maintenance and traffic management. This requires real-time data from vehicles, standardized data formats, and powerful analytics tools to turn data into actionable insights. There are also challenges of data availability and collaboration across Europe. Road operators expect it to take 3-5 years to fully implement and benefit from this technology.

Furthermore, it describes the future opportunities provided by digital shadows and twins for various services such as CCAM (Connected, Cooperative and Automated Mobility). The study also identified several challenges already identified in the development, maintenance and operation of digital models, shadows, and twins. Digital twins for Predictive Infrastructure Management, C-ITS applications and to facilitate CCAM were identified as the most promising and desirable applications. But in order to develop and deploy those future services, several challenges need to be overcome first, predominantly in the realm of data (quality, timeliness, coverage, standardization) and organisational aspects.

Finally, the deliverable provides conclusions with regard to the topics listed above and answers research question regarding digital twin state of the art. The deliverable serves as a basis for future work to be carried out in DROIDS in order to clarify the road operator's role in digital twins, the data items under road operator responsibility, the trust and security aspects, and the recommended data strategy for the digital road operators in Europe.

DROIDS project description

DROIDS is a CEDR Transnational Road Research Programme Call 2022 project aiming to provide the road operators, including European National Road Authorities (NRAs), increased knowledge and support to reap optimal benefits from digitalisation as they evolve to become digital road operators operating the physical, operational and digital road infrastructures. As digital road operators, the road operators will provide better road user services while improving road transport's safety, efficiency and sustainability.

The background of the research is the ongoing transformation of the road operators to digital road operators responsible for operating both the physical and digital road infrastructure. Some road operators have already developed their processes and services accordingly, while some are still reflecting on the developments and discussing the transformation.

First the project will look at the evolving roles of the road operators as they transform themselves into digital road operators. Special focus is given to new roles brought by digital road operation while changes foreseen about the existing roles are addressed. DROIDS pays specific attention to the role evolution in different CEDR member countries with currently varying roles and digital maturity.

Secondly, the project studies the evolution of digital twins from road data banks to comprehensive real-time digital twins of the road transport system, including the infrastructures, traffic, land use, road environment etc. Here, the integration of the digital twins with the processes in the road operator's core business and tasks is assessed in a thorough manner.

Thirdly, trust has been identified as the key attribute for road operator originated data/information concerning its use by private sector stakeholders such as vehicle manufacturers and service providers. Thereby DROIDS also highlights the issues related to ensuring trust and security in the maintenance, sharing, and use of the digital road infrastructure.

Finally, the work of DROIDS concludes in the production of an overarching data strategy for the physical and digital road operators taking on board the results from DROIDS and other ongoing projects (such as CEDR Data Call 2022 PRESORT and TIARA projects).

Expected achievements and benefits to road operators:

- DROIDS offers road operators a clearer understanding of the prerequisites and roles associated with becoming a digital road operator, vital for road operators considering this transition.
- It emphasizes the crucial step for road operators: adapting processes to maximize benefits from digital tools.
- While DROIDS provides insights for process adaptation, the actual implementation must align with each road operator’s unique digital and organizational maturity.
- The project results will outline specific recommendations regarding actions and roles tied to HD maps, electronic traffic, and transport regulations, aiding road operators in decision-making

Glossary

ADS	Automated Driving Systems
AIM	Asset Information Modeling
BIM	Building Information Modeling
C-ITS	Cooperative Intelligent Transport Systems
CEDR	Conference of European Directors of Roads
DIM	Deconstruction information model
DROIDS	Digital Road Operator Information and Data Strategy project funded by CEDR.
DT	Digital Twin
EC	European Commission
EU	European Union
GNSS	Global Navigation Satellite System
IoT	Internet of Things
NRA	National Road Authority. NRA is often used in Europe. This study uses a term “road operator” that also includes NRAs.
ODD	Operational Design Domain
OTL	Object Type Libraries
PIARC	World Road Association
PIM	Project Information Model
SOTA	State-of-the-Art
TRL	Technology Readiness Levels

Content

Tables

Figures

1 Introduction

Road operators, including the National Road Authorities (NRAs) in Europe, are pursuing benefits from digitalisation as they evolve to become digital road operators with responsibilities, amongst others, to operate the physical, operational and digital road infrastructures. As digital road operators, road operators should be able to provide better road user services while improving road transport's safety, efficiency and sustainability. In order to do so, increased knowledge and experience are necessary among the full spectrum of digital possibilities. AIM, BIM, and Digital Twins are some of the instruments that can help to reap the benefits of being a digital road operator. This document provides an overview of the current state of the art in this field so that road operators can benefit from the collective knowledge and experience that already exists to either start becoming digital road operators or further accelerate and increase their digital savviness.

In general, the aforementioned tools, with digital twins currently in the global spotlight as one of the most hyped trends, could allow road operators to either improve their current tasks in terms of (cost) efficiency or quality or even pursue or develop new tasks that were previously unattainable. These new tasks are by definition not part of the road operators' portfolio or responsibilities but could be seen in the light of opportunities to achieve certain (policy) goals.

For example, digital twins can support and enhance traffic management by providing the human operator working in a traffic management centre with a visualized real-time environment to monitor and control traffic flow. The operator receives real-time data on the traffic flow situation and may change the variable message sign display input depending on the traffic situation. Digital twins may also unlock the potential to support or facilitate automated driving systems (ADS) which in turn can have a positive effect on traffic safety, throughput, and associated emissions.

The term "road operator" is used in this deliverable to describe any public or private entity that is responsible for the planning, maintenance and management of the road, including management of traffic flows. The term "road operator" therefore also covers road authorities that are public authorities responsible for similar tasks. The term has been here adapted from the European Commission delegated regulation (EU) 2022/670 of real-time traffic information services (EC 2022). The term National Road Authority (NRA) is often used in Europe to describe a Member State national authority that is responsible for the previously mentioned tasks; in this study, the term road operator is also used to cover NRAs.

The scope of the study and DROIDS project limits to the *TEN-T road network, motorways and national highways and roads*, which are the core business for the road operators. Although it is recognised that many of the use cases also concern and extend to cities. Also, naturally all modes used on highways are relevant, including, e.g. bicyclists and pedestrians, which may interact in different road traffic scenarios.

Digital twins will support national road authorities and other road operators' tasks by (Kulmala 2021):

- enhancing the effectiveness of planners, builders, users, and maintainers in all parts of the lifecycle of road network infrastructure and operations,
- providing a reliable digital copy of the state and properties of the road infrastructure throughout its lifespan,

- facilitating the real-time situational picture and reporting of the infrastructure level of service, condition, and use,
- enabling well-timed and informed maintenance of the infrastructure,
- facilitating the prediction of incidents and disturbances on the road network, and the preparedness of the road operator,
- improving risk management, and
- improving the level of service offered to road users

These impacts above were estimated to result in the following effects on the effectiveness of operations financed by the Finnish Transport Infrastructure Agency in the first phase (digital model) only (Kulmala 2021). Note that BIM is already widely utilised in FTIA, and thereby the figures for road planning and building are quite low:

- road and winter maintenance 0.5 – 2 %,
- road planning 0.2 – 0.5 %,
- road building 0.3 – 0.6 %,
- asset management 1 – 4 %, and
- traffic management 0.1 – 0.2 %.

The **Scope of the research** is extracted from the expected results of DROIDS Work Package 2 “NRA roles in digital twins” and Work Package 3 “Digital Twin application evolution” as presented in the Table 1 below. The two deliverables D2.1 and D3.1 have been merged as one deliverable, i.e., this one.

Table 1 DROIDS project Work Package 2‘s expected end results and the scope of this deliverable. The term NRA refers to the National Road Authority, which of the European road authorities often use and was used also in the CEDR funding call of this project: elsewhere in this study the term “road operator” is used instead.

DROIDS WP2 expected end result	WP2	WP3	Deliverables
ER1 An analysis of and guidelines for, the role of NRAs in an ecosystem of digital twins for road infrastructure, including:	(X)	(X)	
ER1.1 The state of the art	X	X	This deliverable (D2.1 & D3.1)
ER1.2 What information should NRAs maintain and share for future use	X		
ER1.3 How the information should be maintained and made available for maintenance contractors, map producers and road users throughout the lifecycle of the road infrastructure	X	X	

This deliverable’s results provide the basis for the next phases and work packages knowledge creation in the DROIDS project, i.e., input for further research and analysis. The decomposed research questions for this deliverable can be viewed in Table 2 and Table 3 below.

Table 2 DROIDS project Work Package 2 research questions and related research questions which of the latter are addressed in this state-of-the-art study chapters. The term NRA refers to the National Road Authority, which of the European road authorities often use and was used also in the CEDR funding call of this project: elsewhere in this study the term "road operator" is used instead.

DROIDS WP2 Research Question (answered in Deliverable 2.2)	**Related Research Questions answered in this Deliverable 2.1 State of the Art of Digital Twins for Road Infrastructure:**	**Deliverable Chapter**
(RQ1) What role the NRAs should take in the larger ecosystem of digital twins for road infrastructures, and how they should fulfil this role?	1. What is the state of the art digital twin definition for road transport and operator needs? 2. State of the art: What actors are related to digital twins? 3. State of the art: What potential benefits or challenges do digital twins have for road operators?	Chapters 3–6
(RQ4) How much responsibility should NRAs take for establishing and maintaining base data sets supporting automated driving such as High-Definition (HD) Maps, compared to the role of commercial Map Providers?	4. What state-of-the-art data is needed in digital twins?	Chapter 4
(RQ5) What services and data is expected to be shared from NRAs?	5. What state-of-the-art services related to digital twins are needed and available (or unavailable) at the moment?	Chapter 4
(RQ6) How do these different standards and specifications serve the future digital operator role of NRAs? (This is studied also more in other DROIDS deliverables)	6. What state-of-the-art standards and specifications are available for digital twins?	Chapter 4
(RQ10) How should the information be maintained throughout the life cycle of the road infrastructure, given the many different stakeholders involved in the maintenance of the physical infrastructure?	7. What are the stages of the road infrastructure life cycle and how can state-of-the-art digital twin help to manage them? 8. What stakeholders are involved in the information life cycle of road infrastructure?	Chapter 5

Table 3. DROIDS project Work Package 3 research questions and related research questions which of the latter are addressed in this state-of-the-art study chapters. The term NRA refers to the National Road Authority, which of the European road authorities often use and was used also in the CEDR funding call of this project: elsewhere in this study the term "road operator" is used instead.

DROIDS WP3 Research Question (answered in Deliverable 2.2)	Related Research Questions in Deliverable 3.1 Digital twin State of the Art – Technical aspects	Deliverable Chapter
(RQ2) What kind of digital representations (what kind of digital twins) should be maintained by NRAs? What will be the requirements for model-based AIM?	9. What kinds of digital twins exist? (Complementing findings of literature research) 9.1 What is the detail of data (complexity) now? 9.2 What is the objective of using these Digital Twins?	Chapter 3 Chapter 4
(RQ3) Will NRAs need to extend the level of geometric and topological complexity for this data in order to prepare for model-based AIM and connected/automated driving?	10. What is the desired detail/complexity of data for AIM?	Chapter 4

Chapter 2 of this deliverable explains the methodology of the study and project as well as the research methods used. Chapter 3 introduces definitions and framework of digital twin, actors and roles as well as technology maturity. Chapter 4 introduces technologies utilised by digital twins, such as data, architectures, services and software as well as associated technologies of Building Information Modelling (BIM) and Asset Information Modelling (AIM). Chapter 5 introduces road operator applications for digital twins – first a general view of decision support and then details of road infrastructure and traffic management. These are supported by an identification of state-of-the-art European and global digital twin initiatives and projects. Chapter 6 discusses digital twin challenges and future opportunities, also presenting the digital twins' desired state for selected road operators and the difference between current and desired states. Chapter 7 finally concludes the study findings.

2 Methodology

The study methodology

The study's initial research questions and expected results were derived from the CEDR funding call of Data Call 2022, which were then formalised in the DROIDS project proposal's project plan. The scope of the study was limited in the CEDR Call and DROIDS project proposal to a qualitative assessment of digital twin state-of-the-art. The research questions were iteratively reviewed together with the project team as the research work progressed. During the research question reviews it was evaluated what background information and knowledge would be required from the study that would later benefit the next deliverables and stages of the project, and therefore, the final results of the project, i.e., the National Road Authorities Data strategy.

The DROIDS project has also been working with digital twin taxonomy, the first development cycle of which was synchronized with this deliverable. The aim of the taxonomy development was to ensure the use of common definitions of key concepts and terms, such as digital twin, and language throughout the project. The taxonomy was reviewed by external partners of CEDR road authorities and the DROIDS Advisory Group. The latter included public authorities, universities, research centres and private industry members such as service providers.

Methods

Methods of the study included a literature review, interviews, and a workshop as well as project team internal collaboration in meetings. The results from existing and prior work conducted in CEDR projects were considered in desktop research as a starting point to enable the work carried out now and in the future work of the DROIDS Work Packages. The close liaison with CEDR projects PRESORT and TIARA was very useful in ensuring the state-of-the-art information acquired in those.

Project Methodology

The DROIDS project utilises the Digital Transformation Framework (DTF) structured approach that supports the design, development, planning and management of necessary organisational transitions. The DTF adopted for the DROIDS project is illustrated in Figure 1. Within the DTF, it is important to ensure vertical and horizontal alignment between the different columns and layers.

Vertical Alignment: This refers to the strategic alignment between requirements, gaps, and actions to fill these gaps, which form the three phases of the project. It follows a top-to-bottom approach, translating overall goals into relevant business cases and roadmaps. The information gained in one layer supports the content creation in the layer below, ensuring a consistent way of achieving the business cases, overarching strategy, and implementation roadmap.

Horizontal Alignment: This ensures completeness by not focusing only on technology or stakeholders but also considering other important organizational factors. It ensures alignment between stakeholders, core business, internal processes, and IT for an organization. This alignment produces the expected outputs holistically and is taken into account in the individual work packages. It pays special attention to alignment with key stakeholders.

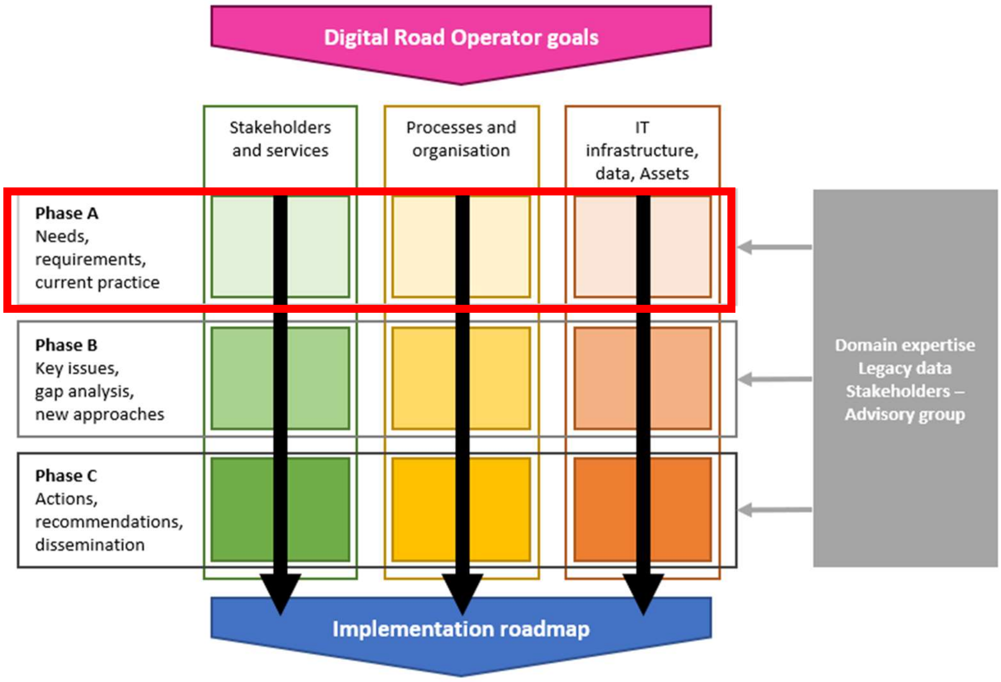

Figure 1 DROIDS project's Framework

This Work Package 2 and Work Package 3 deliverables 2.1 and 3.1 are part of the first horizontal DTF Phase A that determines needs, requirements, and current practices as shown in the Figure 1.

Workshop and questionnaire methodology

To gather information about current practices, needs, and requirements of the road operators regarding digital twins (in alignment with Phase A of the DTF), we engaged with stakeholders through workshops, interviews, and questionnaires.

On 15th Jan 2024, an online workshop was carried out in collaboration with the PRESORT project (ImPRoving thE uSe Of third-paRTy data by road operators, funded by CEDR) to gather inputs from the National Road Authorities. During the workshop, a breakout room discussion was carried out with registered participants from road operators to capture the current and desired state of digital twin and Asset information modelling (AIM) within their organizations. The session was conducted in an interactive manner where participants were asked to work together on an online tool called "Conceptboard". This platform facilitated seamless contributions, regardless of group size.

For stakeholders unable to attend the workshop, a questionnaire was sent after the workshop. The questionnaire included similar questions to capture both the current state and desired future state of the digital twin.

The workshop and questionnaire were designed to gather insights related to the following questions (including but not limited to):

- What kind of assets do you maintain digitally?
- What data related to assets do you maintain?
- What is the level of data complexity, penetration rate and update frequency?
- What kind of AIM do you currently maintain/have?
- What kind of AIM would you desire to make?
- What data is required to make the desired AIM?

- What level of data complexity and detail is desired for AIM?
- What kind of digital twins are you using and what is the context/objective?
- What data do you use for existing digital twins?
- What kind of digital twin is desired (most relevant) in your organization? What would be the objective?
- What kind of data is required to build that digital twin?
- What are the current challenges/barriers you face in making AIM / Digital twins?

The workshop breakout session was attended by three road operators from Belgium (Flanders), Ireland, and the Netherlands. Additionally, the questionnaire received one response from Belgium (Flanders).

Interview methodology

Several interviews were conducted with experts at various organizations such as Road Operators, traffic managers, and emergency services. These interviews, both face-to-face and hybrid with online call attendance, allowed for exploring more in-depth details regarding the state of the art, current use of digital twins and the ambitions for the mid and long-term future. Due to the nature of the results, spanning a broad spectrum from pragmatic aspects to desired future use, the outcomes of the interviews are integrated into the various chapters.

State-of-the-art methodology

The state-of-the-art review asks the following questions, especially for the use of literature review, that are here adapted from Barry et. al (2022): How did we get here? Where are we now? Where we could be going? Among the study research questions, the previous questions are reflected in the study structure and how the analysis was conducted.

3 Digital Twins

3.1 Definitions and framework of Digital Twins

History of Digital Twin

The idea of a Digital Twin (DT), though not explicitly called that at the time, has been around since at least the 1960s, with organizations like NASA (The National Aeronautics and Space Administration) using physical duplicates of systems to test and understand their real-world counterparts (Miskinis 2019). The conceptual foundation came in 2002 with Dr Michael Grieves' work at the University of Michigan, who applied the concept to product lifecycle management (Singh et al., 2021). However, the term "digital twin" itself is credited to John Vickers of NASA in a 2010 roadmap report (Singh et al., 2021). This terminology helped solidify the concept and led to its wider adoption across various industries.

The concept of Digital Twin has grown and been redefined several times by various authors based on its applications. The literature has often referred to digital twins as digital models, layout, counterparts, doppelgangers, clone, footprints, software analogues, representations, information constructs or simulations of their physical counterpart (Singh et al., 2021). Initially described as a virtual representation for objects in aerospace (aircraft, vehicles), DTs have evolved to encompass a broader range of physical entities. Today, DTs can represent anything from machines and products to complex biological systems like humans and trees (Schluse & Rossmann, 2016).

Definitions of Digital Twin

Digital Twin in the context of transport has been defined in several ways by various authors.

Irfan et. al. (2022) defined Transportation Digital Twin (TDT) “as a virtual representation of transportation systems that maintain a digital replica of physical transportation system elements such as vehicles, roadways, pedestrians etc. A TDT system must be a real-time representation of the corresponding physical transportation elements to mimic the properties, behaviour, and interactions between various transportation elements.”

Another definition by Jones et. al. (2020) mentions “Digital Twin as consisting of three components, a physical product, a virtual representation of that product, and the bi-directional data connections that feed data from the physical to the virtual representation, and information and processes from the virtual representation to the physical.”

The Digital Twin Consortium (2024), defines DT as “A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.“

An article by Maintain-AI (2023) defined DT as “A Digital Twin is a digital representation of a physical asset, process, or system. It integrates near real-time monitoring, data sources and AI-driven solutions to provide an immersive visualisation of an entity. In the context of transportation and road infrastructure, a Digital Twin provides a dynamic, data-driven depiction of roadways, allowing road professionals and highway practitioners to enhance performance and make informed decisions.“

Arisekola & Madson (2023) studied Digital Twins for Asset Management using a social network analysis-based review. The study identified in global analysis popular topics of real-time data, decision making and infrastructure management. Real-time data and decision-making are key focal areas of research to date. Local analysis also identified visualisation, data integration, simulation and benefit realization in different local clusters of research.

A key point that brings together most definitions of DT other than being a virtual representation of a physical entity is the bi-directional transfer or sharing of data between the physical and the digital counterpart, including quantitative and qualitative data, historical data, environmental data, and most importantly, real-time data. (Singh et al., 2021).

Reviewing the definitions of publications about Digital Twins within the last years, several properties and keywords can be identified, which describe the concept. Nevertheless, the following four keywords appear regularly in the context of the Digital Twin (Wilking et al., 2021):

- **Physical Counterpart**: The Digital Twin is viewed as the counterpart of a physical product.
- **Connection**: The Digital Twin analyses data that is received by the physical counterpart or other sources.
- **Model Usage & Simulation**: The Digital Twin is built upon models which are fed with the data it receives. Models within the Digital Twin concept are used to simulate scenarios which are based on real-time data. With the output of these simulations predictions about future system behaviour can be given.
- **Bidirectional Orientation**: Digital Twins are not static. Real-time data can be used to reach higher maturity levels of the model as they get more precise.

