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Perspective

Digital Twin Road: value and implications involving data and application

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Abstract
With the advancement of digital technologies, the creation of a digital twin of the road has moved from a theoretical concept to a tangible reality. Digital twins enable rapid simulations and robust data management, thereby ostensibly empowering policymakers and engineers to make expeditious and well-informed decisions. This paper examines the potential applications, benefits, and implications of deploying the digital twin of a road, a real-time virtual replica of physical road infrastructure, from four critical perspectives: physical modelling and numerical simulations, data management, law, and sustainability assessment. This paper explores the potential of digital twins to offer advancements in the efficiency and sustainability of road infrastructure. By enabling comprehensive monitoring and optimisation, the digital twin of a road facilitates applications in sustainable design, predictive maintenance, and efficient operation. Real-time data collection and analysis could allow for proactive maintenance and better resource management, while the integration of advanced materials and sensor technologies can enhance road durability and performance. Additionally, the digital twin of a road could support a holistic life cycle approach, facilitating better decision-making and planning for future infrastructure projects, with the potential to contribute to smarter and more sustainable transportation networks. The implementation of digital twins of roads, however, faces several challenges and raises numerous concerns. Key issues include the integration of diverse data sources, ensuring data accuracy and reliability, and addressing data protection and security concerns, requiring robust legal and regulatory frameworks to manage and protect personal data.

Article highlights

- Digital twins of roads are explored focusing on physical modelling and numerical simulation, data management, legal aspects, and sustainability.
- Benefits include long-term pavement analyses, prediction of pavement deterioration, lifespan extension and improved road safety.

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- Challenges involve advanced sensor data fusion, data privacy concerns, and potential unequal impacts on marginalised communities.

Keywords Digital twin · Digital twin road · Infrastructure

1 Introduction

Road systems are widely regarded as essential transportation infrastructures that facilitate the mobility of individuals and goods, with the density of well-maintained paved roads being closely correlated with economic development [1]. However, the road system faces various issues and critical challenges. Infrastructure is at its limit and availability is often restricted due to construction sites, while road-based passenger and freight traffic has increased significantly in recent years. Other dramatic challenges include climate change, resource depletion, and the mobility transition. Additionally, automated driving is an ongoing technical paradigm shift for the vehicle, without yet intelligently integrating the road [2]. On the other side, road transport is a significant contributor to climate change due to substantial greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2). Recent data from the German Federal Environment Agency ("Umweltbundesamt") shows that in 2022, the transport sector—including domestic air, road, rail, and inland waterway transport—was responsible for 20% of the overall GHG emissions [3]. Notably, over 97% of the emissions from the transport sector can be attributed to road transport, encompassing both private and freight transport. This situation highlights the urgent need for drastic reductions in emissions from road transportation, which can be achieved not only by vehicle-related improvements but also by optimising road infrastructure, enhancing maintenance planning, and improving traffic flow.

In addition to emissions from vehicles, the construction, maintenance, and decommissioning of road infrastructure contribute significantly to GHG emissions [4]. Furthermore, the construction of road infrastructure has destructive effects on ecosystems [5]. Consequently, improving the overall sustainability of roads and the transportation system requires to pay equal attention to the environmental and social impacts of road infrastructure across its entire life cycle [6]. To address some of these challenges, the creation and implementation of digital twins of roads has been proposed as a potential approach for enhancing the sustainability of road infrastructure [7].

In recent years, the concept of digital twin has gained significant attention across various sectors. Notably, the manufacturing industry views digital twins as a pivotal driver of Industry 4.0 [8]. A digital twin is a dynamic, digital replica of a physical object, system, or process that continuously generates and integrates real-time data to simulate and predict its behaviour in a virtual environment [9]. This simulation supports the development of designs and processes based on defined needs and requirements, ostensibly enhancing monitoring capabilities and improving decision-making [10]. According to Kritzinger et al. [11], unlike digital models and digital shadows, this framework relies on bidirectional, automated or semi-automated, data flows, known as "twinning." This process creates a feedback loop, where data from the physical entity updates the digital model, and insights from the digital simulation, inform and optimise the physical counterpart as illustrated in Fig. 1. Additionally, digital twins facilitate the adoption of a life cycle approach in the development and management of products and projects, aimed at optimised time and resource utilisation [12, 13].