DROIDS definition of Digital Twins

While the concept of Digital Twins has numerous definitions, a clear and concise one specifically for road transport applications can be elusive. To address this gap, a Digital Twin definition within the context of road transport and operator needs was formulated as a part of the DROIDS project's road operator (NRA) Digital Twin taxonomy. This definition incorporates key elements gathered from various existing definitions, tailoring it towards the unique perspective of road transport and its operators.

The DROIDS definition of Digital Twin is as follows:

Road transport Digital Twin is a realistic virtual representation of the real-world physical road transport systems. The road transport Digital Twin can include, depending of a purpose and defined functional scope, digital representation of elements such as road infrastructure, traffic with vehicles and pedestrians, road environment, traffic regulations and restrictions as well as land use. The road transport Digital Twin has a bidirectional real-time data connection between the physical and the digital representation. It can support road operator decision making with dynamic monitoring, analysis, and predictive modelling capabilities of the road transport systems that enable road operators for instance to enhance traffic flow, road safety, infrastructure asset management and sustainability or to facilitate automated driving or other future purposes.

The DROIDS definition of Digital Twin will be iteratively reviewed throughout the project based on input and feedback from the project stakeholders. Therefore, the above-mentioned DT definition can be changed in later (DROIDS) deliverable reports. The final definition will be published in the final report (Data Strategy).

Digital twin misconceptions – Digital model, shadow and twin

Digital twin is an evolved concept which founded on the upgraded forms of its previous concepts. Digital model and digital shadow are two concepts, which digital twin is often mistaken with them.

Digital model does not communicate data or update the physical structure and similarly physical structure does not update the digital model. According to Semanjski (2023), The digital model refers to a virtual model that comprehensively replicates a physical system. Here, the system refers to a number of elements that contribute to the same purpose or aim, and hence compose a system. The type of the model is selected so that it serves, in the best possible way, the purpose of its development (e.g., research) and can be of various types as numerical, logical, empirical, etc. Within the digital model concept there is a physical system and its virtual model, and the data transfer among them, either does not exist (e.g., traditional models) or exists but is done in a manual way in either direction (e.g., updating of a model-based simulation). Hence, a change in the state of the physical system has no direct effect on the virtual model and vice versa. (Semanjski 2023)

Examples of a digital model could be but are not limited to plans for buildings, product designs and development (Fuller et. al. 2020).

Digital shadow has a one-way data communication flow from the physical structure to the digital shadow. The digital shadow concept is seen as an upgrade of the digital model concept, where there is an automated (one-way) data transfer between the physical system and its virtual representation. Hence, a change in the state of the physical system will result in updating the state of its virtual counterpart, but not vice versa. An example of this could be a public transport network (physical system), where the status of the network, vehicles' occupancy, the position of the vehicles, and other observables are continuously sensed, and the virtual model would be updated based on this data flow. The data can be sensed by different types of IoT (Internet of Things) sensors and refreshed with a defined refresh rate. The public transport operators could use such digital shadows to monitor the status of their operations. (Semanjski 2023).

Digital twin, on the other hand, is characterised by a two-way data communication flow between physical structure and digital twin. That means a change made to the physical object automatically leads to a change in the digital object and vice versa. It should be noted that the models can be upgraded to shadow and further to twin, and vice versa, due to the dynamic nature and need of the user and infrastructure updates.

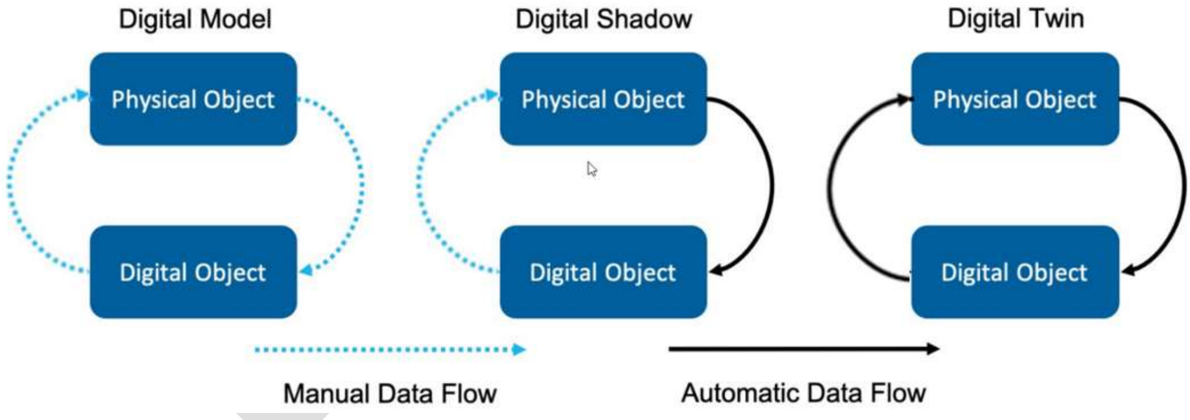

Figure 2: Difference between Digital Model, Digital Shadow, and Digital Twin (Adapted from Fuller et. Al., 2020)

3.2 Actors and roles

The key stakeholders and roles with regard to digital models, shadows or twins of the road infrastructure based on the interviews and literature analyses are presented below in *Table 4*.

Analysis of the Table 4 indicate that most stakeholders are today **active users** of a digital model or shadow of at least some parts of the road infrastructure.

It should be noted that many stakeholders are **active** also in many aspects of the digital representation of the road infrastructure but mostly only in a specific aspect of it. Depending on the role of the stakeholder in the transport data service ecosystem, an individual stakeholder can have either an active or a passive role in the development, operation and maintenance of the digital representation. In addition, the role of individual stakeholder might differ from other similar stakeholders reflected by the p/**A** markings in the table. For instance, some major information service providers can be very active also in developing their own digital twins while some minor service providers can be quite passive.

The roles of the various stakeholders will be elaborated further in the later stages of the DROIDS project.

Table 4 Today's roles in digital models, shadows and twin of road infrastructure. "A" means active roles of stakeholders in funding or carrying out the specific aspect of the virtual representation of the infrastructure. "p" means a more passive role.

	Aspect of road infrastructure digital model/shadow/twin			
Stakeholder	**Development**	**Operation**	**Maintenance**	**Use**
Road authority/ operator	**A**	**A**	**A**	**A**
Traffic manager	**A**	**A**	**A**	**A**
Traffic information service provider	p/A	p/**A**	p/**A**	**A**
Digital map provider	**A**	**A**	**A**	**A**
Meteorological service provider	p/**A**	p/**A**	p/**A**	**A**
Road infrastructure planning contractor	**A**	p	**A**	**A**
Road infrastructure building contractor	**A**	p	**A**	**A**
Road works or maintenance contractor	p	p	**A**	**A**
Rescue service provider				**A**
Law enforcement				A
Communication infrastructure provider	**A**	**A**	**A**	**A**
Transport authority	p	p	p	**A**
Communication authority	p	p	p	**A**
Land use authority (e.g. city, region)	**A**	**A**	**A**	**A**
Research / academic institutes	p			**A**
ADS provider				p
Vehicle manufacturer				p
Vehicle fleet operator	**A**	**A**	**A**	**A**
Vehicle owner/ driver/ occupant			p	p

3.3 Digital twin technology maturity and stage of development

This chapter presents an overview of digital twin technology maturity and stage of development as found in the literature. Evaluation methods of academic research keyword occurrence, patent search words, technology readiness level, commercial hype cycle and impact radar as well as complexity levels are presented.

Academic research has been active with research on digital twins. The following statistics in Figure 3 of search word “digital twin” was extracted using the Strobel (2018) script that extracts the historic word occurrence of a search term in the Google Scholar web search engine. According to the results, there has been a steady climb in the 2000s and peak occurrence was reached in 2022 with 62,600 keyword hits.

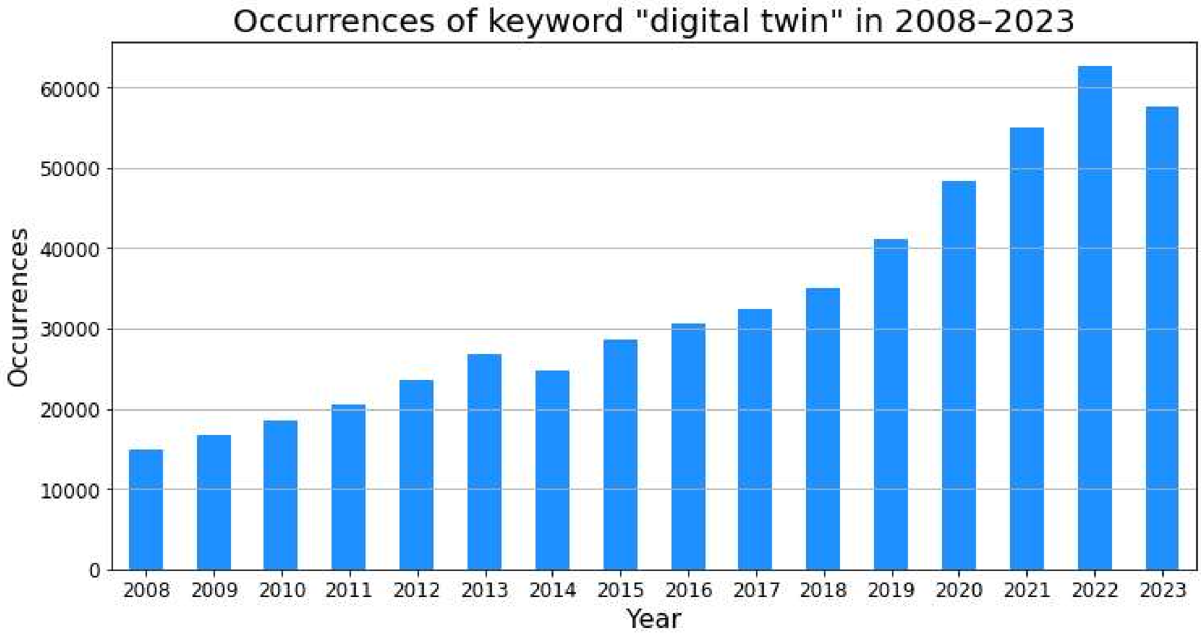

Figure 3 The historical occurrence of search word "digital twin" in the Google Scholar web search engine (script by Strobel (2018) was used).

United States (US) patent search of the words “digital twin”, within three words of each other in the abstract, showed in 2021 according to Parker (2021) that practical applications were slow in developing. First two applications were filed in 2015, then six in 2016, 13 in 2017 and 33 in 2018 (applications are published only after 18 months). In 2020 there were 17 US patents issued and 80 published applications pending. Parker further noted that inventors might avoid using the term digital twin although marketing departments would promote otherwise.

Technology Readiness Levels (TRL) were developed by the National Aeronautics and Space Administration (NASA) in the 1970s as a measurement system to assess the maturity level of a particular technology (NASA 2023). The TRL has also been adapted by the European Commission in the Horizon 2020 Work Programme (EC 2014). A technology project is evaluated against the parameters for each technology level. There are a total of nine technology readiness levels, TRL 1 lowest and TRL 9 highest, i.e. in short, (1) basic principles, (2) concept and formulated, (3) experimental function and/or proof-of-concept, (4) validated in the laboratory, (5) validated in a relevant environment, (6) prototype demonstrated, (7) demonstrated in real environment, (8) completed and qualified through test and (9) actual system. The advantages of TRL include a common understanding of status when communicating about a technology, risk management understanding in the early stages of development, and support to decision-making related to funding and transition of technology. The TRL has also been adapted and mentioned in research studies of digital twin.

Consilvio et al. (2023) estimate the architecture of a Digital Twin-based Decision Support System for road maintenance and evaluation of pavement conditions developed in the study to reach TRL 3. After further development and enrichment, it was estimated to possibly reach TRL 7 when it could also be implemented as a practical project use case.

Botín-Sanabria et al. (2022) did a comprehensive review of the digital twin technology in the most relevant domains and applications in engineering and beyond. Although digital twin applications related to road operator responsibilities, such as road infrastructure and traffic management, are not included in the results comparison, there are related physical twins such as urban space (TRLs 3) and distribution network in logistics (TRL 7). Most of the different domains evaluated had TRL 3 of maturity, although also mature implementations of TRL 7 were also found.

Giorgadze et al. (2022) did a literature review and evaluated the functional maturity of digital twin applications from a user readiness perspective using the Technology Readiness Level scale. Majority of the design-related digital twin applications were proposed at a structured theoretical level, i.e., TRL 3. Construction phase demonstrated proofs of concepts and implemented prototypes on levels 3 and 5 of the TRL scale. Operational & Maintenance applications were assigned to the highest reached level 5; it was argued that most digital twin applications concern this phase and therefore achieve high maturity. The lowest level 1 was assigned to demolition which was not adequately addressed. As a summary, the highest level of 5 would indicate digital twin in the infrastructure sector has achieved medium fidelity prototype applications.

Gartner Inc.'s Hype Cycles provide one opinion and perspective of analysis of technology development. The hype cycle has five stages: Technology trigger, Peak of inflated expectations, Trough of disillusionment, Slope of enlightenment and Plateau of productivity as presented in the Figure 4. Digital twin was considered being at the peak of inflated expectations in 2018 and from there moved forward. Meanwhile, in 2020 Gartner estimated digital twin to reach its plateau of productivity between 2023 and 2028. Concepts related to digital twin, such as "citizen twin", "twin of a person" and "digital twins of government" are still when writing this study at the technology or innovation triggering phase. (Semanjski 2023)

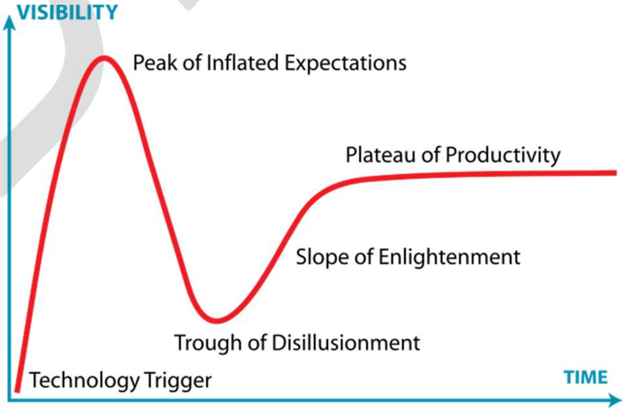

Figure 4 Gartner Hype Cycle. (Gartner Inc. 2007).

Like the Hype cycle, also the estimation of the emerging technologies and trends impact radar by Gartner (2024) presented in Figure 5 indicates range of 1–3 years until digital twin technology will cross over from early adopter to early majority adoption. It is also estimated that the mass of impact on products and markets will be very high.

Figure 5 Gartner Inc. Impact Radar for 2024. Digital twins has been highlighted with a red box.

Complexity and lifecycle of the digital twin has been evaluated by Semanjski (2023), who argues that the complexity level of the digital twin and lifecycle stages of a physical system with the related digital twin applications need to be assessed when evaluating digital twin applications development. Semanjski divides time horizon to three lifecycle phases of design, build and operations. Then he divides complexity levels to three levels of object, process and system. The overall complexity according to Semanjski increases when the lifecycle time horizon or the complexity level increases as presented in the Figure 6Figure 6. For example, creating a digital twin on the lifecycle stage operations of transport system would be vastly more complex than any single object lifecycle stage.

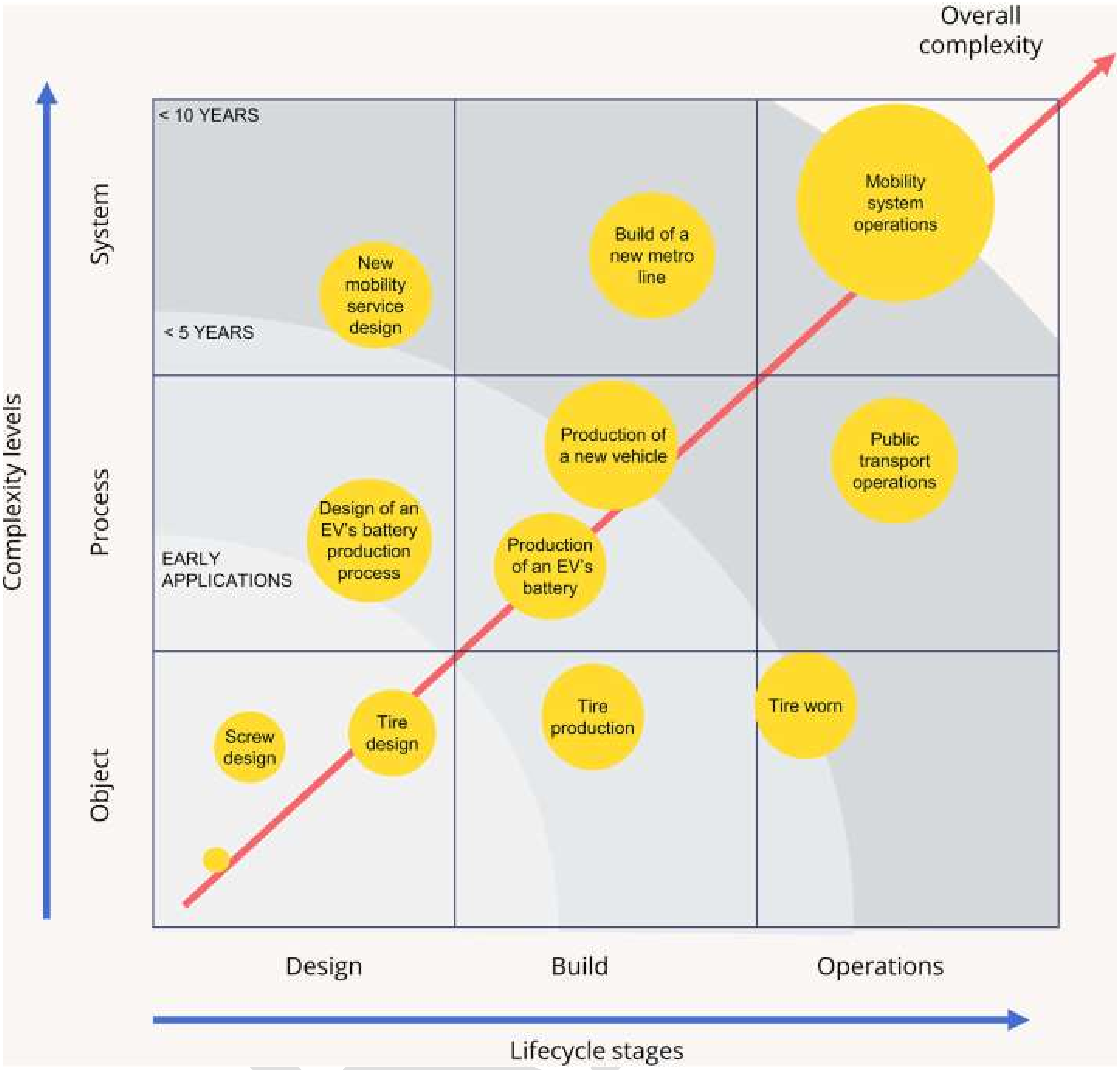

Figure 6 Approximation of lifecycle stages and complexity levels of digital twin according to Semanjski (2023).

Digital twin technology maturity can also be estimated by reviewing the ongoing activities by the European Commission and European member state countries as well as road operators. The initiatives and member state projects as well as current state of development have been early stages of piloting and proof-of-concepts. These initiatives and activities are reviewed more closely in the following chapters.

4 Technologies utilised by digital twins

This section aims to shed light on the technological aspects of Digital Twin.

4.1 Technologies involved in digital twins

Ali et al. (2022) delve into the application of Digital Twin (DT) technology for intelligent transportation systems and discuss how DT for electromobility rely on a complex interplay of several technologies. The foundation lies in the Internet of Things (IoT), where a network of sensors embedded in electric vehicles (EVs) collects real-time data on everything from battery health to traffic conditions. This data flows through a robust network, potentially leveraging 5G for its high bandwidth and low latency, to reach the DT platform. Artificial Intelligence (AI) and machine learning (ML) algorithms then analyze this sensor data within the DT model. This virtual representation of the physical EV can be used to simulate scenarios, predict maintenance needs, and optimize various aspects like charging infrastructure. Additionally, the concept of the Internet of Vehicles (IoV) comes into play when considering communication between vehicles and their environment, which can further enrich the data fed into the DT model. Overall, DT acts as a digital brain for EVs, integrating various technologies to create a smarter and more efficient electric mobility experience.

Tuhaise et al. (2023) delve into the Digital Twin technologies in construction. Authors have systematically reviewed them across the five conceptual layers of data acquisition, data transmission, digital modelling, data/model integration, and services in digital twins.

- **Data Acquisition Layer**: This layer focuses on capturing real-time data from the physical environment. The primary technology is IoT sensor, to collect real-time data across various parameters like temperature, pressure, and worker location.
- **Data Transmission Layer**: Here, the collected data is processed and transferred from sensors to a central platform. The most common technology is Wi-Fi for short-range wireless transmission. Other options include wireless local area networks (WLAN), Bluetooth, and ultra-wide-band (UWB) radio communication. Further protocols like MQTT are utilized for low bandwidth and high latency networks, to ensure reliable data transfer from sensors to the central platform.
- **Digital Modelling Layer**: This layer creates a virtual representation of the physical asset. BIM models are the dominant technology, but some applications utilize 3D point cloud models obtained through laser scanning or photogrammetry. Virtual reality environments are also emerging in this space.
- **Data/Model Integration and Fusion Layer**: Cloud-based computing platforms are the preferred choice for data storage. Integration often relies on custom-developed plug-ins for the 3D modelling software, with Unity 3D being a popular platform for this purpose.
- **Service Layer**: This layer leverages machine learning to analyze the integrated data and provide valuable services. Real-time monitoring of assets and activities is the most common service, followed by early fault detection and predictive maintenance capabilities. Examples include monitoring construction progress, structural health, energy consumption, and worker safety.

Chen et al. (2024) review the usage of machine learning techniques for road condition predictions and discuss findings within the road digital twin framework. They identified a crucial challenge that ML algorithm performance depends heavily on the specific data used. The same algorithm might yield poor results on one dataset but excel on another. To address this, the authors propose that DTs should have a mechanism to automatically select the most suitable ML algorithm for a given dataset based on factors like data structure and user needs. Their review suggests Artificial Neural Networks (ANNs), Recurrent Neural Networks (RNNs), Long Short-Term Memory (LSTM) networks, and the AdaBoost.RT algorithm as promising options due to their accuracy in both short-term and long-term road condition predictions.

The creation of geometric digital twin of road surfaces using photogrammetry and computer vision are discussed by Ding et al. (2023). The authors argue that the use of the mentioned technologies image data would be scalable and less expensive compared to the traditional methods to create a digital twin of a road. The technologies would also offer further benefits such as finding relationships between the assets in the point cloud.

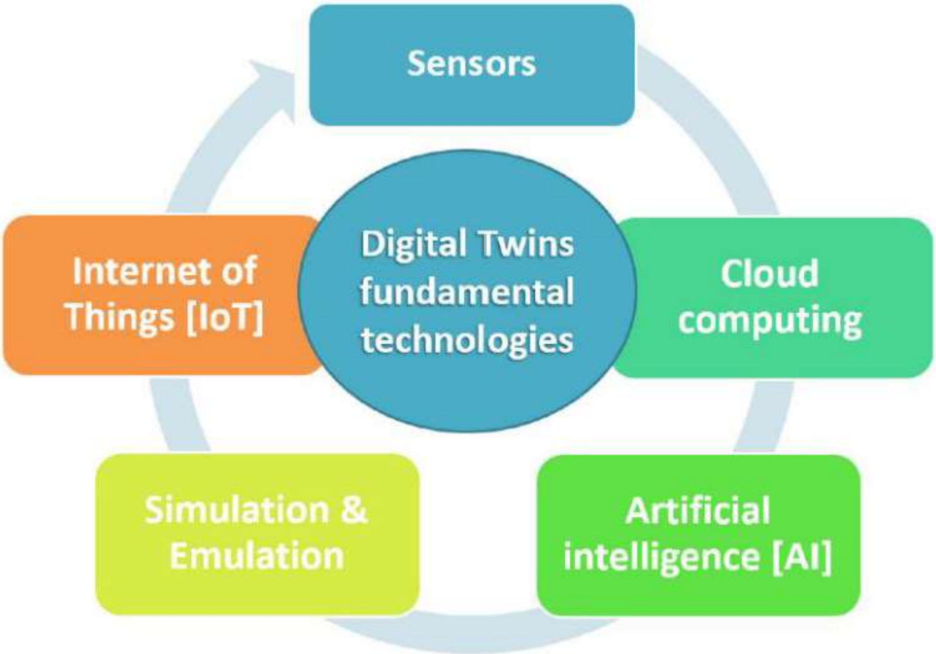

Figure 7: Digital twin fundamental technologies (Cardoso et al., 2023)

4.2 Data used in digital twins

Zhang et al. (2022) review that the early data acquisition for digital twins was a slow and expensive manual process. This limited the amount of data collected and resulted in a narrow snapshot of a physical object's behaviour, often with delays. However, advancements in information technology have revolutionized data collection. Sensors, IoT devices, mobile devices, and wearables can now capture vast amounts of real-time data throughout an object's entire lifespan. This comprehensive data stream, processed through integrated computing infrastructures like cloud and edge computing allows for a complete data record and timely analysis across the physical entity's lifecycle.

However as mentioned by the authors, the Digital Twin (DT) applications rely on several crucial data requirements to function effectively. These requirements ensure that the data used by the DT is comprehensive, up-to-date, adaptable, and usable for various purposes. Given below is a breakdown of the key data requirements as mentioned by the authors:

- Comprehensive Data Gathering: DT systems need a wide range of data encompassing normal and abnormal states, common and rare events, and various scenarios. This ensures the virtual model captures the full spectrum of the physical object's behaviour.

- Real-Time Data Interaction: Seamless data flow is critical between the physical entity, the virtual model, and DT services. This allows for:
    - Updating virtual models based on real-time sensor data from the physical object.
    - Optimizing the physical object's behaviour based on virtual model simulations.
    - Continuously improving DT services with real-time data.
- Data Universality: Data portability across different DT applications, regardless of the physical object or scenario, is essential. This necessitates standardized data formats and communication protocols.
- Knowledge Mining: Extracting valuable insights from raw data is crucial for building accurate virtual models. This involves identifying and filtering irrelevant or abnormal data to uncover hidden patterns and relationships within the data.
- Data Fusion: Data from various sources (sensors, models, services) can be noisy or inconsistent. Data fusion techniques combine and reconcile this data to reduce uncertainty, improve accuracy of simulations, and extract more relevant information for specific goals.
- Iterative Optimization: This refers to a continuous process of incorporating new data with historical data to generate even more insights. Each optimization cycle aims to add valuable information to the data pool while considering constraints like data redundancy.
- Convenient Data Usage: DT users have diverse needs based on their roles. Field operators require different data than technicians or senior managers. To address this, data access should be provided as on-demand services with functionalities like searching, matching, combining, and visualizing data relevant to specific user needs.

Considering the above-mentioned requirements Zhang et al. (2022) introduced a new notion called Digital Twin Data (DTD). DTD refers to a wide spectrum of data closely related to the Digital Twin. It encompasses a wide range of information from both the physical world (sensors on machines) and the virtual world (simulations) and tends to make the data from the two spaces corrected and supplemented by each other through data fusion, to achieve more accurate and comprehensive information for the DT-related applications.

As shown in the below Figure 8, Digital Twin Data (DTD) can be broken down into six different categories: physical entity data (properties and status of the real-world object), virtual model data (digital representation with simulations), service data (information about functionalities offered by the Digital Twin), domain knowledge (expert experience and industry standards), and fusion data (a combination of all the above for a comprehensive picture). Connection data ensures consistency by comparing information from various sources. The figure also shows how these different parts are interrelated.

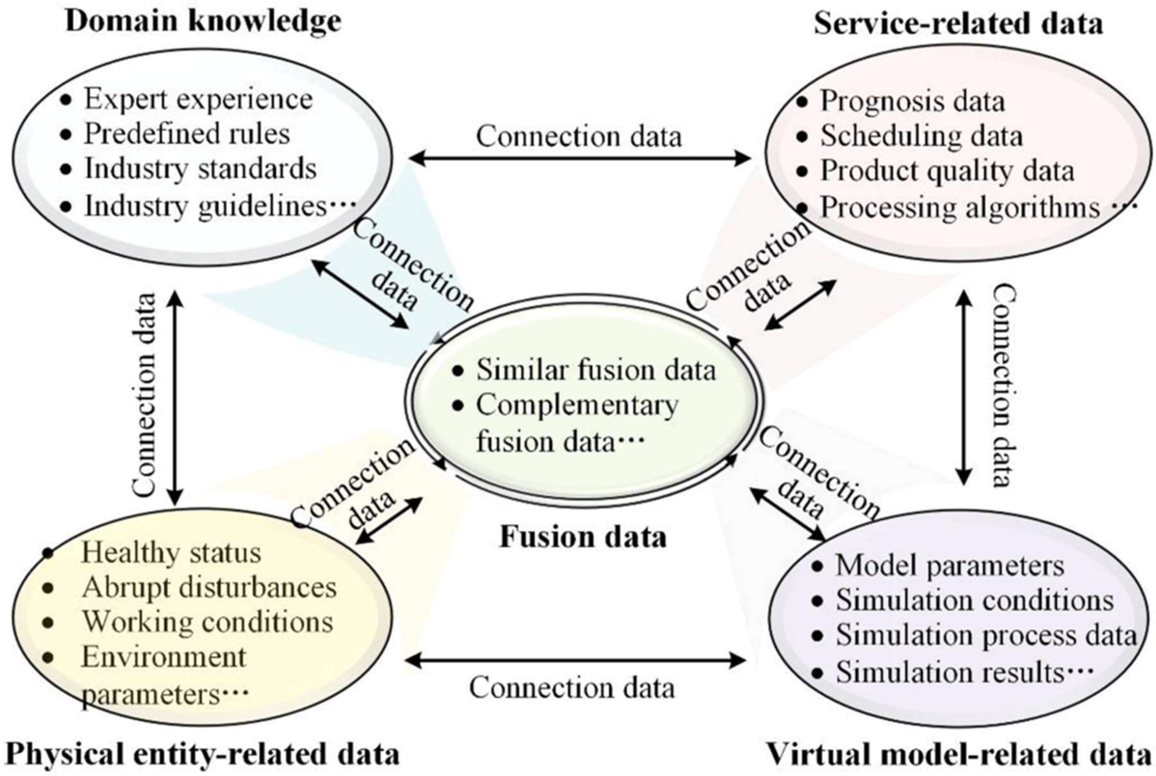

Figure 8: Composition of digital twin data (DTD) (Zhang et al., 2022)

The authors also propose seven principles for managing Digital Twin Data effectively (Figure 9). The complementary principle emphasizes gathering data from both physical and virtual aspects. Timeliness ensures real-time data exchange for synchronized updates. Standardization allows Digital Twin Data from different sources to be easily shared and analysed. The association principle focuses on uncovering relationships within Digital Twin Data to extract valuable insights. Fusion merges data for improved accuracy and comprehensiveness. The information growth principle encourages continuous optimization through iterative data fusion. Finally, the on-demand principle aims to make Digital Twin Data easily accessible to users by packaging it as on-demand services, eliminating the need for extensive technical knowledge. The outer layer shows the data while the corresponding principles which should be observed for the sake of better fulfilling the requirements are represented by the inner layer.

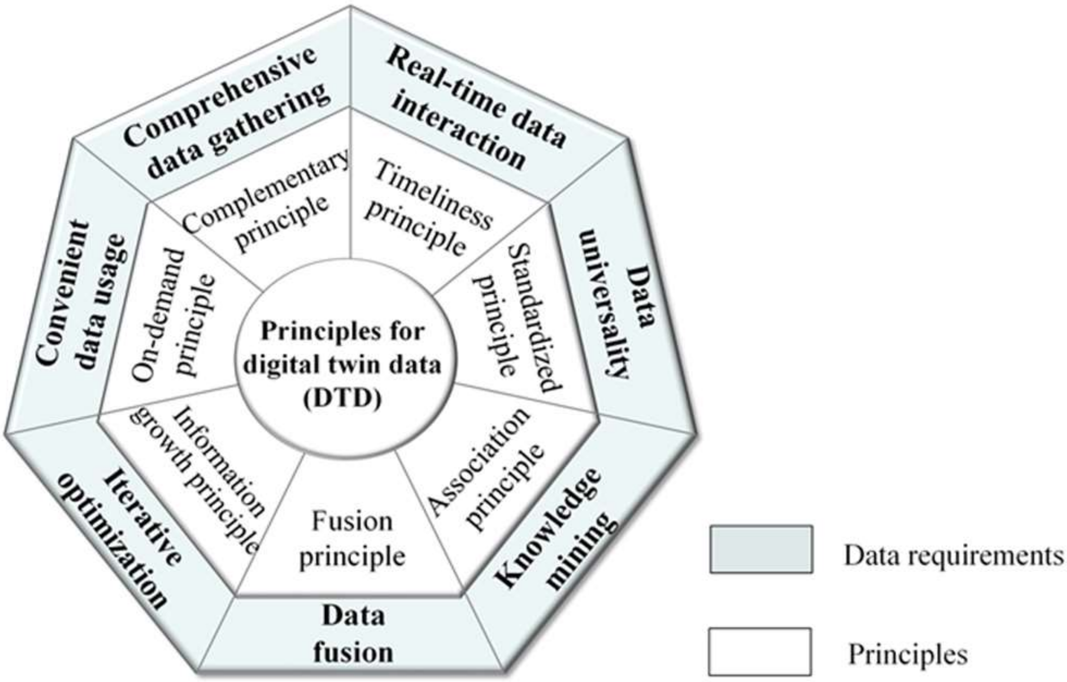

Figure 9: Principles for digital twin data (DTD) (Zhang et al., 2022)

Matchett et al. (2022) mention the various data types encompassed in Digital Twins. These include graphical data (photographs, videos, drawings, GIS maps, 3D models) describing the physical object's form, components, and size. Additionally, DTs incorporate documents containing data on specifications, procurement, warranties, and manuals. Numerical data, such as simulations, measurements, and parameters, is also included. The selection and incorporation of this data are driven by the DT's intended purpose, ensuring it adds value to the specific objectives. However, the authors agree that the DT data is central to its visualization, analysis, representation, and decision-making value.

Matchett et al. (2022) have also provided a non-exhaustive list of graphical and non-graphical data and their sources for Road Asset Management as shown in the below table:

Table 5 Type of data that could be in incorporated in Digital Twin for Road Asset Management Matchett et al. (2022)

Type of Data	Graphic Examples: Maps, models and drawings	Non Graphic examples: databases, documents	Possible Sources of Data
Asset ☆	As-built drawings, 3D corridor models, GIS maps of road network, road servitude plans	Road logs, link tables, asset databases, reports, specifications	RAMS, Department of Transport GIS,
Pavement ☆	Strip maps, GIS maps	Condition databases, measurement data, engineering condition indices, functional indices	Pavement Management System (PMS)
Public Operations	Live Maps of roadworks, operating conditions, reported defects, closures, planned interuptions	Travel advisories, route guides, contact details for local emergency services	Social Media, Automobile Association, tourist guides
Social	Community maps, settlement locations, jurisdiction boundaries, tourist facilities, commercial centers	Contact information, demographics, community leadership data	Demarcation plans, tourism databases
Environment	Weather maps, climatic zones, environmental sensitivity maps, geology maps, test pit data	Rainfall data, population data	Council for Geosciences data, South African Weather Service, Stats SA
Traffic ☆	Volume/capacity maps, link flow maps, origin/destination diagrams, counting station location maps, weigh in motion (WIM) locations, land use maps	Traffic counts, vehicle classifications, overload ratios, land use	SANRAL Traffic Counting Database, overload control data, commercial data e.g. TOMTOM, Waze, Google
Maintenance ☆	Linear referencing maps, drainage keyplan, fencing diagrams, road sign layouts	Maintenance records, works orders, contracts, payment certificates	SANRAL records, department of roads and public works
Safety	iRAP (safety) diagrams, accident hotspots, accident locations,	Road safety audit reports, accident records	Road authorities, traffic police data, insurance companies, road accident fund
Legal	Access plans, right of way diagrams, land ownership plans, wayleave diagrams and maps	Demarcation information, road proclamations	Directorate of surveys and mapping, deeds records

☆ Denotes data that is expected to be contained in a RAMS. The other data types may be considered as part of the situational analysis, but would likely be stored in separate repositories, reports and references.

In the table, RAMS refer to the Road Asset Management System which is defined as “an all-encompassing systems approach to road infrastructure asset management”.

Focused more on mobility, Rinne and his colleagues (Rinne et. al. 2022) divide data in digital twin into three categories including data for *Infrastructure and traffic environment* (e.g. detailed street structure, traffic signs, accessibility), *Traffic* (e.g. number of vehicles, cyclists, pedestrians) and *Conditions and context* (e.g. air quality, roadworks, maintenance needs, resident feedback). Some examples of key data which are extracted by Mobility Lab Helsinki are mentioned in Table 6.

Table 6 Data types relevant to digital twin for mobility (Rinne et. al. 2022).

Traffic infrastructure	Traffic	Conditions and context
• Base information about traffic infrastructure • Traffic guidance • Temporary infrastructure changes • Public transport infrastructure • Other sources of traffic infrastructure data	• Traffic volumes • Travel times • Routes and Origin/Destination matrices • Public Transport • Digitraffic • Other traffic data	• Accidents and incidents • Maintenance and roadworks • Weather and road conditions • Air quality and noise • Public transport interphases • Other condition and context data

In conclusion, Digital Twin Data (DTD) is a critical concept for ensuring the effectiveness of Digital Twin applications. By encompassing a wide range of data from both the physical and virtual worlds, DTD fosters comprehensive understanding and facilitates real-time interaction between the physical entity, the virtual model, and DT services. Effective DTD management requires adherence to specific principles, including gathering complementary data from both physical and virtual aspects, ensuring timeliness, and implementing standardization for seamless data exchange. Ultimately, DTD serves as the foundation for knowledge extraction, data fusion, and continuous improvement, empowering various DT users with on-demand data access for informed decision-making.

4.3 Digital Twin Architecture

The digital twin's architecture is a complex combination of physical and digital components. They work together to synchronize the digital twin with its physical prototype and provide data insights to end-users (Landyshev, 2023). The architecture of digital twin is a “general principle” and “logical from” which “structures” the “components” to support different “functions” of digital twins, including data collection, data enrichment, modelling, analysis, situational awareness, and actuation (Kovacs & Mori 2023, Butterworth 2017).

4.3.1 **Components of Digital Twin Architecture:**

Generally speaking, the architecture of digital twins has three main components: the Physical layer, the Communication or Integration layer, and the Digital twin layer (Nwogu et al., 2022) (Campos et al., 2019). Each layer will integrate a variety of components dependent on the designer's needs and requirements. However, some basic components include sensors in the physical world (to gather information from the real environment), a physical twin, edge processing capabilities, data security, the digital twin itself, data processing capabilities (enabled by machine learning (ML), artificial intelligence (AI), big data, etc.) and communication interfaces such as the internet, Bluetooth, satellite, etc (Botín-Sanabria et al., 2022).

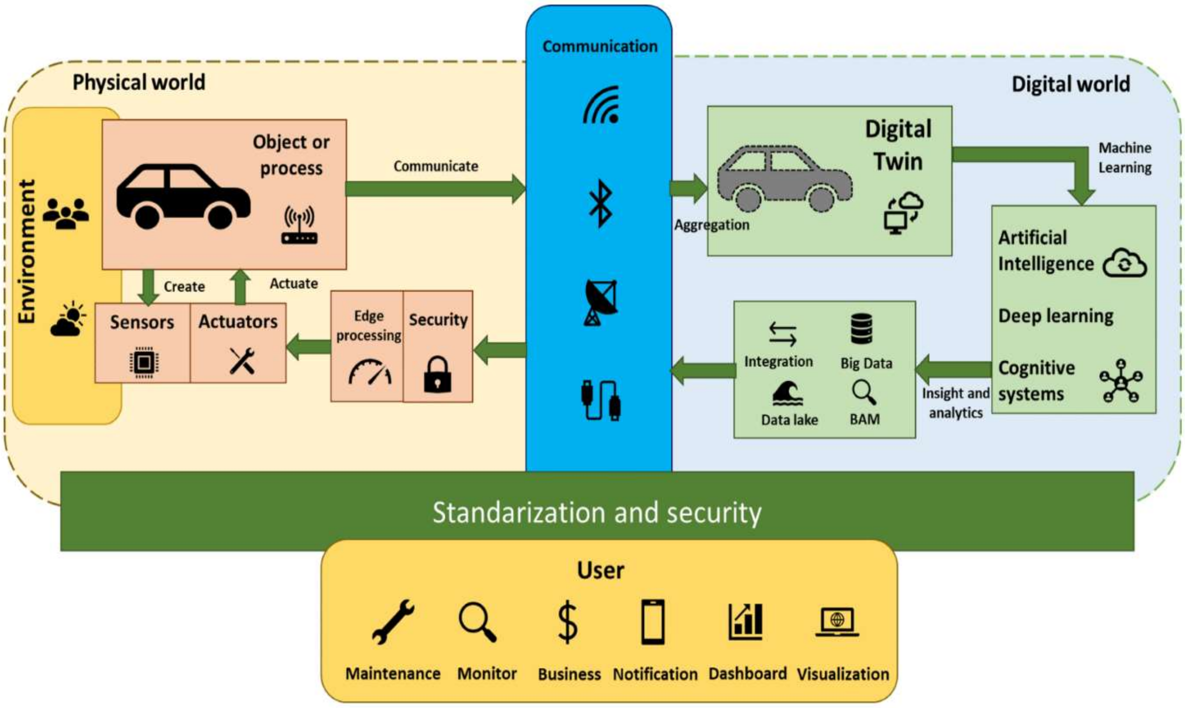

Figure 10: Digital Twin Architecture proposed by Botin-Sanabria et al., 2022

Some research, however, has detailed it regarding the use case. For example, Faliagka (Faliagka et al., 2024) suggest a six-layer architecture for smart mobility as shown in Figure 11. It includes a physical layer, data acquisition layer, edge computing layer, data storage layer, digital twin layer and application layer.

Within this architecture data from devices, sensors, humans, and even external services is first collected and processed in the Data Acquisition layer. This filtered and shaped data is then stored in specialized databases depending on its type in the Storage layer. The Digital Twin layer takes centre stage, analysing the processed data and using models to predict future states, make decisions, and even trigger actions on devices through the Edge Computing layer. Finally, the user interacts with these insights and functionalities through user-facing applications in the Application layer.