In the construction sector, the application of this concept is still emerging, with current use mostly limited to specific tasks such as planning and scheduling [14]. These early applications have only scratched the surface of digital twins' potential, particularly in managing the entire life cycle of construction projects [15]. Despite this nascent stage, scholars have suggested that digital twins provide significant opportunities for civil engineering, including road infrastructure, but also pose considerable risks [16–22].

A digital twin of a road creates a cyber-physical system (CPS) that integrates a physical road (system) and its virtual replica, enriched with real-time data and analytics. This integration allows for comprehensive monitoring, simulation, and optimisation, promising to revolutionise road infrastructure, potentially improving its efficiency and sustainability. As a disruptive technology, digital twins of roads not only influence the design, construction, and operation of roads but also pose novel challenges and concerns. Thereby, the specific architecture, technological implementation as well as the required type and amount of data of a digital twin always depends on the intended use case and application.

This contribution explores possible applications and challenges associated with digital twins of roads, focusing on physical modelling and numerical simulations, data management, legal frameworks, and sustainability assessment. Thereby, the authors seek to address questions such as: What are the specific possibilities and applications of a digital twin of the road? What challenges must be overcome to realise its purpose? This study employs a mixed-methods approach,

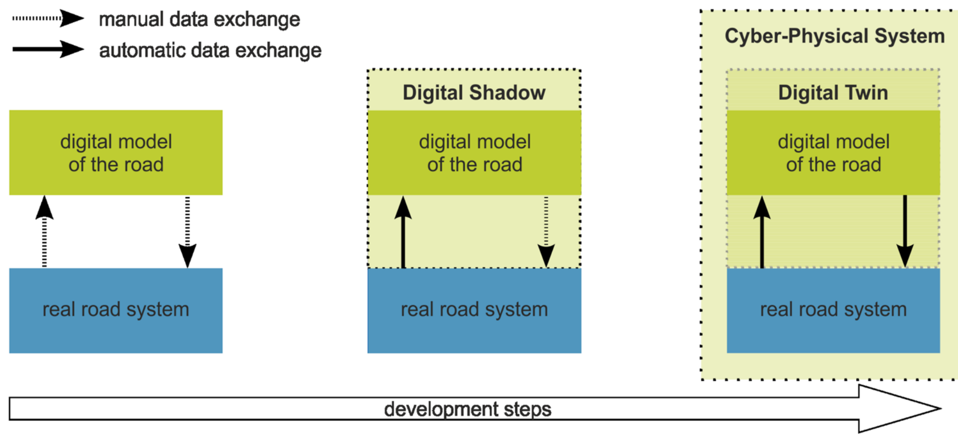

Fig. 1 Development steps towards a digital twin of the road

combining prototyping-based research, literature analysis, and critical legal examination to explore the applications and challenges of digital twins for roads. Given the evolving nature of digital twin technologies, we adopt an iterative, step-wise refinement approach following the prototyping workflow outlined by Carey [23]. To address the sustainability implications of digital twins, a comprehensive review of recent scientific contributions on the sustainability performance and assessment of digital twins in road infrastructure was conducted. This review informs the integration of sustainability considerations into the digital twin framework. Furthermore, to examine the legal and governance challenges associated with digital twins, a critical reading of relevant legal and policy literature was performed to assess the regulatory and ethical implications of implementing digital twins for roads, particularly regarding data protection, regulatory compliance, and governance structures for infrastructure digitalisation. By integrating these methodological components, this study ensures a holistic, interdisciplinary approach that captures the various dimensions of digital twin development and implementation.