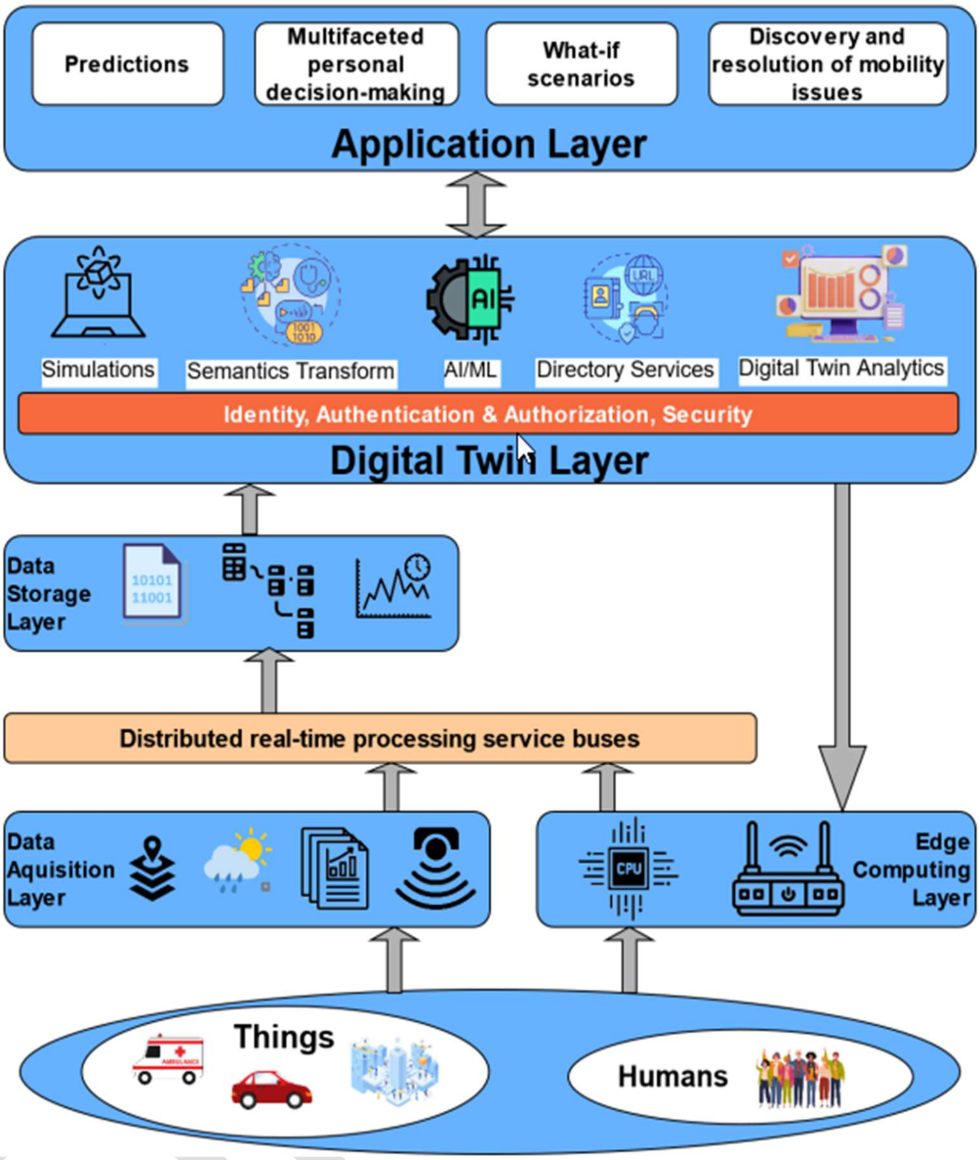

Figure 11: METACITIES - Architecture for smart mobility by Faliagka et al., 2024

Another detailed architecture developed by Warke (Warke et al., 2021) is a six-layer structure that consists physical layer, data transfer and collection layer, data storage and processing layer, communication layer, cloud computing and storage level and virtual layer. The first two layers encompass the physical devices and their data sources. Layer 3 bridges the physical and virtual worlds by collecting data and enabling communication. Layer 4 refines this data into valuable information. Layers 5 and 6 store and analyse the information, with Layer 6 providing a virtual replica for user interaction, decision-making, and optimization.

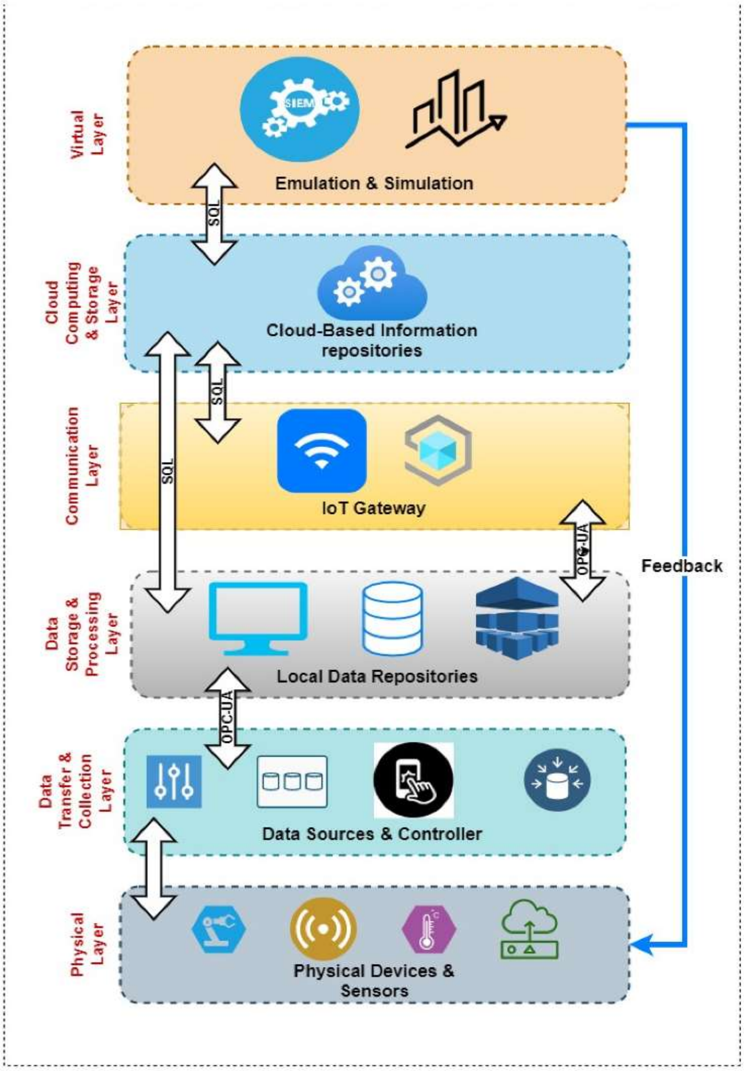

Figure 12: Six layer architecture of Digital Twin by Warke et al., 2021

Wang et al., (2022) suggests a very detailed architecture for connected vehicles in a mobility digital twin. The Mobility Digital Twin (MDT) framework has three main components:

- **Physical Space:** This real-world space includes entities like people (drivers, pedestrians etc.), vehicles, and traffic infrastructure (traffic lights, signs, etc.). Sensors placed here gather data about these entities.
- **Communication Plane:** This plane acts as a bridge, transmitting data between the physical space and the digital space. It allows for real-time and non-real-time data exchange.
- **Digital Space:** This space holds digital replicas of everything in the physical space. It also includes data lakes storing collected data and computer programs to process this data. This processing can involve functions like storage, modelling, learning, simulation, and prediction.

Each component in this architecture has three aspects: human, vehicle and traffic which have their respective digital twin.

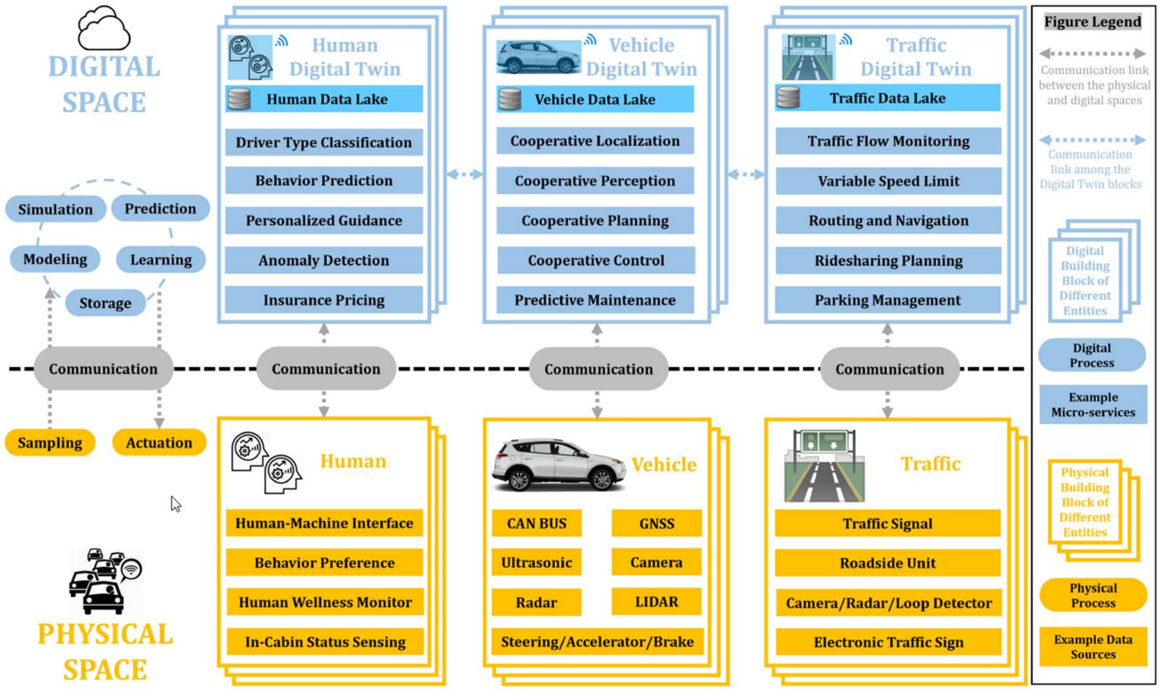

Figure 13: Mobility Digital Twin Framework by Wang et al., 2022

The communication layer or plane as referred in the above studies and architecture proposals is further presented in the 5GAA report on "V2N2X Communications: Architecture, Solution Blueprint and Use Case Implementation" (5GAA 2024) which describes for different stakeholders on how to realise various V2X applications and use cases using cellular network communications. This includes information sharing structures between backend systems, which relates to the different architecture models of digital twins with bidirectional data exchange between the physical and digital infrastructure.

In conclusion, there is no single, universally accepted architecture for digital twins. The specific components and their arrangement will vary depending on the use case and the designer's needs. However, all digital twin architectures share some common elements, including a physical layer, a communication layer, and a digital twin layer. The physical layer includes the real-world entity that the digital twin represents, as well as sensors that collect data from that entity. The communication layer transmits data between the physical layer and the digital twin layer. The digital twin layer is a digital representation of the physical entity that can be used for a variety of purposes, such as monitoring, analysis, and optimization. As digital twins become more sophisticated, we can expect to see even more variation in their architectures.

4.3.2 Digital Twin Maturity Levels

Evans et al. (2019) classified several maturity levels for DTs as presented in Table 7, which are agnostic of the industry domain or the technologies used to build the models. In the literature, the majority of DT concepts are at levels 0–3 of maturity, and few have started the integration with real-time data streams due to the significant challenge of data gathering, filtering and processing in real-time, as well as device malfunctioning and poor calibration which may create anomalies or missing data points.

Table 7 Maturity levels for Digital Twins (Evans et al. 2019)

Level	Principle	Usage
0	Reality capture (e.g., point cloud, drones, photogrammetry or drawings/sketches)	Brownfeld (existing) as-built survey
1	2D map/system or 3D model (e.g., object-based, with no metadata or building information models)	Design/asset optimization and coordination
2	Connect model to persistent (static) data, metadata and building information model (BIM) Stage 2 (e.g., documents, drawings, asset management systems)	4D/5D simulation, design/asset management, BIM Stage 2
3	Enrich with real-time data (IoT, sensors)	Operational efficiency
4	Two-way data integration and interaction	Remote and immersive operations; control the physical from the digital
5	Autonomous operations and maintenance	Complete self-governance with total oversight and transparency

4.4 Digital twin services and software

This section aims to explore various software and services that are designed for creating and managing Digital Twins. Some digital twin software and services for transport network are as follows:

- **Bentley Systems - iTwin Platform:** This platform allows for the creation, visualization, and analysis of digital twins of infrastructure assets, including highways and roads. It provides a comprehensive set of tools for managing data, modelling infrastructure systems, and simulating real-world scenarios. https://www.bentley.com/software/itwin-platform/

- **Siemens - MindSphere:** This cloud-based platform provides an open IoT operating system that can be used to connect and manage digital twins of highways and roads. It allows for the integration of data from sensors, cameras, and other devices, as well as the creation of applications for monitoring, optimization, and control. https://www.siemens.com/nl/nl/products/software/mindsphere.html

- **Eclipse – Ditto**: This open-source framework acts as an IoT middleware, providing an abstraction layer for seamlessly connecting physical devices (sensors, cameras) on highways to their digital twin representations. https://eclipse.dev/ditto/

- **Dassault Systèmes - 3DEXPERIENCE Platform:** This platform provides a holistic view of the product lifecycle, from design and engineering to manufacturing and operation. It can be used to create digital twins of highways and roads, which can then be used for simulation, optimization, and maintenance purposes. https://www.3ds.com/3dexperience

- **GE Digital - Predix platform:** This cloud-based platform provides an operating system for the Industrial Internet of Things (IIoT). It can be used to connect and

manage digital twins of highways and roads, as well as to develop applications for predictive maintenance, asset optimization, and safety management.
https://www.ge.com/digital/iiot-platform/predix-edge

- **PTC – ThingWorx:** ThingWorx is designed specifically for the Industrial Internet of Things (IIoT), making it a good fit for industrial applications like highway and road infrastructure management. ThingWorx excels at collecting data from various sensors commonly used in highways like traffic flow sensors, weather monitoring stations, and pavement health monitors. It can then analyze this data to identify issues like congestion, potential road damage, or weather-related hazards.
https://www.ptc.com/en/products/thingworx

- **IBM – Watson IoT Platform**: While IBM Watson IoT Platform might not be the most specialized solution for highways and roads, it can still be a valuable tool for creating digital twins in this domain.
https://www.ibm.com/cloud/internet-of-things

- **IBM Maximo Application Suite:** This suite of software applications provides a comprehensive solution for managing the lifecycle of physical assets, including highways and roads. It can be used to create digital twins of infrastructure assets, which can then be used for maintenance planning, scheduling, and execution.
https://www.ibm.com/products/maximo

These are just a few examples of the many digital twin software and services that are available for highways and roads. The best solution will depend on the specific needs of the project and the organization.

4.5 Standards and Specifications

Digital Twins relies heavily on standardized practices to function effectively. These standards act as a common language, ensuring hardware, software, and data from various sources can seamlessly interact. Flamigni et al. (2024) provide a comprehensive list of various standards that are relevant to the concept of Digital Twin.

There are several standardization bodies that are relevant to the digital twins of road infrastructure. Some of the major standardization bodies include International Organization for Standardization (ISO), International Electrotechnical Commission (IEC), European Telecommunications Standards Institute (ETSI), European Committee for Standardization (CEN), European Committee for Electrotechnical Standardization (CENELEC), Object Management Group (OMG), Organization for the Advancement of Structured Information Standards (OASIS), Institute of Electrical and Electronics Engineers (IEEE), Standard Performance Evaluation Corporation (SPEC), World Wide Web Consortium (W3C), and European Space Agency (ESA).

Although there aren't any standards specific to road DT, various standards related to interoperability, data management, secure communication, asset management, Internet of things, and 3d modeling align well with the core functionalities of a Road DT system. Some examples of standards that might be relevant for the DT of road transport systems are provided in Table 8.

Table 8: Standards relevant to Digital Twin of road infrastructure

Standard	Type	Use
ISO/IEC 21778:2017 (JSON)	Communication protocol	lightweight data-interchange
ISO/IEC 21823-1:2019 (IOT)	Internet of Things (IOT)	Peer to peer Interoperability among IoT systems
ISO/IEC 21823-2:2020 (IOT)	Internet of Things (IOT)	Transport interoperability among IoT systems.
ISO/IEC TR 30164:2020 (IOT)	Internet of Things (IOT)	UNIBO: Design principles, solutions and technologies applying to edge computing for IoT systems and applications.
ISO/IEC TS 23167 (CLOUD)	Cloud computing	UNIBO: Technologies and techniques applied to and used in conjunction with cloud computing.
ISO/PAS 17506:2012 (COLLADA)	Data model	Data exchange, sharing
IEC 61131-3 (CONTROLLERS)	Textual modeling language	Remote control and command of machines
ETSI MEC - MULTI-ACCESS EDGE COMPUTING	Edge computing	UNIBO: Multi-Access Edge Computing (MEC) reference architecture and integration with the telco domain.
IEEE 802.1 AS	Deterministic communication	Real-time monitoring of machines/devices (Anomaly detection, Predictive Maintenance, Asset performance management/Operations optimisation)
Data Distribution Service (DDS) standard	Communication protocol	data-centric connectivity standard
FMU/FMI	Data exchange, sharing	Used for the exchange of models with internal and external partners using different modelling tools

Standards and specifications are discussed more in detail in the DROIDS deliverable D3.2: Information maintenance and availability (Soni S., 2025).

4.6 *Technologies Associated with Digital Twins*

4.6.1 Building Information Modeling (BIM)

There are several definitions of Building Information Modeling (BIM) available from Wikipedia to the International Standardisation Organisation (ISO), more or less consistently describing BIM as follows: a process or method of managing information related to facilities and projects in order to coordinate multiple inputs and outputs, using shared digital representations of physical and functional characteristics of any built object, including buildings, bridges, roads, process plant.

According to the U.S. National BIM standard (NBIMS), “Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition. A basic premise of BIM is a collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder.”

BIM is a complex process of managing not only design documentation in 3D form but also includes all the consecutive stages of the design analysis, followed by construction management, and facility management after the site completion.

Building Information Models (BIMs) are files (often but not always in proprietary formats and containing proprietary data) that can be exchanged or networked to support decision-making about a place. Current BIM software is used by individuals, businesses, and government agencies who plan, design, construct, operate, and maintain diverse physical infrastructures, such as water, wastewater, electricity, gas, refuse and communication utilities, roads, bridges and ports, houses, apartments, schools and shops, offices, factories, warehouses, and prisons.

Whilst BIM refers to the process that encompasses the entire lifecycle of the project, there are several other information models that exist in different phases of the project lifecycle. Figure 14 showcases the BIM information workflow through the design, construction, and operation phases of the project (Catenda 2024). During the design and construction phase, Project Information Model (PIM) exists whereas after the construction, the knowledge and information is handed over to the Asset Information Model (AIM) for the operation and maintenance of the assets.

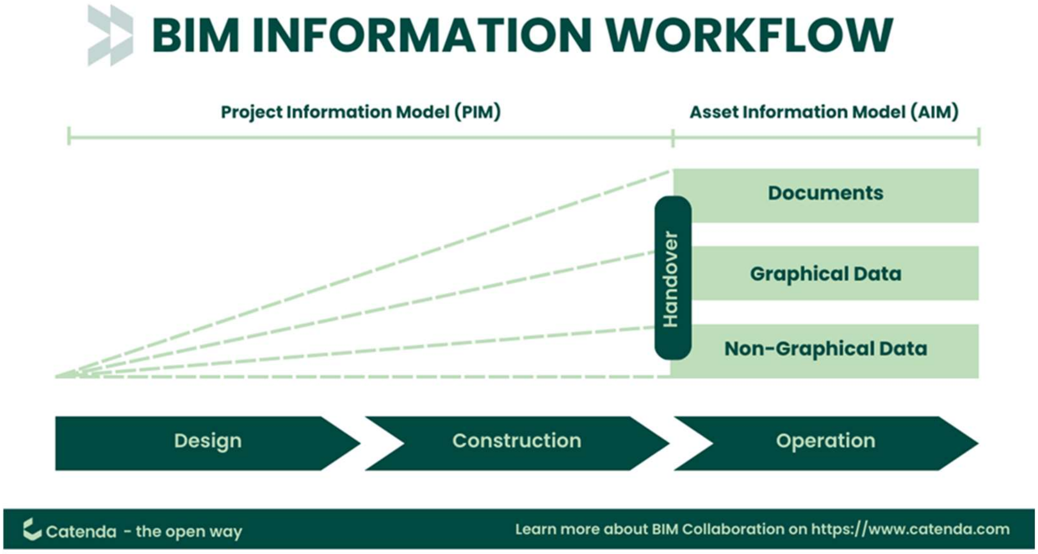

Figure 14: BIM information workflow from PIM to AIM (Catenda 2024)

Project Information Model is the information model developed during the design and construction phase of a project (BSI 2013). PIM includes the federated building information model, non-graphical data, and associated documentation. The PIM Is developed progressively, first as a design intent model and then as a virtual construction model. The design intent model is then developed into a virtual construction model containing all the objects to be manufactured, installed, or constructed.

As the design progresses, the PIM develops, and the level of detail increases. Ultimately, once the construction is complete, the Project Information Model (PIM) eventually becomes an as-built model to represent the real as-constructed condition of the built asset. After that, the PIM transfers to the AIM to continue informing asset management (AM)/facility management (FM) during the operational phase.

4.6.2 Asset Information Modeling (AIM)

Richard McPartland (2017) has defined Asset Information Model or AIM as the collated set of information gathered from all sources that supports the ongoing management of an asset. The AIM comprises models, data, documents, and other records related to or required for the operational phase of an asset. AIM might include information outlining the original design intent, details of ownership, survey work undertaken, operational performance details as well as 3D models developed on the project. DEWorks (2024) defines AIM as a digital representation of an asset, such as a building or infrastructure, that allows for efficient management and maintenance of the asset throughout its lifecycle. It involves the creation of a digital twin, which is a virtual replica of the physical asset that can be used to analyse, simulate, and optimize the asset’s performance. (Patacas et al., 2015) define AIM as a data model that contains all digital data that is required to operate an asset.

Asset Information Modeling (AIM) extends Building Information Modeling (BIM) principles beyond the construction phase into the entire lifecycle of an asset. By creating a detailed digital representation of the physical and functional characteristics of an asset, comprehensive information can be accessed throughout a project's lifecycle. These models include data about design, construction, operation, and maintenance. AIM production typically integrates into the later stages of the BIM workflow, specifically during the operational and maintenance phases when the digital model transitions into a dynamic tool for ongoing asset management.

When a construction project is completed, some pieces of information are transferred from the PIM to the AIM. Project Information Model (PIM) is the information model developed during the design and construction phase of a project. It includes the federated building information model, non-graphical data, and associated documentation. The PIM Is developed progressively, first as a design intent model and then as a virtual construction model. The design intent model is then developed into a virtual construction model containing all the objects to be manufactured, installed, or constructed.

As the design progresses, the PIM will develop and the level of detail will increase, including, first, objects based on generic representations, and then specific objects with specifications and method statements attached along with information about space allocation for operation, access, maintenance, installation, replacement and so on.

Ultimately, once the construction is complete, the Project Information Model (PIM) is developed into an Asset Information Model (AIM), to be used during the operational phase. In this transitional period, all the data scattered in the organization is identified, validated, and combined into one single source.

An AIM can provide graphical and non-graphical data and information as well as documents and metadata. It can relate to a single asset or to a portfolio of assets. An AIM can be created from existing asset information systems, from new information, or from information in a Project Information Model (PIM) that was created for the construction of a new asset.

AIM encompasses comprehensive data related to the physical asset, including design specifications, construction details, operational parameters, maintenance schedules, and any other pertinent information that contributes to a holistic understanding of the asset's lifecycle.

There are several kinds of information that can be found in the AIM:

- Information on the original design intent.
- 3D models and other related ones.
- Information about the asset owner, ownership details, surveys, rights, conditions & restrictions, jobs that have been underway, operational performance attributes, etc.

(Heatton and Parlikad, 2020) proposed a BIM-based approach for designing and developing Digital Twins (DTs). This approach leverages the object-oriented nature of BIM models to create an Asset Information Model (AIM), which serves as the foundation for the Digital Twin. The paper presents a case study from the West Cambridge campus to illustrate the development of a single 3D model. This model integrates multiple BIM models with rich metadata attached based on a pre-defined asset classification schema. The key aspect of this approach is aligning the development of an AIM to facilitate DT creation.

The proposed approach consists of three key steps, as depicted in below Figure 15:

- Asset Classification: BIM models are analyzed to classify assets based on their functional purpose.
- AIM Database Development: An AIM relational database is built using data extracted from an exported IFC (Industry Foundation Classes) model. IFC is a common file format for exchanging BIM data between different software applications.
- Federated Model Creation: The BIM models are linked to the relational database within a single federated model. This federated model serves as the central information hub for the DT.

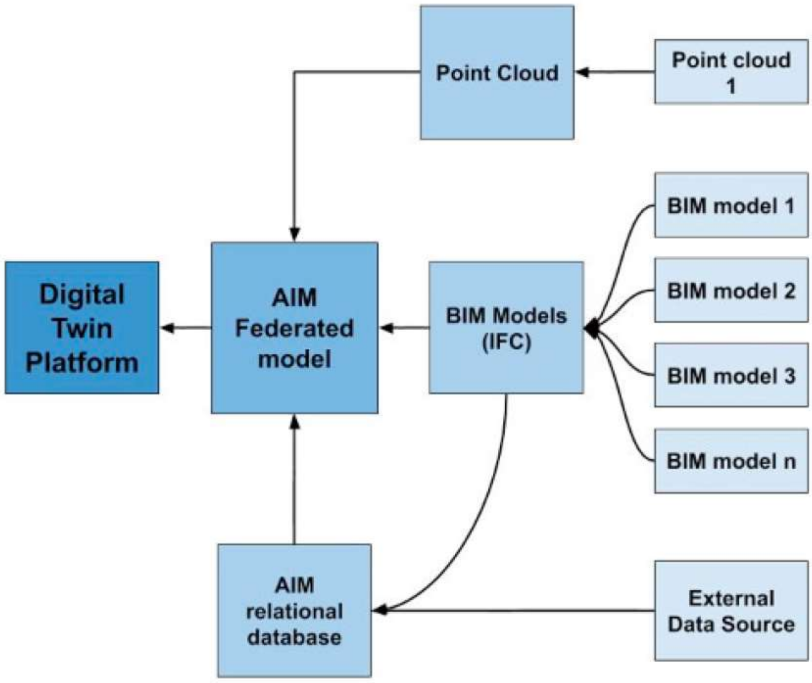

Figure 15 overview of the approach (Heatton and Parlikad, 2020)

Sharafutdinova et al. (2023) studied requirements for AIM for Industrial Facility, which include mainly three general components: level of development (LOD), level of information (LOI), and level of accuracy (LOA) of model elements (Figure 16). Authors argue that when creating AIM, a balance of LOD, LOI, and LOA is needed because, for different tasks, an optimal ratio of these parameters is required.

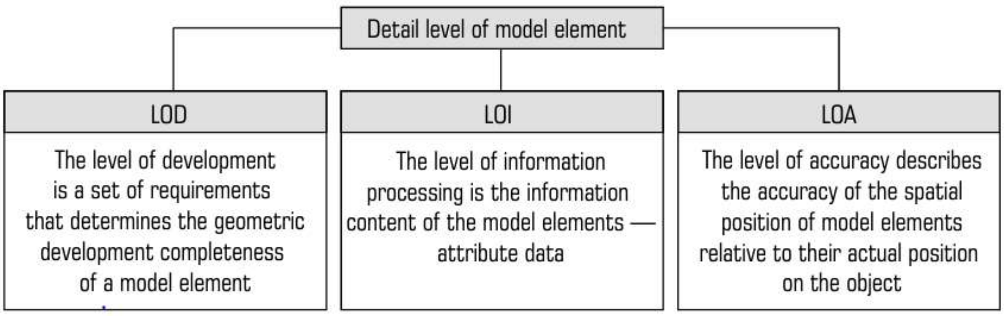

Figure 16 Detail levels of model elements (Sharafutdinova et al., 2023)

Level of Development (LOD): The authors argue that the LOD requirements for AIM have received the most attention. Existing standards provide more comprehensive guidance for building structures, likely reflecting BIM's initial focus on civil engineering. Conversely, crucial aspects like LOI currently lack detailed requirements, and LOA remains entirely undefined.

Level of Information (LOI): LOI plays a vital role, particularly in operational tasks. It's important to note that LOD and LOI requirements can differ significantly depending on the specific operational task at hand.

Level of Accuracy (LOA): For many operational tasks, maintaining up-to-date spatial data on model elements is essential. This directly impacts the quality of operational decision-making.

4.6.3 Comparison between BIM, AIM, and Digital Twin

Table 9 presents an example comparison with some of the main differences between Digital Twin, BIM, and AIM technologies.

Table 9: Comparison between BIM, AIM and Digital Twin (adapted from Delgado & Oyedele, 2021)

Category	BIM	AIM	Digital Twin
Phase	Entire lifecycle: Design, construction, operation, and Deconstruction	Operational	Operational
Focus	Design, construction, and management of a building's physical characteristics	Information management throughout an asset's lifecycle	Real-time data integration with a virtual model (with offline applications)
Update	When needed	Periodically	Real-time
Communication	Uni-directional	Uni-directional	Bi-directional
Data type	Static 3D model with embedded information	Comprehensive data about the asset, including BIM, maintenance records, and warranties	Dynamic data streams from sensors and other sources
Purpose	Improve collaboration, identify clashes, optimize design, and generate construction documentation	Facilitate efficient operation and maintenance of assets	Monitor asset performance, predict future issues, and optimize operations
Relation	BIM can be a foundation for a digital twin	AIM can contribute data to a digital twin	Digital twin builds on BIM and AIM to create a real-time representation
Enabling technologies	**Modeling of Topological Data** - Geometrical modeling tools - Data schemes and ontologies - Visualization tools **Task Automation and Coordination** - Databases and common data environments - Discipline coordination and federation tools - Construction planning and scheduling tools	**Data management** - Software and tools - Data storage solutions **Data collection** - One-way communication with sensors - On-site data collection **Data processing** - Frequent updates on changes	**Data Gathering** - Sensors and Internet of Things **Physical-Digital Connection** - Web communication frameworks and protocols - Mobile data connectivity - **Processing Services** - Cloud and Edge computing

4.7 DROIDS Framework of Digital Twin

Figure 17 represents the relationship between the various models and Digital Twin. As known from previous sections, BIM encompasses all the processes and products involved throughout the entire lifecycle of the project from design to deconstruction. Before a certain physical infrastructure element is built or after it has been demolished or deconstructed, an information model can exist without a direct link to the real world.

For example, PIM contains information about the design component during the design and construction phase. Once construction is completed, the PIM information is handed over to the Asset information model for the operation and maintenance of the assets. Furthermore, at the end of the project lifecycle, the AIM information can be handed over to create a deconstruction plan in the Deconstruction Information Model (DIM).

The Asset information model also has a link with the physical world, however, it does not have a real-time data connection with its physical counterparts. Digital Twin on the other hand can be derived out of AIM when necessary, communication channels are established to enable bidirectional real-time data flow. Thus, AIM can be considered a subset of a Digital Twin.

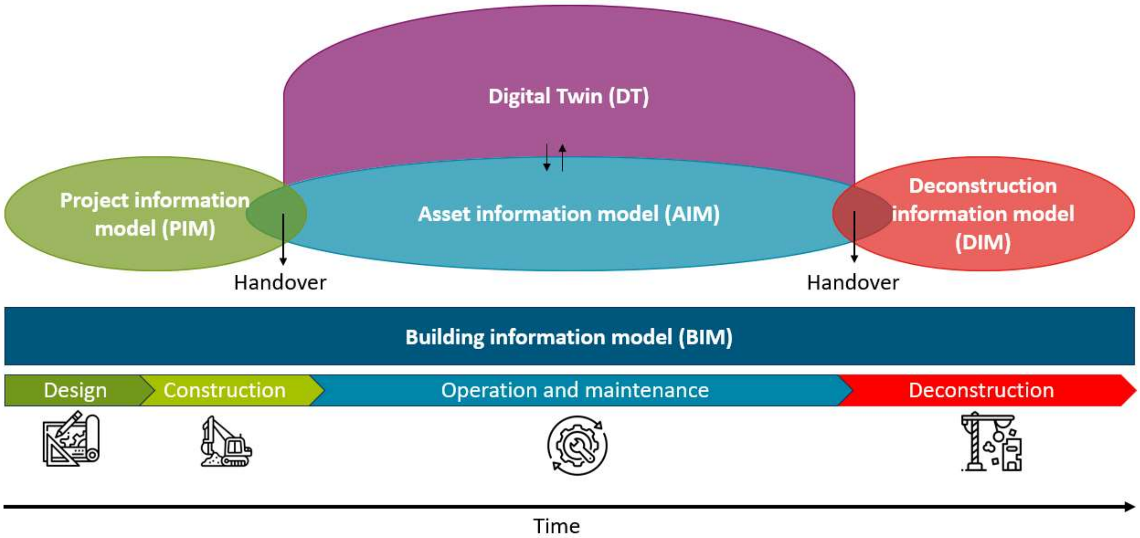

Figure 17 Relationship between different models and Digital Twin.

5 Road operator applications of digital twins

This chapter reviews state-of-the-art of road operator applications of digital twins, i.e., how digital twins are used by road operators. The first subchapter introduces multiple use cases of digital twins, depending on road operator tasks and assets, to support road operator decision-making. The next subchapters then review the most important use cases for road operators: road infrastructure and traffic management. Finally, European initiatives with other use case examples as well as the current state of the digital twin at selected road operators are introduced.

5.1 *Digital twins for road operator decision support*

Road operator responsibilities may vary between countries, but most commonly included are planning and construction of new roads, safety, asset management, traffic management, road maintenance, and right of way and abutting development regulation (PIARC 2019). The use of land and spatial planning has an important role in infrastructure development. The road operator assets include physical, digital, and operational infrastructure, but also human resources as well as equipment and materials. Road authorities also take responsibility for the sustainable development of infrastructure, including environmental impacts, such as air pollution and climate change, and impacts on ecosystems (PIARC). Additionally, road authorities take part in risk and disaster management, for example as a part of the traffic management responsibilities. Disasters caused by nature or humans may have an impact on the road network, where collaboration with other authorities such as rescue services is essential.

Digital twin technology provides opportunities for road operators when applied to the previously mentioned responsibilities it has. The study by AlBalkhy et al. (2024) classified the applications of DT into six groups: sustainability and environmental, facility management, safety, health, and risk management, structural performance, construction management, and architectural and urban-related applications. As presented above, many of these groups relate to the responsibilities of road operators.

Different applications of DT can also be identified from the literature as published research partly reflects DT development and usage. Digital Twins for Asset Management were studied by Arisekola & Madson (2023) using social network analysis-based review. The study identified local research area clusters of Facility Management, Infrastructure Management, Disaster Management, DT Platform, and DT Investment.

Digital twin applications for infrastructure assets were summarised from literature by Giorgadze et al (2022) in a study of developing lifecycle infrastructure digital twin. The applications were classified according to four lifecycle phases of design, construction, operational & management, and demolition. The four classifications with sub categories are presented below in Table 10.

Table 10 Digital twin applications for infrastructure assets, classified by lifecycle phases. (Giorgadze et al 2022)

Design	**Construction**
D1. Conceptual preliminary & detailed DT-driven design **D2.** Retrofit design **D3.** Reconstruction and expansion **D4.** Decision making **D4.a.** Material selection **D4.b.** Energy analysis **D4.c.** Sustainability analysis **D4.d.** Procurement **D4.e.** Supplier selection **D5.f.** Feasibility analysis	**C1.** Progress monitoring **C2.** Tracking changes and updating models **C3.** Quality controls **C4.** Timely realignment actions **C5.** Safety monitoring **C5.a.** Trace proximity between worker and hazards **C5.b.** Machinery monitoring **C5.c.** Ergonomics **C6.** Training environments **C7.** Material monitoring **C7.a.** Dynamic tracing of on-site demand and supply status
O&M	**Demolition**
OM1. Logistics processes and energy simulations **OM2.** Sustainable management of utility tunnels **OM3.** Inspection and defect detection **OM4.** Structural Health Monitoring of bridges **OM5.** Enrichment of Industry Foundation Classes (IFC) for damage components	**DM1.** Exploitation of knowledge from predecessor to next generation

Land use and spatial planning might be a potential application for digital twin technology. For example, Adade and de Vries (2023) studied digital twins for active stakeholder participation in land-use planning: the development of digital twins had not yet accomplished much of features that could improve stakeholder influence. Smit et al. (2022) studied quality dimensions for establishing digital twin maturity level for spatial planning in the Netherlands, which partly opens what different opportunities and challenges could emerge: most contributions focused on digital twin technical aspects of maturity, but also legal integrity of digital twin models, participation capabilities, and exploitation of policy ambitions were identified.

Risk and disaster management can be applied through digital twin technologies to support the safe operation of the road network. For example, Ye et al. (2023) report on the digital twin approach that was used for tunnel construction safety early warning and management with successful prediction of collapse accidents. Zhang et al. (2024) propose a digital twin framework for tunnel fire safety management driven by dynamic sensor data and AI. Yu et al. (2022) present a concept of digital twin driven construction of intelligent disaster prevention and mitigation for infrastructure (IDPMI). Cheng et al. (2023) analyzed digital twins in emergency management of civil infrastructure (EMCI) to help improve the emergency response capability of civil infrastructure under extreme circumstances such as natural disasters and human-caused hazards. Improved emergency response can for example help to optimise evacuation decisions and the use of road networks.

An exemplary overview of digital twin for road operator decision support is presented in Figure 18. The figure has been adapted from the literature mentioned in this chapter, mainly from VLOCA (2024) and Semanjski (2023). The DROIDS digital twin framework, presented in chapter 3.1, has also been adopted in the figure by leaving out the design lifecycle, as the digital twin was seen having two ways of data communication earlies on handover between construction and operation and maintenance. The lifecycle of construction as well as deconstruction and disposal have been left for possible additional (de)construction measures on the road infrastructure.

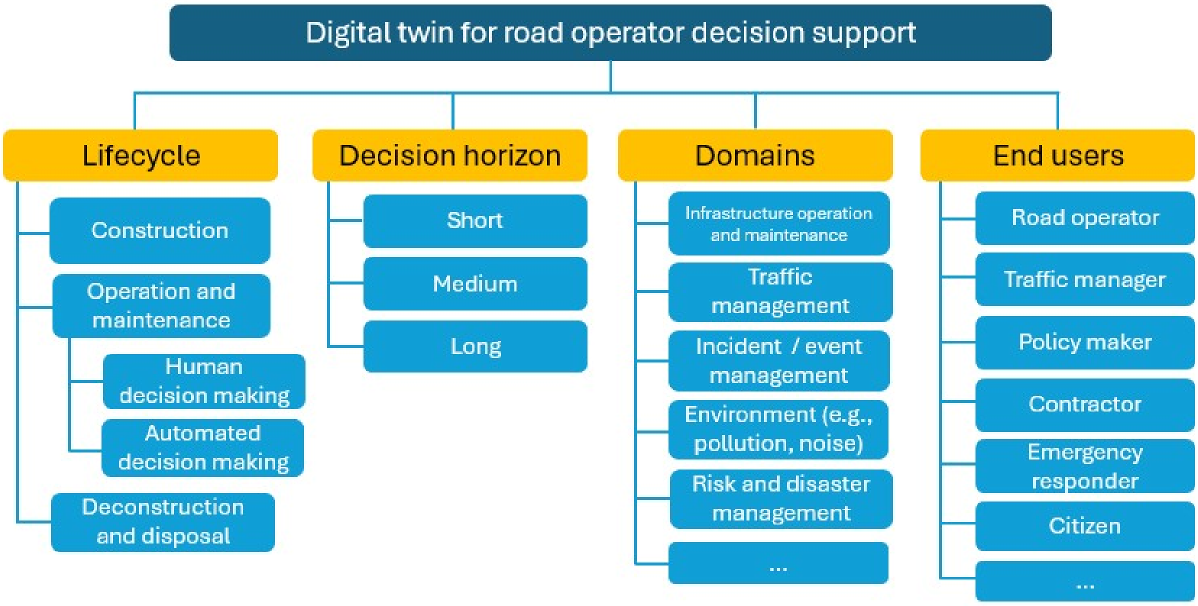

Figure 18 Digital twin for road operator decision support adapted from VLOCA (2024) and Semanjski (2023) as well as the DROIDS framework of digital twins (Chapter 4.7).

The next two chapters review applications of digital twins for two of the main strategic and operational responsibilities of the road operator: first, planning, building, and maintenance of road infrastructure, and second, traffic management of the road network.

5.2 Road infrastructure

This chapter reviews the state-of-the-art of road infrastructure digital twin. The chapter introduces shortly the elements of road infrastructure and asset management life cycles. Then proceeds to the literature review method, results, and analysis.

5.2.1 Road infrastructure assets life cycle and digital twin

Road infrastructure consists of roadway including pavement or road surface, lanes, and shoulders. Typical structures on the road are for example bridges and tunnels. Along the road can also be found utilities such as electricity, telecommunication, and sewer or drainage systems. The roadside and its intersections can include signage, traffic signals wireless roadside units, or other sensors such as cameras, radars, and loop detectors. Other infrastructure includes for example street lighting, barriers or guardrails, and traffic signs.

Road operators' responsibilities include managing the road infrastructure's physical assets, i.e., asset management, through its life cycle. The asset lifecycle from construction to disposal with decision points is presented in the Figure 19 below according to the PIARC asset management guide.

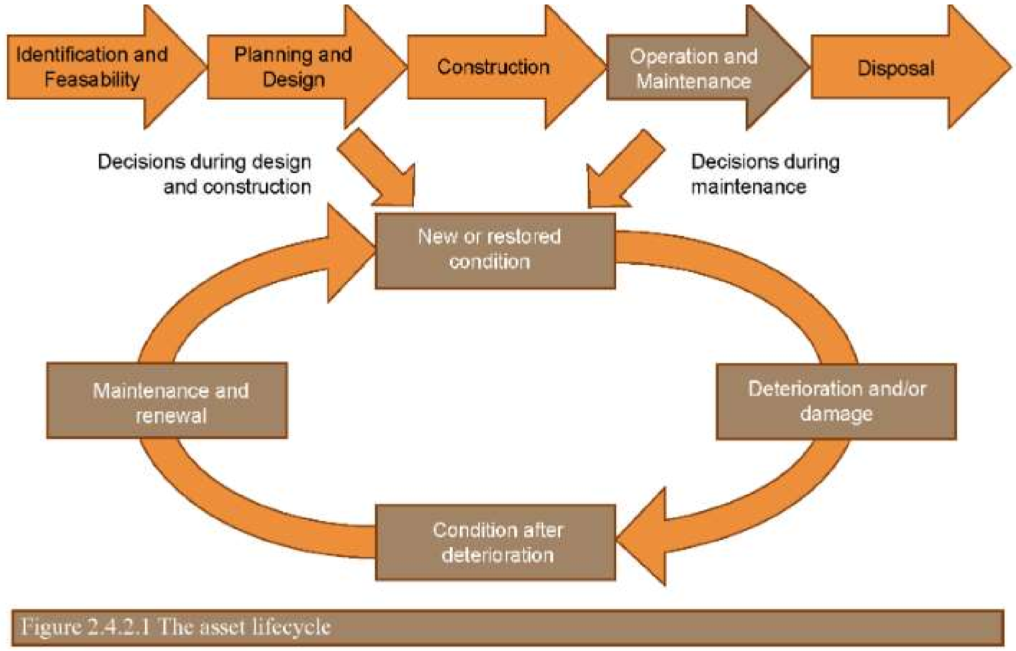

Figure 19 The road infrastructure asset lifecycle. (PIARC 2024)

The lifecycle of an asset covers the following four stages: creation of a new asset, routine maintenance, renewal or replacement and decommissioning. Asset planning includes funding and cost requirements for a short-, medium- and long-term period for each asset.