Section 2 presents the concept of a digital twin of the road. Sections 3 and 4 explore and discuss its possible applications and challenges from the aforementioned perspectives. Finally, Sect. 5 concludes and provides future directions for research on digital twins of roads.

2 Digital twin road

Digital twins of roads can take on various forms, aimed at improving various aspects of planning, infrastructure management and optimisation, traffic management and monitoring, or cooperative intelligent transport systems. Recent literature highlights a range of applications, including the management and monitoring of pavement conditions [24–27], urban road planning [28], advanced traffic monitoring and management [29], and enhancing cooperative, connected, and automated driving (CCAM) [30–33].

The concept of digital twins has gained considerable traction across various industries, including manufacturing, urban planning, and civil infrastructure. However, when it comes to road infrastructure specifically, the existing body of research remains relatively sparse and largely exploratory. Research on digital twins for roads as cyber-physical systems is still in its early stages. The few existing studies primarily focus on specific applications, such as pavement condition monitoring, traffic flow optimisation, cybersecurity resilience, asset lifecycle management, and road maintenance scheduling, rather than developing an integrated, scalable framework for a digital twin of the road system.

Several recent contributions have explored potential applications of digital twins in road infrastructure, but most of these works remain conceptual or limited to pilot studies. For instance, some studies have investigated the use of digital twins to monitor pavement performance using sensor data, enabling predictive maintenance strategies [24–27]. Sierra et al. [26] introduce a cognitive digital twin approach for pavement health monitoring, integrating Unmanned Aerial Vehicles (UAV)-based data collection and machine learning for predictive analytics. Similarly, Consilvio et al. [27] propose a digital twin-based intelligent decision support system for road maintenance, integrating Artificial Intelligence (AI)-driven clustering techniques for pavement condition assessment and intervention planning. Others have examined digital twins in urban traffic management and urban road planning, focusing on integrating Internet of Things (IoT) and AI to optimise traffic flows and reduce congestion [28, 29]. Kušić et al. [29] propose a real-time synchronized digital twin model for motorways, leveraging real-time sensor fusion for traffic simulation and predictive analytics. Jiang et al. [28] propose a DT-MCDM-GIS framework to integrate multicriteria decision-making (MCDM) with digital twins and Geographic Information Systems (GIS) for sustainable urban road planning. This approach considers factors such as land use, traffic congestion, air quality, and noise pollution, ensuring a holistic planning framework [28]. However, these studies often treat digital twins as isolated tools rather than fully integrated cyber-physical systems that dynamically interact with road users, vehicles, and broader transportation networks. The lack of comprehensive, interdisciplinary approaches in current research highlights a critical gap that our project seeks to address.

Beyond infrastructure and traffic monitoring, digital twins are increasingly being recognized for their role in cooperative intelligent transport systems (C-ITS). The integration of digital twins with V2X (vehicle-to-everything) communication enables real-time adaptation of infrastructure to changing traffic conditions and autonomous vehicle navigation. Marai et al. [34] propose to rely on IoT sensors and 360° cameras to provide real-time road monitoring, which plays a crucial role in enabling self-driving vehicles and smart mobility solutions. Schwarz and Wang [35] further elaborate on the role of digital twins in connected and automated vehicles (CAVs), emphasising how real-time digital twins facilitate dynamic driving decision-making, V2X communication, and enhanced safety mechanisms. Similarly, Thonhofer et al. [31] focus on the utilisation of infrastructure-based digital twins for CCAM, supporting real-time decision-making for autonomous vehicles and smart road services. Ulrich et al. [32] discuss the socio-technical aspects of digital twins in road infrastructure, emphasising the importance of policy, governance, and legal considerations in their deployment. Ammar et al. [21] highlight digital twins in asset data management, focusing on safety hardware such as crash barriers and road signs. Their work demonstrates how real-time data analytics and predictive maintenance strategies can enhance road safety, which is particularly relevant for the future of C-ITS. Wang et al. [33] present a smart mobility digital twin that utilises cloud-based digital twins to enhance automated vehicle navigation, improving efficiency and real-time decision-making. Similarly, Gao et al. [36] explore cooperative localisation in Transportation 5.0, where digital twins are used for enhanced real-time positioning, vehicle tracking, and decentralised control. These studies highlight the potential for digital twins to support autonomous and cooperative mobility solutions, bridging the gap between infrastructure and vehicle intelligence.