Digital twin can be used in road infrastructure asset lifecycles with the following considerations that are adapted from this study's previous chapter on digital twin definitions. Digital twin may be used in the early stages of construction or creation of an asset from the moment the bidirectional data flow between the asset and the digital model has been established. In later stages of the lifecycle during operation and maintenance, the digital twin would be the most applied and possible largest benefit received as predictive maintenance decisions and actions can be taken.

5.2.2 Road infrastructure assets and digital twin

Literature review was conducted to evaluate state-of-the-art of road infrastructure assets and use of digital twin. The Table 11 presents the reviewed articles with considerations on infrastructure type and asset lifecycle.

The literature review was conducted using mainly Google Scholar and Elsevier ScienceDirect databases. Search words included "digital twin" AND "road infrastructure". Total of 119 articles were found. After review of the article's title, abstracts, and conclusions, the number was reduced to 30. Of those the ones presented in the Table 11 were selected. The table presents road infrastructure assets presented in each article as well as the lifecycle phase of construction or operation and analysis, modeling, and tools applied. The articles are summarised further in this chapter.

Table 11 Digital twin of road infrastructure articles reviewed. Columns include type of infrastructure, Life Cycle (LC) and analysis, modeling or tolls mentioned in the article.

Article	Road infrastructure asset	LC: Construction	LC: Operation	Analysis, modeling, or tools
Tita et al. (2023).	Bridge management		x	Traffic flow simulation, a finite element analysis for the structure, Digital twin-BIM technology
Tang et al. (2023)	Mountain highways		x	Knowledge-Guided Fusion Modelling of Mountain Highway
Sandaker (2022) M.S. thesis	Bridges, with case study bridge		x	Correlation analysis, point cloud 3D modeling
Parker (2021)	Bridges	x	x	Validation of digital models and parameters to model and verify
Rodriguez et al. (2023)	Pavement management	x	x	Predictive pavement deterioration model, BIM
Consilvio et al. (2023)	Road pavement maintenance	x	x	Digital Twin-based Decision Support Tool
Heise (2023)	Road infrastructure management		x	Structured requirements analysis, information sources
Diren & Althen (2023)	Tunnel		x	Traffic simulation and the tunnel management platform, Virtual Reality
Yu G. et al. (2021)	Tunnel		x	Fault cause analysis of fans in a tunnel

Bridge management digital twin-BIM technology was reported by Tita et al. (2023). Prestressed concrete box-girder bridge structural performance evaluation and anomaly detection were based on GNSS monitoring and sensor technologies. According to the results, the technology can offer significant maintenance and operation advantages by capturing a virtual representation of the bridge with physical and functional attributes. Bridge structure performance and maintenance can be evaluated with up-to-date condition information that enhances asset management practices, and schedules, and extends the lifespan of the structure. This furthermore enhances the safety of the structural integrity. Collaboration among the stakeholders was enhanced with better data exchange, information sharing and coordinated decision making.

Mountain highways and knowledge-guided fusion expression method for digital twin scenes was proposed by Tang et al. (2023). The research methodology was implemented for highway management and aims to improve current modelling of complex scenes and visual representation for real-time management. Three strengths were reported: efficient fusion expression of digital twin scenes for mountain highways, real-time visualization and release of dynamic data, and example of digital twin system design for operation and maintenance of mountain highways. Limitation includes experimental design on Personal Computers (PCs) and uncertainty due to the lack of actual application in the domain.

Supporting structural health monitoring of aging bridges with digital twins was focused on Sandaker (2022) thesis. A bridge support structure, not the whole bridge, was modeled for the use of digital twin by using as-built drawings and additional 3D scanning. The study challenges with automated model updating and lack of standardization slowing the process. Sensor locations in the bridge can also cause issues, such as the interconnection of sensors between the support structure and the concrete structure. There were additional difficulties with the scanned point cloud used for the 3D modeling. Data flow from the bridge to the model and vice versa should be studied further.

Bridge owner might not want or need a true digital twin as Parker (2021) argues since there is uncertainty if automatic change in the digital model is wanted, or what mechanical or physical changes could be automatically applied to the bridge. Parker refers to Fuller et al. (2020) that "digital model" would better represent the state-of-the-art, i.e., there is no change or data flow between the digital and physical object. Parker notes that there are US patent portfolios that are directly applicable to bridges, and structural health monitoring, but the term digital twin is not used (only one of 130 articles) although digital twin software is heavily advertised. Parker notes that initial fidelity between the digital model and the physical object need to be established. This requires model parameters to be identified and verified before instrumentation installation.

Pavement maintenance and lifespan extension with a digital twin in a port, i.e. a harbor town to discharge cargo, have been studied by Rodriquez et al. (2023). The study suggests the following key concepts to provide the information quality required for the predictive framework developed: surveying platforms such as unmanned aerial vehicles (UAV) and LiDAR as well as cameras; sensor systems; Building Information Models (BIM); computational modeling and digital twins. The developed pavement maintenance framework uses a logistic model (road operation) to interact and build a predictive pavement deterioration model.

Road maintenance combined with digital twin and decision support systems integration was reported together with framework architecture by Consilvio et al. (2023). The architecture is organized into physical, database, server, and application layers. The aim of the physical layer is to collect data from the whole lifecycle of the road, from design to operation. The database includes documentation and model data. The server layer uses historical data from the asset management, geometrics, and semantic data from BIM models as well as analysis in the decision support tool. The webserver layer can visualize and update BIM models. Application of the proposed architecture to road pavement maintenance was done in a case study on the A24 Italian motorway. There was an expectation to reduce the volume of major interventions and maintenance costs. In the paper the highest level of digital twin integration was defined as "automatic and bidirectional interaction between the physical and digital objects, is used in prescriptive maintenance strategies, where the final step of proposing a maintenance action is provided."

Road infrastructure management challenges when defining and using a digital twin based on existing data were studied by Heise (2023). The study describes the systems and organisation of infrastructure management in Bavaria, Germany. Three use case categories of current condition, correlation of past data and forecasting of condition were selected. Required data was then mapped to evaluate the three use cases. The results indicate that different structured and distributed available data must be linked and evaluated which is strongly use case dependent. Each specialised institution, with distributed database systems, and subsystems data has very heterogeneous characteristics that can lead to different data models for abstraction. Implementation of digital twin is suggested to have a linked evaluation of distributed data.

Tunnel operations with managed digital twins and a case study of a tunnel project in Germany have been published by Diren & Althen (2023). Digital twin use on predictive maintenance information and its benefits in the future for example in air handling is suggested. Tunnel management can also be done by displaying information for stakeholder engagement and interaction as well as assisting users with operational figures. Digital representation (or model) of the use case tunnel with traffic interaction is introduced. Use case benefits were limited to functional such as staff training and performance testing of the control system. Yu et al. (2021) have proposed a digital twin-based decision analysis framework for the operations and management of tunnels. The framework was utilized for a fault cause analysis of fans in a tunnel while demonstrating an automatic decision analysis process and validity.

Conclusions from the previously reviewed articles are here discussed. Road infrastructure assets where digital twin was applied included bridges, pavement, highways, and tunnels. Most of the road infrastructure digital twin studies presented suggested architectures and data models that were tested with a use case. Few of the papers seem to not include fully automated bidirectional communication and changes between the digital and physical object; it can be argued that the presented "digital twins" were mostly digital models or digital shadows, i.e., there is no data flow between the physical and digital objects or only from the physical infrastructure to the digital model. Although these studies and use cases presented the next steps to engage further in the full automated digital twin, this indicates further a lower-level technical fidelity of the existing digital twin implementation and the complexity and scale that the fully automatic implementation would require.

5.3 Traffic Management

Traffic management contains three types of services: traffic information, traffic control and demand management services. Some of the services provided today are the following (EU EIP 2021, Appel et al., 2018):

Traffic information services

- Forecast and Real-time Event Information
- Traffic Condition and Travel Time Information
- Speed Limit Information
- Road Weather Information
- Multimodal Travel Information

Traffic management and control services

- Dynamic Lane Management
- Variable Speed Limits
- Ramp Control/Metering
- Hard Shoulder Running
- HGV Overtaking Ban
- Incident Warning and Management
- Traffic Management for Corridors and Networks
- Crisis and Disaster Management

Demand management services

- Road User Charging
- Intelligent and Secure Truck Parking
- Abnormal Goods Transport Regulations
- Urban Vehicle Access Regulations

European specifications in the form of guidelines exist for the services themselves (EU EIP 2021) but not yet for the digital twins. The digital twins for traffic management are still in the development phase.

The concept of interactive traffic management has been developed and promoted by the TM2.0 platform. The concept aims to use a set of common interfaces, principles, and business models to facilitate the exchange of data between vehicles and traffic management centers. A key part of the concept is that all stakeholders share the common operational picture of the traffic status in the road network. (TM2.0 2024) In practice, this means a shared digital shadow of the traffic conditions evolving towards digital twins in the future.

The European TANGENT project has provided data requirements for multimodal network traffic management with the following hierarchy: (Comerio et al., 2022)

Road transport network data

- Road transport network (roads, limited access zones, etc.)
- Road equipment position
- Public transport network
- Road transport network events (real time/ historical)
- Public transport network events (real time/ historical)
- Road transport network incidents (real time/ historical)
- Public transport network incidents (real time/ historical)

Road transport data

- Road traffic measurements (occupancy, speed, flow)
- Floating vehicle data
- Road travel times

Public transport data

- Ticket validation data
- Floating public transport vehicle data (real time/ historical)
- Delays (real time/ historical)
- Occupancy (real time/ historical)

Influencing factors

- Forecasted weather data (real time/ historical)
- Holiday/seasonal calendar
- Planned events (sport, entertainment etc.) (real time/ historical)

Other

- Demand Responsive Transport fleet characteristics
- Dynamic pricing or access zones/areas
- Data about other transport modes

Digital twins for traffic management could thereby contain the aforementioned data. In addition, it should naturally also contain the data on the status of traffic management systems including messages displayed and disseminated, traffic circulation and incident management plans currently in force as well as the status of the individual system components (whether the roadside or mobile sensors, stations, dynamic signs, and data communications etc. are functioning properly or not). Furthermore, also crisis and disaster data should be included as these are extremely critical to the transport network operation resilience while occurring quite seldom. A specific data type there contains evacuation plans.

Digital twin related research projects and studies have given special attention to issues related to road transport. These have related to improving traffic data (e.g. Kušić, et al. 2023, Li & Zhang 2023, Rundel & De Amicis 2023, Vanderhoydonc, et al. 2022, Wang, et al. 2022) and enhancing signal control (Dasgupta, et al. 2023, Wagner, et al. 2023).

Angarita, et al. (2022) addressed network traffic management and its optimisation specifically. They provided insight for the optimization coupled traffic signal and route planning optimization for connected and automated vehicles, integration of demand responsive transport with public transport modes, synchronized public transport and traffic control, and Dynamic Congestion Pricing schemes. Different negotiation and arbitration models for transport network management proved to be essential for integrated decision-making as the network management must consider economic, environmental, socio-political and other factors while entailing the involvement of various stakeholders with their own objectives and priorities. Thereby, they discuss different consensus definitions, approaches to selecting the optimal solution when the stakeholders have different preferences, the state-of-the-art decision-making approaches based on the principles of Agent-Based Modelling. Finally, they provide guidelines that delineate the development of a consensus-reaching mechanism, discussing its objective, scope, domain of application, stakeholders, data needs, and modeling approach. (Angarita, et al. 2022)

The Austrian, Dutch and Finnish national road traffic management experts were interviewed to clarify the status of digital twin use in traffic management.

In **Austria**, ASFINAG is responsible for the traffic management of the Austrian highway network. They have had digital road infrastructure models for more than 10 years starting with BIM, road surfaces, and regulations. During the past years all digital models have been integrated into digital shadows and new data types have been added including the traffic and weather condition data. The raw data is provided via standardized interfaces such as DATEX II and SENSORIS to the service providers and vehicle manufacturers according to the user's needs. Currently, the data has been provided to and used by the SRTI (Safety Related Traffic Information) stakeholders, including the Data4Roadsafety ecosystem, but the future uses have increasing complexity and also challenges especially due to the legally binding nature of some of the regulation-related data. (Allmer 2024)

So far, the digital shadows have not led to digital twins, but ASFINAG hopes to have the required feedback loop from the vehicle manufacturer side to make this development step. The vehicle manufacturers have not used all of the ASFINAG data due to lack of trust, and a special case has been incident detection. The vehicle manufacturers and their vehicles are quicker than the road users to detect accidents and other incidents such as obstacles on the lane. On the other hand, ASFINAG is much quicker and more reliable to know when the incident has been cleared and the road operation becomes normal again. Hence, the integration of data from both stakeholders would benefit both. (Allmer 2024)

Concerning weather data, ASFINAG has had high hopes of getting improved weather data. Weather data has so far been collected mainly for winter and road maintenance purposes, with the network divided into 42 different road sections of an average length of 40 km. Each section has several road weather stations providing data on temperatures, water film thickness, and salt concentration. There is the issue that the road weather sensor only covers on spot in the road cross-section, and that spot cannot represent the whole cross-section. ASFINAG has thousands of cameras, which also offer a lot of possibilities in this respect. The possible improvement of weather data could occur by utilizing data on temperature and slip data from vehicles. A number of vehicle manufacturers such as Audi, Mercedes, and Volvo have been offering such data but it has not been widely utilized for various reasons. (Allmer 2024)

The main issue is not to provide of a digital model of the road infrastructure and the road transport system but also to maintain it, i.e. to set up a real-time digital shadow. ASFINAG has also worked on the issue of digital shadows of road works sites, but this has not been solved fully yet. Also here, the real-time maintenance of the digital shadow has been a problem. GNSS position accuracy has been an issue for the digital shadow of road works sites, but the GALILEO HAS (High Accuracy Service) has shown a lot of accurate positioning promise for the road works sites and for all C-ITS use cases. (Allmer 2024)

The use of digital twins in decision support at traffic management centers has also been discussed in ASFINAG. There are several options to proceed such as the utilization of simulation for selection of the optimal traffic management measures and the utilisation of the vehicle ecosystem support approach. (Allmer 2024)

In **Finland**, the state-owned company Fintraffic Road is responsible for the traffic management of Finnish highways. They have developed a digital model or shadow for the traffic situation including traffic volumes and speeds on selected sections as well as the locations and properties of roadworks, incidents, and a set of events. The background is the digital model of the road infrastructure called Digiroad. Weather and climate data have their own digital models. The traffic center operator's user interface T-LOIK integrates all of these in its different layers as a digital decision support system. (Rossi & Kariniemi 2023)

For the control of the most critical tunnels, a digital twin of the tunnel exists and provides for automated congestion detection and tunnel closure although manual operation is also possible. The vision is to have more automated warnings in the tunnels based on e.g. weather information utilizing the multitude of sensors and other devices in tunnels. (Rossi & Kariniemi 2023)

Development is ongoing in Fintraffic to enhance road surface condition detection, improve data analytics for traffic management, speed up rerouting already when anticipating incidents, to integrate data from various sources including fleet management and crowd-sourced data, drones, etc. The actual knowledge of winter maintenance actions such as plowing or salting would be useful for enhancing the digital shadow of the road transport system. (Rossi & Kariniemi 2023)

The rescue and police authorities play an essential role in incident management. With regard to the rescue authorities, the emergency centers have a key role in acquiring information on incidents that have occurred via manual and automated emergency calls. The centers then maintain a digital twin (shadow) of the incidents and push incident information to Fintraffic, other rescue authorities as well as the police. The other rescue organizations have today only a few digital twins. They utilize the Fintraffic data on traffic situations and have built their own PRONTO accident database containing all tasks from the rescue sector and comprehensive alarm functions. The tasks from the emergency center are accepted into the database and then the database contains a diary of the development of the incident in question. This is mainly a digital model as it is mostly not in real-time. The rescue authorities need fast routes for the emergency vehicles and thereby also good real-time traffic situation information. They are also keen on having real-time information on any dangerous materials carried onboard the incident-involved vehicles. The digital twins of tunnels are already used in rehearsals of tunnel incident clearance. (Timonen 2024)

The police in Finland are utilizing the data and information of the digital models and shadows of Fintraffic (traffic situation, speeds, weight in motion, road weather) and the rescue authorities (especially the incident information from the emergency centers) to enhance their own police and enforcement processes and operations. The vehicle register of the Finnish Transport and Communications Agency Traficom has been found to be a regularly used digital model for the police in identifying non-registered, non-inspected, or stolen vehicles in the field. The digitalization of the police's own processes is not very advanced yet. (Ihalainen 2023).

In **the Netherlands**, Rijkswaterstaat (Ministry of Infrastructure and Water Management) is responsible for traffic management on the highways. In 2022 Rijkswaterstaat published their Traffic Management Road Map which illustrates ambitions in the field of Smart Mobility in general and Traffic Management in particular. Although the term Digital Twin itself is not mentioned the document shows how Traffic Management is in a state of transition where digitalisation, connectivity, and collaboration are indispensable. Along the following four tracks this transition is envisioned:

- exchanging and using data (e.g. data from others);
- developing assets (e.g. smarter roadside systems);
- influencing the behavior of road users;
- cooperating with partners

Smart Mobility, i.e. the combination of innovations that make it possible to organise mobility better and more cost efficient) are seen as a key enabler to achieving these societal goals. The road operator services are expected to benefit, one way or another, from (enhanced) digitalisation, connectivity and collaboration. In the future, many services will focus more on cooperation, so that partners can make an optimal contribution to traffic flow and safety together. The Traffic Management Road Map states that **"**with this improved digital view, we can do our work better, faster and more efficiently in all network services".

Rijkswaterstaat is highly advanced in the provision of digital models for the physical road infrastructure's construction and maintenance.

With regards to data, attention is paid to privacy and security as well as making the road operator data available to everyone, reliably and in high quality and not only visible visually but also digitally. It is expected that a great deal of traffic data will originate from new sources, for example directly from vehicles and therefore road operators must not only be prepared to share data but also to be able to receive and process relevant data in their processes.

Traffic management is teamwork and requires collaboration between all road operators. Rijkswaterstaat, as the largest road operator feels responsible for the network system as a whole. Therefore, they also entered into more partnerships with private parties for instance in projects like SOCRATES$^{2.0}$ - in which governments and the private sector share data to advise road users on optimal routes – that lay the basis for structural and intensive automated data exchange and coordination. A shared common operational picture of what is actually happening on the road networks at the moment plays a vital role. As a first step, this common operational picture is a real-time digital shadow of the road networks' traffic status where the cooperating stakeholders together maintain their parts of the digital shadow. The future aim is a digital twin, where the cooperative traffic management measures and other actions of the stakeholders will affect the real-life operational picture.

Today, Rijkswaterstaat has a good coverage digital shadow of the traffic conditions on its main road network and is already enhancing the digital shadow with data from external stakeholders such as vehicle manufacturers.

SOCRATES$^{2.0}$ also provided essential building blocks to prepare Europe for the future of automated mobility, which is relevant because an increasing presence of highly automated vehicles or Connected and Automated Vehicles (CAVs) is expected to have a significant impact on traffic management. Stakeholders, such as public agency operators and toll road operators, need to adapt their Traffic Management Center (TMC) policies and procedures. and vehicle manufacturers need to adapt their in-vehicle systems to be able to react appropriately to traffic management messages (Alkim et al, 2023). See Chapter 6.3 for further implications.

5.4 European and global digital twin initiatives

This chapter below lists mobility and transport-related European and global digital twin initiatives. The initiatives, projects, funding and consortiums were found using search engines, interviews and literature such as Semanjski (2023). The results are presented in alphabetical order.

Augmented CCAM is a project of Augmenting and Evaluating the Physical and Digital Infrastructure for CCAM deployment which also includes digital twins. (https://augmentedccam.com/)

DIGEST was a project developing the concept of a digital twin model to benefit road operators as well as all road users including connected and automated vehicles. (Ulrich, et al 2023)

Digital Europe Programme (DIGITAL), Data-driven communities workshop reported by digital twins "The data space for climate-neutral and smart communities will also be important for Urban Digital Twins. Several EU projects are piloting the concept (DUET, LEAD, DigiTranScope, URBANAGE, etc.), while Eindhoven, Newcastle, Rennes, Luxembourg and the UK also putting in place twins focusing on their specific needs. (https://digital-strategy.ec.europa.eu/en/library/data-driven-communities-fostering-local-data-ecosystem-sustainability)

Digital Twin Consortium drives the awareness, adoption, interoperability, and development of digital twin technology. It is a collaborative partnership with industry, academia, and government expertise and is open to any business, organization, or entity. (https://www.digitaltwinconsortium.org/)

Digital Twin hub (DT hub) was established by Cambridge University's Centre for Built Digital Britain (CDBB). DT hub is a collaborative web-enabled community for those who own, or who are developing, digital twins within the built environment. (https://digitaltwinhub.co.uk/)

FEDeRATED proposal of EU federated network of platforms, i.e., interoperable network of virtual worlds based on digital twins and connecting Events. Digital Twin in freight transport and logistics has been introduced in the activities (2024). (https://www.federatedplatforms.eu/)

Gaia-X is a secure and federated data infrastructure for Europe. Digital twins have been introduced for example as a part of planning and citizen participation in smart urban planning. (https://www.data-infrastructure.eu/GAIAX/)

Hi-Drive is a Horizon 2020 project developing higher levels of automated driving, where digital twins are investigated especially in the tunnel use case.(https://www.hi-drive.eu/project/)

Local Digital Twins (LDT) Technology Workshop was organised by the European Commission in 2021. (https://digital-strategy.ec.europa.eu/en/events/workshop-local-digital-twins-technology)

MetaCCAZE project is a European Union co-funded project for European cities and urban mobility. The project is expected to have digital twin transport and mobility related initiatives. (https://www.metaccaze-project.eu/)

Open & Agile Smart Cities & Communities (OASC) is global network of communities that assists local administrations of all sizes in their digital transformation. Although for cities, the work includes also European digital twin topics such as traffic management as well as asset and infrastructure management. (https://oascities.org/)

Open urban digital twins in Flanders is an open evolving draft that reflects the current thinking around digital twins in urban or local environments (https://vloca-kennishub.vlaanderen.be/Open_urban_digital_twins). The documentation includes architecture, design principles, maturity levels, and related initiatives. Use cases such as pandemics, air quality and traffic, flooding and traffic as well as sound and traffic can be relevant also for road operators. It seems to be part of the Flemish Open City Architecture Knowledge Hub (https://vloca-kennishub.vlaanderen.be/).

SPHERE is a Horizon 2020 project that aims to provide a BIM-based Digital Twin Platform to optimize the building lifecycle. Although for buildings, can offer relevant ICT platforms and real-time data development experiences. (https://sphere-project.eu/)

5.5 Current state of Digital Twin at selected road operators

In order to gain insights into the current state of Digital Twin at road operators, the information collected from the discussion with road operators during the workshop, interviews, and questionnaires were analyzed. The discussions revolved around the current state of digital twins in their respective organizations and the challenges they face in implementing and maintaining them.

As it came out during the discussion in the workshop, most organizations are in the early stages of implementing digital twins. They are capturing static data and trying to link it to dynamic data. However, they do not yet have a fully functional digital twin of an entire ecosystem. Most of the digital representations are either digital models or digital shadows.

Some organizations have asset information management systems in place, which are used to manage and maintain information about the organization's assets. The associated information includes but is not limited to tender specifications information, observations, complaints and reports, condition measurements, inspections, management tasks, maintenance tasks, condition assessment etc.

Organizations are also using Geographic Information Systems (GIS) to manage their data. They are trying to integrate GIS with asset management systems to create a centralized asset registry. Within the organizations, the current level of data complexity is low with incomplete attribute information or unmapped assets.

The participants shared the following insights about the state of digital representations and digital twins within their organizations:

- The road authority at the Flemish region of **Belgium**, Vlaanderen shared that they are in the process of developing a digital twin for their network asset data, but it is not yet optimized. They currently have a system for asset information management, which mostly contains static data. They are trying to link this static data with dynamic data from sensors on the assets and also with BIM models for more detail. The goal for the organizations is to move towards more predictive maintenance using digital twin technology and be more proactive in managing their assets. However, they do not yet have a decision-making system for predictive maintenance.

  Additionally, it was reported that the current level of data complexity for existing models/representation was low, with a medium penetration rate, low update frequency, and high geographical coverage.

- Rijkswaterstaat (Dutch road authority) in **the Netherlands** is also working on a digital twin. They have a simplified representation of a highway, similar to a metro map, which indicates traffic lights or signals above the road. This is not projected on a real map or location, and its primary purpose is to present information on a video screen for traffic operators in the traffic control center.

- Transport Infrastructure Ireland (TII), in **Ireland,** uses enterprise Geographic Information System (GIS) and is trying to integrate an asset management technology with their enterprise GIS technology. They are also trying to automate processes to consume data in a more automated fashion. They see GIS as a significant stakeholder and not just a mapping tool. They view BIM as project-focused and not suitable for managing data at an enterprise level.

- **In Finland**, the Finnish Transport Infrastructure Agency (FTIA) is responsible for road infrastructure planning and maintenance. The FTIA members interviewed recognized that the digital twin term has multiple interpretations. At the moment implemented systems like infrastructure have been digital models rather than digital twins. The digital models contain sufficient data to develop models to forecast reliably the operation and evolution of the system in time enabling the control of the system via all processes needed. (Savolainen 2023)

  Infrastructure monitoring, to feed data for the digital models, or shadows, is done for selected parts of the road infrastructure, for example to bridges to follow lifecycle development. It is important to know the vulnerability and likely wear of the different elements of the road infrastructure. Monitoring sensors are used together with models only when and where needed. The digital model is available at the Digiroad.fi website as open data which any service provider or developer may use. FTIA is currently improving its digital models, and shadow, to merge the data from the contractors' digital systems. (Savolainen 2023)

  There is a consideration of being distinguished between digital twins and models for the whole network and selected road sections. BIM has been available for a selection of road sections, typically sections to be built or rebuilt. The whole network may cover data such as road surfaces, lanes, and guardrails, while data such as the steel used to strengthen the construction are not utilized in the whole network models. Producing BIM for the whole network could take an extremely long time and a lot of resources. The road register system in place contains key road attributes, based on road addresses and coordinates of nodes (links), to facilitate the FTIA processes for over a decade. The national road infrastructure project management information process has been developed, as presented in Figure 20, to ensure the flow of data between the BIM tools used in projects, planning, georeferencing, and road information databases. The aim is to collect all necessary information about the completed projects, i.e., digitize automatically already in the construction phase, not after the road is made. For this use, the BIM portal has been tendered and the collection of BIM models and documents is starting. (Savolainen 2023)

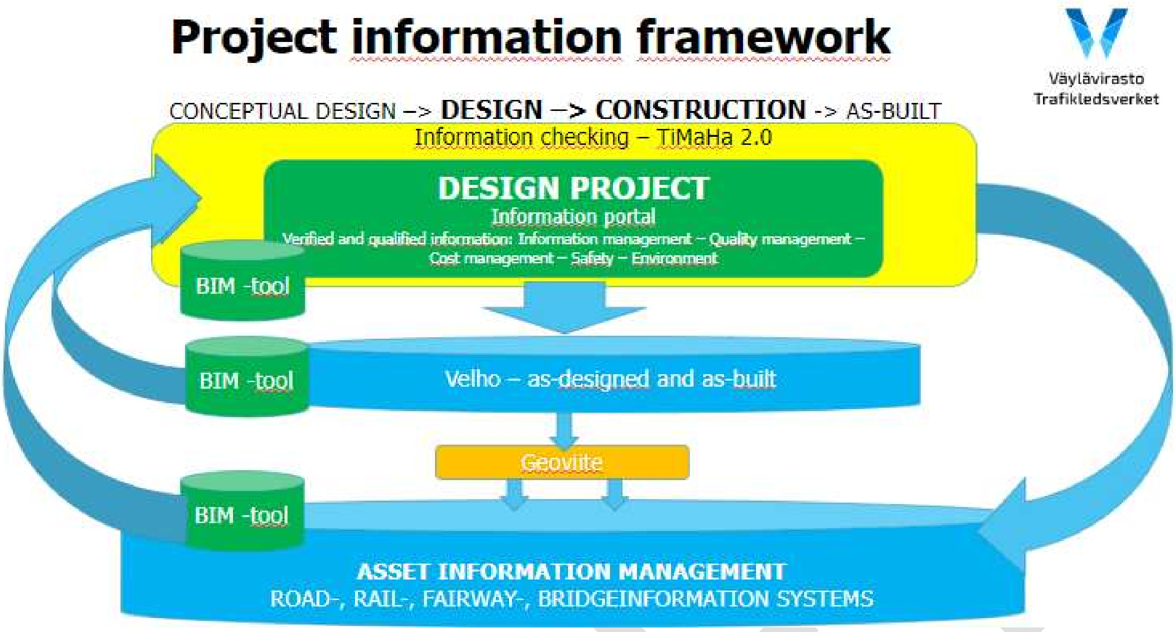

Figure 20 Finnish Transport Infrastructure Agency (FTIA) project information framework development. (Savolainen 2023)

In the future, better data accuracy, more attributes, and real-time data are required. This can be used to update the current forecast models of maintenance and other measures undertaken on the network. The coverage and timeliness of the maintenance and other measure data have been constantly improved, e.g., from carriageway-specific data to lane-specific data. The next steps include better terrain models, such as ditches, embankments, rock excavations, culverts, roadside vegetation descriptions, etc. The vision of the digital model, and future digital twin, is 100% coverage real-time 3-D model fulfilling the quality requirements agreed. Model calculations and modeling have already become much more complex. The development of open standards and work done in cities will also be interesting in the future. (Savolainen 2023)

The participants also discussed the challenges they faced in obtaining data for the creation of the Digital Twins. The most common challenges are as follows:

- **Data Collection:** Organizations face challenges in data collection, especially when it comes to capturing necessary data to maintain an aging infrastructure. It is sometimes difficult to obtain crucial information such as material, structural design etc. which gets missing over time due to changes in organization or governance.
- **Privacy Issues:** While there are no privacy issues with asset data, however, when it comes to data related to road users, such as C-ITS data or floating car data, there are privacy issues that need to be addressed.
- **Legal issues**: There are also sometimes issues related to determining the ownership of assets especially old infrastructure which makes it difficult to identify who is responsible for monitoring and maintaining it.

The participants agreed that they are still in the early stages of implementing digital twins and do not yet have examples of how digital twins have significantly benefited their organizations. They acknowledge that it is a challenging process that requires improving their technology and processes. They express a desire to move towards more predictive maintenance and proactive asset management decision-making in the future. They acknowledge that different stakeholders have different requirements, and the role of stakeholders in the larger ecosystem will determine their responsibilities.

While the adoption of digital twins by national road authorities is still in its early stages, there is a clear recognition of the potential benefits of this technology. However, several challenges need to be addressed, including data collection, privacy issues, legal issues, the need for more granular data, and the integration of various technologies. Most organizations anticipate that it will take three to five years to fully implement and benefit from digital twin technology.

5.6 Use cases of digital twins in mobility

Depending on the available data and application area, digital twin mobility can include different use cases. Mobility Lab Helsinki (Rinne et. al. 2022) has provided many of these use cases.

- **Urban transport system modeling, planning, and impact assessment**
  - Modeling and impact assessment of New constructions, interventions, and policies (e.g. land use planning, traffic planning, low-emission zones, road use and congestion charges, tunnels, construction works, and new services)
  - Analysis and simulations of traffic, parking, businesses, the vitality of the city center, emissions, energy use, etc.

- **Mobility and transport services**
  - Optimised operations and service provision (on-demand, others)

- **Infrastructure maintenance**
  - Optimised street maintenance (e.g. winter maintenance, up-to-date traffic signs, road condition monitoring and maintenance)
  - Predictive maintenance

- **Navigation and wayfinding**
  - Information, routing and navigation tools for citizens with specific requirements and functional limitations (e.g. the visually impaired, wheelchair users, baby strollers, language barriers, cognitive challenges, etc.)

- **Traffic management and service operations**
  - Dynamic traffic management: alleviating congestion, prioritising active and green mobility

- **Traffic light optimisation**
  - Improving traffic flow based on situational awareness through active traffic light optimisation according to different priorities (e.g. active modes, public transport, emissions, congestion)

- **EV charging**
  - Planning and modelling charging infrastructure needs and requirements to match the demand in the near-, mid-, and long-term
  - Current and predicted availability information on charging stations

- **Automated driving**
  - Operating automated vehicles in the urban environment

It is worth highlighting that not all potential use cases are even known yet.

6 Digital Twin challenges and future opportunities for road operator

6.1 Desired state of Digital Twin within selected road operators

The discussions during the workshop and responses to questionnaire provided some information on the desired state of digital twins within road operators. Based on the conversations, the desired state of digital twin and Asset Information Models (AIM) would be to effectively utilize them in various use cases to enhance the efficiency and effectiveness of operations. Some of the desired use cases for digital twins that were discussed are as follows:

- **Predictive Maintenance for Assets**: Asset management appears at the top of the list of desired use cases. The road operators already maintain digital representations of various assets in the infrastructure such as roads, bridges, tunnels, and all types of furniture of roads, such as guardrails, markings, signs, street lamps, Electromechanical assets etc. A detailed list of various assets being managed by Vlaanderen (road authority in Flanders, Belgium) can be found on the following website: https://wegenenverkeer.data.vlaanderen.be/.

  The digital twin and AIM is desired to be used to predict maintenance operations on specific asset types, thereby reducing downtime and improving asset lifespan.

- **BIM to AIM to Digital Twin** – In Belgium, the information stored in existing BIM models is standardized using the object type libraries (OTL). The objective is to use the existing BIM and AIM models to create a digital twin for asset management.

- **Monitoring and response:** A digital twin of the highway could help in continuous monitoring of the traffic situation along with any incidents. This information can help in effectively managing the situation by managing traffic flow, lane closures, and faster response times.

- **Cooperative Intelligent Transport Systems (C-ITS) Services**: The digital twin and AIM could be used to provide C-ITS services to road users, enhancing safety and efficiency on the roads.

- **Optimizing Traffic Management**: By leveraging the digital twin and AIM, traffic management could be optimized, leading to smoother traffic flow and reduced congestion.

- **Winter Management**: The digital twin and AIM could be used to manage winter conditions on the roads, such as monitoring the slipperiness of roads and planning for salt spreading operations. This use case would rely on new data collected from vehicles, such as traction control systems, to provide information about the actual situation on the roads. This data could be used to create a map of slippery roads. It would require a good coverage of data collection as well as cooperation from many vehicle manufacturers and 3rd party data providers.

The conversation also highlighted several requirements and challenges for these use cases, including:

- **Need for real-time data from vehicles** – It is crucial to receive real time data from vehicles to ensure that digital twin remain up to date. A real time flow of data along with well-established data processing algorithms would lead to a real-time digital twin of the situation on highways. A real-time digital twin can help in asset management. For example, if the data indicates that roads are slippery, the organization needs to have enough trucks to spread salt on the roads.

- **Good coverage of data collection** – It is important to gather data from multiple vehicle manufacturers to ensure good coverage of data from vehicles.

- **Standardization of data across different vehicle brands** - Another challenge that adds up is that data from different vehicle manufacturers is not standardized. Each vehicle measures different parameters, and sometimes the sensors are located in different parts of the car, leading to different interpretations of the data. Thus it is important to ensure that data capture and communication are standardised to ensure consistency and quality of digital twin.

- **Ability to act on the data to implement solutions** – This challenge focuses on the organization's capability to handle, manage, and use data to implement solutions. A lack of data management and processing skills in an organization could lead to ineffective data use.

- **Additional data sources** – It might be worthwhile to explore the use of additional data sources such as Light Detection and Ranging (LiDAR) to capture road geometry in more detail, traffic data, weather data, etc.

- **Organizational changes** – Implementations and proper utilization of digital twins may involve a shift in the organizational mindset and ways of working. The existing practices aren't mainly data-driven in various organizations, rather based on a less efficient approach.

The participants also discussed the need for a common ground in Europe to make data more available and discussable. They also mentioned the challenge of data being collected but not being used for asset management purposes. In addition, the importance of including algorithms and analysis tools was emphasized as they help in extracting the value out of data. The desired state would address these challenges and requirements to fully leverage the potential of digital twin and AIM in these use cases.

6.2 Difference between current and desired state of Digital Twins within selected road operators

The **current state** of Digital Twins within selected road operators is that most organizations are in the early stages of implementing digital twins. They are capturing static data and trying to link it to dynamic data. However, they do not yet have a fully functional digital twin of an entire ecosystem. Most of the digital representations are either digital models or digital shadows. Some organizations have asset information management systems in place, which are used to manage and maintain information about the organization's assets. Organizations are also using Geographic Information System (GIS) to manage their data. They are trying to integrate GIS with asset management systems to create a centralized asset registry.

On the other hand, the **desired state** of Digital Twins within road operators is to effectively utilize them in various use cases to enhance the efficiency and effectiveness of operations. Some of the desired use cases for digital twins include predictive maintenance for assets, monitoring and response, Cooperative Intelligent Transport Systems (C-ITS) services, optimizing traffic management, and winter management. The desired state would address several requirements and challenges to fully leverage the potential of digital twin and Asset Information Models (AIM) in these use cases. These include the need for real-time data from vehicles, good coverage of data collection, standardization of data across different vehicle brands, and the ability to act on the data to implement solutions. The participants also discussed the need for a common ground in Europe to make data more available and discussable. They also mentioned the challenge of data being collected but not being used for asset management purposes. In addition, the importance of including algorithms and analysis tools was emphasized as they help in extracting the value out of data. Most organizations anticipate that it will take three to five years to fully implement and benefit from digital twin technology.

6.3 Future opportunities

The global digital twin market was valued at €9.4bn in 2023 and is expected to reach €102.5bn by 2028. There is a growing focus on predictive maintenance across the industry. (MarketsanMarkets 2023).

Digital Twins facilitating Automated Driving Systems (ADS) can be part of future opportunities. The CEDR funded TM4CAD project explored the role of infrastructure systems across various Infrastructure Support for Automated Driving (ISAD) levels in creating ODD awareness for CAD systems. The starting point was various categories of distributed ODD attribute information and defined acquisition principles of the information based on exchange between the stakeholders, ultimately to enable CAD systems to be aware of their ODD in real-time. TM4CAD has demonstrated the basic mechanisms of ODD management via real-world use cases, which build on the premise of interaction between traffic management systems and CAD vehicles. This provides road operators insight into methods to inform CAD systems about the kinds of support they can provide for CAD operations on European roads.

To gain a complete understanding of traffic management for CAD, the TM4CAD project has:

- Identified the full range of ODD attributes for consideration, based on experience from working on ODD issues in standardization activities and in other related research projects;
- Integrated the different perspectives of the CAD vehicle system developers and the national road authorities and operators to focus on the overlapping areas;
- Introduced the concept of Distributed ODD attribute Value Awareness (DOVA) and the role of infrastructure in it;
- Developed recommendations based on the technical constraints of the ODD-relevant information that can be perceived and exchanged in real time by the road operators and the sensing systems of the CAD-equipped vehicles;
- Provided insights on how to support CAD operation and ODD management, how ISAD should be refined for traffic management use, and
- Detailed how traffic management systems and CAD vehicles can best interact to improve traffic operations.

The TM4CAD project has introduced the DOVA concept as a mechanism to enable early deployment of Connected Automated Driving (CAD) by providing infrastructure support to the CAD system to aid its capability for Operational Design Domain (ODD) awareness. ODD definition and awareness are key to the safe operation of CAD systems. Various ODD attributes and the potential for infrastructure support for real-time information gathering for each of the ODD attributes are relevant, as well as time criticality of updating each ODD attribute value, which depends on its rate of change. Depending on the level of infrastructure support and the level of CAD on-board sensing, various kinds of information relevant to the ODD can be supplied as part of a DOVA framework. (Khastgir et al. 2023) To enable the DOVA approach in a pragmatic manner and unlock its potential, the use of digital twins is foreseen.

The DOVA framework enables the ADS to benefit from off-board sensing and information infrastructure to become aware of ODD attribute values which it may not be able to measure or sense directly using onboard sensors. For example, a CAD system will not be able to detect foggy conditions more than a couple of hundred meters ahead on its path, nor will it be able to distinguish how badly they degrade visibility. It could, however, receive this information from an existing roadside weather station or a new special-purpose visibility sensor located in fog-prone locations, which can provide this information through over the air communication directly with the CAD system or indirectly through a cloud-based repository. This would enable the CAD system to have awareness of this current operating condition and compare it with its ODD visibility constraints to determine how it should respond. (Khastgir et al. 2023)

ODD attribute awareness via the DOVA framework is one factor influencing the safe operation of CAD systems. Other factors influencing CAD safety assurance and automation driveability, visualized in Figure 21, include:

1) Technological and behavioral competencies of the CAD system
2) Driving behavior of the CAD system
3) Rules of the Road

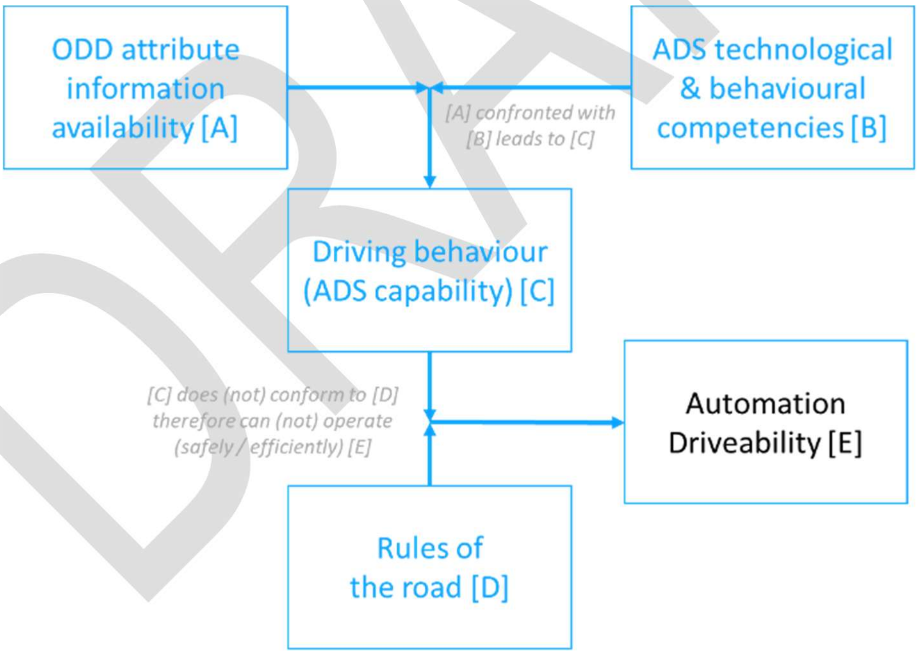

Figure 21: Relationships among ODD awareness, ADS capabilities, rules of road and safety assurance. (Khastgir et al. 2023)

While the DOVA framework facilitates the provision of ODD attribute information, it does not inherently ensure the safe operation of CAD systems. Through the DOVA framework, CAD systems gain access to ODD attribute information, allowing them to assess their technological capabilities within a specific environment. This capability aids the CAD system in determining a vehicle's adherence to traffic regulations and its ability to navigate without conflicts with other road users. Essentially, an ADS equipped with the requisite attribute information should be able to make safe and efficient driving decisions, allowing it to operate effectively in a particular local condition. However, the successful implementation of the DOVA framework necessitates investment in infrastructure by road operators and commercial entities. This investment is crucial for the collection and sharing of diverse ODD attribute information and thus the road operator's ambition to go beyond its formal obligations (facilitating ADS is currently not one of them). The choice of ODD attributes and the timeliness of updates, reflecting information criticality, will impact infrastructure investment decisions, taking into account both cost and effectiveness considerations.

An increasing presence of highly automated vehicles or Connected and Automated Vehicles (CAVs) is expected to have a significant impact on traffic management, while stakeholders, such as public agency operators and toll road operators, need to adapt their Traffic Management Centre (TMC) policies and procedures. In the meantime, vehicle manufacturers need to adapt their in-vehicle systems to be able to react appropriately to traffic management messages (Alkim et al, 2023).

Impact of CAVs on traffic flow

Traffic congestion in urban areas has significant negative effects on the economy, society, and the environment, prompting a need for innovative solutions. Traditional responses involve expanding road infrastructure and implementing traffic management measures, but these have drawbacks. CAVs have emerged as a potential solution, promising improved safety and mobility. However, the success of CAVs depends on their penetration speed, effectiveness, and potential negative impacts, often underestimated in studies. CAVs are designed for safety, but human drivers take calculated risks based on perception and communication. Coding these aspects into automated vehicle operation is challenging, and could lead to potential deterioration of traffic characteristics and road capacity. When CAVs act in a coordinated manner, they could offer a promising solution. Such systems, managed centrally or decentralized, can enhance traffic efficiency and mitigate negative impacts. Traffic management for CAVs could allow for more effective strategies and benefit overall traffic system performance.

From automating vehicles to automating traffic

Up until now, the design of AVs and CAVs by manufacturers has considered essentially a static road network, where infrastructure characteristics and regulations are embedded in the vehicle system and do not respond to dynamic external inputs (Bishop 2005, Diakaki et al, 2015). The dynamic components have been limited to interactions with other vehicles or obstacles, essentially only for safety purposes, while decisions are taken, advantaging the individual vehicle only. Limited work has been done on standardizing messages for Advanced Traveler Information System (SAE J2354, 2019), whereas there is no standardization on the response that vehicles may implement once such messages are received. On the other hand, a large body of research (see, e.g., Papamichail et al, 2019) has suggested various ways of implementing active traffic management strategies that interact directly with CAVs via messages exchanged among vehicles or with the infrastructure; however, due to the limitations above, such strategies have not been implemented. Efforts in this area should give the possibility to the main stakeholders involved in traffic management, namely, public agency operators and (toll) road operators, to exchange active traffic management-related messages with CAVs. Vehicle manufacturers should consider such features in the design of future CAV systems aiming at a harmonized integration of CAVs within the transport system, also considering design principles that are not selfish but would lead to collective systemic benefits.

In the meantime, traffic management stakeholders, such as public agency operators and (toll) road operators, need to adapt their Traffic Management Centre (TMC) policies and procedures to account for the increasing presence of CAVs so that both existing and novel traffic management measures, involving, for example, flow metering, variable speed limits, lane use management (including hard shoulder running), dynamic rerouting, and, in general, real-time messaging, are able to seamlessly interact with the operation of CAVs through the use of connected vehicle-to-infrastructure (V2I) communications. This will require an upgrade of the (mostly digital) infrastructure, to account for the improved sensing and actuating capabilities that will be moved from the infrastructure to the CAVs, as well as the development of data fusion engines, which would be capable of processing various types of traffic and vehicle data, resulting in efficient monitoring of the operational traffic situation.

Research efforts should support such developments and actively enable such transitions focusing, among other aspects, on the dynamic responses needed to be designed into the CAV, the standardization of these messages, responses to that messaging, as well as integration with the upgraded digital infrastructure and its novel decision support system widely employing innovative data fusion engines.

Predictive Infrastructure Management can be another future opportunity for Digital Twins. Existing digital representations of infrastructure assets can be transformed into dynamic models. These models will be continuously updated with real-time data collected from embedded sensors, providing a comprehensive view of asset health. Advanced analytics will be applied to this data, enabling the prediction of potential problems before they become critical failures.

By anticipating potential issues, such as developing cracks in bridges or sections of roads nearing their lifespan, targeted interventions can be planned and scheduled. This proactive strategy minimizes disruptions, optimizes resource allocation, and extends the lifespan of critical infrastructure assets.

Digital twin for Cooperative Intelligent Transport Systems (C-ITS) applications can help in improving emissions, traffic safety and flow. Traffic engineers could create realistic simulations within the digital twin using real-time traffic data. By testing different scenarios, like accidents, construction zones, or changing weather patterns, they could optimize traffic flow strategies for the real world. Additionally, real-time data from the physical network would feed into the digital twin, allowing for real-time congestion prediction. Accidents and emergencies could be detected in real-time through the digital twin. Emergency response teams could be alerted instantaneously, allowing for faster intervention and improved safety outcomes.

6.4 Challenges

During the workshop, several challenges related to data were mentioned by the participating road operators. Some of the key challenges related to data are:

1. **Data Collection and Registration**: There is a challenge in collecting and registering data, especially when it comes to inspections. For instance, different inspectors might have varying interpretations of what constitutes a problem, leading to inconsistencies in data. This issue is compounded when data is not registered or updated regularly, leading to gaps in the data.
2. **Definition of Criteria**: Defining criteria for what constitutes a specific issue (like a pothole) can be challenging. Different stakeholders might have different definitions, leading to discrepancies in data. This issue extends to the use of AI and machine learning, where defining the criteria for what the AI should look for or consider a problem can be complex.
3. **Data Complexity**: The complexity of the data required for asset information models and digital twins can pose a challenge. Different levels of testing might require different levels of data fidelity or complexity. Managing and maintaining consistency across these different levels can be difficult.
4. **Data Availability**: There are challenges related to the availability of data. For instance, many designs might not be available, or the data might be outdated. This issue is particularly relevant for aging infrastructure where original plans or maps might no longer be available.
5. **Data Overload**: There can be an overload of information, especially when data is being collected from multiple sources. This can make it difficult to identify relevant information and can lead to issues in data management.
6. **Cross-Domain Integration**: Integrating data across different domains (like asset management and traffic management) can be challenging but is necessary for maximizing the utility of the data.

These challenges highlight the need for standardized procedures for data collection and registration, clear and consistent definitions of criteria, effective management of data complexity, strategies for dealing with data availability issues, and robust systems for handling data overload and cross-domain integration.

Pileggi et al. (2021) identify various challenges associated with Digital Twins. Some of the key challenges mentioned are as follows:

- *Digitization needs:* In order to enable the proper functioning of the digital twins, it is crucial to address the following challenges regarding digitization.
    - Connectivity: This refers to the way that the Digital Twin connects to the physical asset and collects data from it. Wired networks are reliable but expensive, while wireless networks are more flexible but may have latency or security issues.
    - Data: The Digital Twin needs data from the physical asset throughout its lifecycle, including design data, manufacturing data, and operational data. This data can be heterogeneous and come from different sources. The quality of data is another important factor.
    - Modeling: The Digital Twin can use different types of models to represent the physical asset, such as physical models, data-driven models, or geometrical models. Hybrid approaches can also be used.
    - Deployment: The Digital Twin can be deployed on the cloud, on the edge of the network, or on the device itself. The deployment location depends on

factors such as latency requirements, security considerations, and the scope of the Digital Twin.
    - APIs: Digital Twins need to interact with other systems, such as other Digital Twins or human operators. APIs are used to facilitate this interaction.
    - Security: Security is important for Digital Twins because they contain sensitive data about physical assets. Security mechanisms need to be in place to protect this data and ensure that the Digital Twin cannot be tampered with.

- *Laws and Regulation:* The law needs to adapt to the changing digital landscape. This includes creating regulations for data, AI models, and other digital property. These regulations should ensure traceability and accountability throughout the production and use of these technologies.

- *Organizational Barriers:* Several organizational barriers to adoption of digital twins are:
    - Lack of visionary leadership: Leaders need to understand the benefits of digital twins and how they can be used to achieve business goals.
    - Change in working practices: Digital twins require changes to working practices, and organizations need to be prepared for this.
    - Many open questions: There are many unanswered questions about digital twins, such as how to share data and ensure security.
    - Unclear ecosystem support: The digital twin ecosystem is still evolving, and there is a lack of standards and best practices.
    - Skills and competencies: Implementation of digital twins within an organization requires employees with relevant skills and competencies. Development and recognition of digital competencies are essential to having skilled people who can have the ability to engineer a solution that brings the desired benefits.

Parker (2021) points out that any deviation between the physical bridge and the digital bridge should be a point of concern that raises attention to the engineers. The bridge owner might not want to have an automatic modification to the bridge. It is questioned whether it is possible to change from the digital model to the physical bridge as the digital twin definition requires, i.e., bidirectional communication. Parker also lists cases where too much trust has been given for digital models which have caused issues such as bridge collapse.

European Commission event report on Data-driven communities: fostering a local data ecosystem for sustainability (EC 2021) includes Urban Digital Twins sections where the following issues are listed: legal security around data sharing, data ownerships, data roles and responsibilities, data availability and quality as well as privacy aspects.

Arisekola & Madson (2023) studied Digital Twins for Asset Management using a social network analysis-based review. The study conclusions list the following main challenges that were identified from the previous research:

- Disparate implementation of digital twin architectures and data integration methods.
- No unified framework for digital twin development.
- No harmonization of analysis techniques for data integrated on digital twin platforms

7 Conclusions

The aim of the research was to study the state-of-the-art of digital twins for road infrastructure (Deliverable 2.1) and digital twin technical aspects (Deliverable 3.1). The study was part of the Conference of European Directors of Roads (CEDR) Transnational Road Research Programme Call 2022 DROIDS project aiming to provide road operators, including European National Road Authorities (NRAs), increased knowledge and support to reap optimal benefits from digitalisation. The study methods included a literature review, interviews, and a workshop as well as project team internal collaboration and workshops. The study provides background information and knowledge that will be utilised further in the other DROIDS project work package deliverables related to digital twin road operator roles, application evolution and trusted service provision. The DROIDS project final results of road operators (NRAs) data strategy will also utilise these results.

The concept of Digital Twin (DT) has evolved from a general idea of a physical replica to a more specific definition involving a virtual representation of a physical entity with bi-directional data sharing. This data sharing allows for real-time monitoring, analysis, and simulation of the physical counterpart.

There are misconceptions about DT, including confusing it with digital models and digital shadows. A key difference is that DT has two-way data communication, while digital models and shadows have one-way or no data communication.

The DROIDS project provides a specific definition for a Digital Twin in the context of road transport: a virtual representation of the real-world physical road transport systems that support decision-making through monitoring, analysis, and predictive modeling.

Digital Twin (DT) technology integrates various other technologies to create a virtual representation of a physical system. The core technologies include Internet of Things (IoT) for sensor data collection, Artificial Intelligence (AI) and machine learning (ML) for data analysis, and cloud-based computing platforms for data storage. The data acquisition layer uses IoT sensors to collect real-time data. This data is then transmitted through a network to a digital model, which can be created using BIM models or 3D point cloud models. Machine learning algorithms analyze the data to provide services like real-time monitoring and predictive maintenance.

A digital twin architecture is a complex system that combines physical and digital components to create a synchronized digital replica of a physical object. The architecture typically consists of three layers: the physical layer, the communication layer, and the digital twin layer. The physical layer includes the real-world object and sensors that collect data from it. The communication layer transmits data between the physical layer and the digital twin layer. The digital twin layer is a digital representation of the physical object that can be used for monitoring, analysis, and optimization. There is no single, universally accepted architecture for digital twins, and the specific components and their arrangement will vary depending on the use case.

Road operator applications of Digital Twins provide decision support for road operators planning and construction of new roads, safety, asset management, traffic management, road maintenance, spatial planning and land use as well as risk and disaster management. Road operators two main responsibilities of road infrastructure and traffic management were reviewed more closely.

For road infrastructure, especially pavement, bridges, and tunnels have been of interest when developing digital twins to support the operational lifecycle of the infrastructure. For traffic management, digital twins could contain an exchange of data such as road transport network, road transport, public transport and influencing factors (such as weather).

In traffic management, many of the digital data needs are already available as digital models or shadows. This is especially the case for traffic state and road weather monitoring data providing the situational picture of the traffic conditions as well as the status of the traffic management services, supporting the traffic management center's human operators. Actual digital twins do not exist yet in full operation although plans for digital twins are capable of real-time support for the choice of optimal traffic management measures for each traffic situation.

The digital twin technologies and solutions reviewed in literature, interviews and workshops presented medium-fidelity implementations at best. Results included many theoretical analyses with proposals for testing and prototypes. During recent years the road operators have been moving from digital models towards digital shadows, i.e., implementing real-time data flows from the road infrastructure or traffic towards the digital models. The term digital twin was also used in different context and had different meanings compared to the taxonomy definition developed during the DROIDS project. The main difference between the DROIDS definition of the digital twin, extracted from literature, interviews and workshops, came from the requirement for the digital twin to have bidirectional communication between the physical and digital object or system, which was often lacking.

The main challenges of digital twins include data collection, definition of criteria, data complexity, data availability, data overload, cross-domain integration, digitization needs, modeling, deployment, APIs, security, laws and regulations, organizational barriers, and disparate implementation. These challenges highlight the need for standardized procedures, clear definitions, effective data management, strategies for dealing with data availability issues, robust systems for handling data overload and cross-domain integration, as well as a unified framework for the development and harmonization of analysis techniques.

Most organizations are in the early stages of implementing digital twins and the desired state of digital twins within road operators is to effectively utilize them in such a way that it enhances the efficiency and effectiveness of current and future operations. **A selection of desired use cases** for digital twin applications includes predictive maintenance for assets, monitoring and response, Cooperative Intelligent Transport Systems (C-ITS) services, optimizing traffic management, winter management and even facilitating Connected, Cooperative and Automated Mobility. But in order to develop and deploy those future services, several challenges need to be overcome first. Most of these challenges are data-related (quality, quantity (overload), timeliness, coverage, availability, complexity, standardization) but also organizational aspects play a crucial role.

The deliverable research questions, explained more closely related to the DROIDS expected results are presented in the study Chapter 1 Introduction, are reviewed below with short concluding answers and references to the corresponding chapters of results.

<u>State of the Art of digital twins for road infrastructure (Deliverable 2.1)</u>

1. What is the state of the art digital twin definition for road transport and operator needs?

   Digital twin definition within the context of road transport and operator needs was formulated as a part of the DROIDS project's road operator (NRA) Digital Twin taxonomy. The definition is based on the literature review presented in Chapter 3.1 and stakeholder feedback. The definition presented below will be iteratively reviewed during the project and final definition published in the final report (Data Strategy).

"*Road transport Digital Twin is a virtual representation of the real-world physical road transport systems. The road transport Digital Twin includes digital representation of elements such as road infrastructure, traffic with vehicles and pedestrians, road environment and land use. The road transport Digital Twin has a bidirectional real-time data connection between the physical and the digital representation. It can support road operator decision making with dynamic monitoring, analysis, and predictive modelling capabilities of the road transport systems that enable road operators for instance to enhance traffic flow, road safety and infrastructure asset management or to facilitate automated driving*."

Also, to further develop a common understanding and knowledge of digital twin for the needs of road transport and operator as well as to help align the digital twin definition, a DROIDS framework of Digital Twin was introduced in the Chapter 4.7.

2. *What actors are related to digital twins?*

The list of analysed actors related to digital twins is presented in the study Chapter 3.2 Actors and Roles Table 4.

The analysis concludes that most stakeholders are today active users of a digital model or shadow of at least some parts of the road infrastructure.

3. *What potential benefits or challenges do digital twins have for road operators?*

The potential benefits and challenges of digital twins have been analyzed in the study Chapter 6.

Desired use cases include predictive maintenance for assets BIM to AIM to Digital Twin, highway monitoring and response, optimizing traffic management and winter management. Benefits and future opportunities offered by digital twins may include facilitating Automated Driving Systems (ADS), predictive infrastructure management, and Cooperative Intelligent Transport Systems (C-ITS).

Challenges highlighted in the workshop with road operators the need for standardized procedures for data collection and registration, clear and consistent definitions of criteria, effective management of data complexity, strategies for dealing with data availability issues, and robust systems for handling data overload and cross-domain integration. In literature, some of the key challenges were related to digitalisation needs, laws and regulation as well as organisational barriers.

4. *What state-of-the-art data is needed in digital twins?*

State of the art data need of digital twins have been analysed in the study Chapter 4.2.

Digital Twin Data (DTD) is a critical concept for ensuring the effectiveness of Digital Twin applications. By encompassing a wide range of data from both the physical and virtual worlds, DTD fosters comprehensive understanding and facilitates real-time interaction between the physical entity, the virtual model, and DT services. Effective DTD management requires adherence to specific principles, including gathering complementary data from both physical and virtual aspects, ensuring timeliness, and implementing standardization for seamless data exchange. Ultimately, DTD serves as the foundation for knowledge extraction, data fusion, and continuous improvement, empowering various DT users with on-demand data access for informed decision-making.

5. *What state-of-the-art services related to digital twins are needed and available (or unavailable) at the moment?*

   State of the art digital twin services and software have been analysed in the study Chapter 4.4.

   Few examples of the many commercial digital twin software and services that are available for highways and roads were given. The best solution will depend on the specific needs of the project and the organization.

6. *What state-of-the-art standards and specifications are available for digital twins?*

   State of the art standards and specifications were presented in the Chapter 4.5.

   Specific standards for digital twins were not identified. There are various standards related to interoperability, data management, secure communication, asset management, Internet of Things, and 3D modelling that align well with the core functionalities of a Road DT system. Standards and specifications are discussed more in detail in the DROIDS deliverable D3.2: Information maintenance and availability. (Soni S., 2025)

7. *What are the stages of road infrastructure life cycle and how can state-of-the-art digital twin help to manage them?*

   Stages of road infrastructure life cycle and digital twin support are presented in Chapter 5.2 Road Infrastructure.

   Lifecycle of an asset covers the following four stages: creation of a new asset, routine maintenance, renewal or replacement, and decommissioning. Asset planning includes funding and cost requirements for a short-, medium- and long-term period for each asset

   Digital twins can help for example to model predictive pavement deterioration, enhance bridge condition monitoring and manage tunnel operations such as automatic tunnel fans operation.

8. *What stakeholders are involved in the information life cycle of road infrastructure?*

   The list of analysed actors and involvement in the different life cycles are presented in the study Chapter 3.2 Actors and roles Table 4.

   Depending on the role of the stakeholder in the transport data service ecosystem, an individual stakeholder can have either an active or a passive role in the development, operation, and maintenance of the digital representation.

<u>Digital twin State of the Art – Technical aspects (Deliverable 3.1)</u>

9. *What kinds of digital twins exist? (Complementing findings of literature research)*

   Chapter 3.1 sheds light on Digital Twin and various other representations related to

Digital Twin. Chapters 4.3 sheds light into various digital twin architectures and maturity levels.

There are various possibilities of digital representations. Digital model is a digital representation of its physical counterpart without any automatic data flow between physical and digital entity. On the other hand, digital shadow maintains one-way automated data flow from physical entity to digital representation, allowing real time model. In contrast, a digital twin is characterized by bi-direction data flow with its physical counterpart.

The architecture of digital twin has usually three main components: the Physical layer, the Communication or Integration layer, and the Digital twin layer. The detailed architecture of digital twin is usually defined based on the use case.

The digital twins can have various maturity levels ranging from capturing the reality of a physical object through 2D/3D models till achieving autonomous operation and maintenance of the physical object through the digital twin.

9.1 What is the detail of data (complexity) now?

Chapter 5.5 discusses about the current state of digital twin at selected road operators.

The report highlights that most organizations are still in the early stages of implementing digital twins and are working towards more comprehensive and dynamic representations. They types of digital representations used by the road operators are mainly either digital model or digital shadows of their physical counterparts. It was reported by a representative from Belgium that the current level of data complexity is low for the application of Digital Twins.

9.2 What is the objective of using these Digital Twins?

The various objectives and use cases for digital twin as reported by road operators or as found in literature are discussed in sections 5.5 and 5.6.

The report discusses the use of digital twins in road infrastructure management by several road operators. Here are some use cases mentioned:

- *Predictive asset maintenance:* Vlaanderen, the road authority in Belgium, is developing a digital twin for its network asset data to improve asset management through predictive maintenance.
- *Highway representation:* Rijkswaterstaat, the Dutch road authority, uses a digital twin for a simplified representation of a highway to present information on traffic lights or signals for traffic control.
- *Automated asset data processing:* Transport Infrastructure Ireland (TII) uses an enterprise GIS and is working to integrate asset management technology for more automated data processing.
- *Infrastructure planning and maintenance:* The Finnish Transport Infrastructure Agency (FTIA) uses digital models for infrastructure planning and maintenance. They use sensor data to monitor selected parts of the infrastructure, such as bridges.
- *Road register system:* FTIA also uses a road register system that contains key road attributes to facilitate their processes. They are working on a national road infrastructure project management information process to collect data during construction for future use in the digital twin

Digital twins can be used in road transport to model assess and optimize traffic flow, perform preventive maintenance on infrastructure, provide navigation assistance for people with specific needs, manage traffic congestion, optimize traffic lights, plan and manage electric vehicle charging stations, and support the operation of automated vehicles.

10. What is the desired detail/complexity of data for AIM?

Various technical details related to AIM is discussed in section 4.6.2 whereas the desired state of digital twin within selected road operators is discussed in section 6.1.

An effective asset information model (AIM) requires careful consideration of both the Level of Information (LOI) and the Level of Accuracy (LOA). LOI ensures the AIM contains the necessary details for specific operational tasks, which can vary greatly. Meanwhile, LOA guarantees the accuracy of spatial data within the model, allowing for reliable decision-making throughout the asset's operation.

Road operators want to use digital twins and Asset Information Models (AIM) to improve their efficiency and effectiveness in various areas. This includes using them for predictive maintenance of assets like roads and bridges, leveraging BIM models for asset management, and using real-time data for traffic monitoring, response, and optimization. Ultimately, they aim for a digital twin that can help manage traffic flow, incidents, and winter conditions, and provide C-ITS services for improved safety and efficiency on the roads which may require data with higher LOI and LOA.

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