A small number of articles has been occupied with the challenges of integrating digital twins into broader civil infrastructure frameworks. Pregnolato et al. [37] highlight the importance of standardized workflows and integration of digital twins into national infrastructure planning. Sohal et al. [38] explore the uptake of digital twins in infrastructure projects, showing that while adoption remains low, the use of IoT, AI, and cloud-based data systems can drive the digital transformation of transport networks. Vieira et al. [7] emphasize the sustainability and resilience of road and rail networks through digital twin integration, advocating for data-driven decision-making to improve long-term infrastructure performance.

This relates to another strand of research on digital twins in road systems, namely sustainability and regulatory integration. Li et al. [39] discuss how advanced information technologies are driving the next generation of smart infrastructure and digital twins not only for predictive maintenance but also for life cycle assessment. Meža et al. [40] present a digital twin framework for sustainable road construction, using secondary raw materials and monitoring environmental impacts through integrated digital twin simulations. This highlights how digital twins can contribute not only to efficiency and performance optimisation but also to environmental sustainability and circular economy strategies in road infrastructure.

Existing studies on digital twins of roads tend to focus on either the technical and engineering challenges—such as sensor integration and numerical modelling—or the data-driven aspects, such as traffic optimization and predictive analytics. However, digital twins of roads cannot be understood purely as technical systems; they are also deeply embedded in legal, environmental, and governance frameworks. Our research aims to bridge these disciplinary divides by developing a holistic understanding of digital twins of roads as complex socio-technical systems. This includes investigating not only their technological feasibility but also their regulatory implications, sustainability potential, and governance challenges. In particular, this paper is based on research conducted in the Collaborative Research Center/Transregio 339 "Digital Twin of the Road System - Physical-Informational Representation of the Future Road System" (CRC/TRR 339) funded by the German Research Foundation (DFG). Developing a digital twin of a road is a complex and multifaceted endeavour that requires an interdisciplinary approach and a blend of diverse expertise. Thus, our approach in the CRC/TRR 339 project is fundamentally interdisciplinary, integrating expertise from civil engineering, materials science, computational modelling, data management, legal and political studies, and sustainability research.

By advancing an interdisciplinary, cross-sectoral approach, our project moves beyond the current exploratory stage of digital twin research for roads. We propose a more comprehensive and systemic framework that considers the technical, environmental, legal, and social dimensions of digital twins in road infrastructure. In doing so, we aim to contribute to the development of a truly integrated digital twin road system—one that is not only technologically robust but also environmentally sustainable and socially equitable. By bridging engineering, data science, sustainability, and legal frameworks, this research sets a new precedent for the development of digital twins as comprehensive socio-technical systems, capable of transforming road infrastructure management at scale.

In a holistic solution concept, the project seeks to develop a "Digital Twin Road", understood as a spatially and temporally multidimensional, digital image of the vehicle, tires, and road with interfaces for an automatic data exchange from and to the real road system. At the same time, the road itself, which has been used mono-functionally for load transfer, is further developed into a multi-functional road by integrating additional functions (e.g., sensitive properties) and customised materials. Together with its digital twin, it forms the CPS of the road of the future as illustrated in Fig. 2 [2].

The Digital Twin Road, as envisioned by the CRC/TRR 339, is designed for analysis, control, and prediction of the physical road system. The goal is to enable real-time analysis, monitoring, prediction, and control of road infrastructure across its entire life cycle, including the design, construction, operation, maintenance, and end-of-life stages. It leverages various digital technologies, including sensors and machine learning to generate, integrate, and analyse large volumes of digital data. The Digital Twin Road integrates real-time data from various sources, including vehicles, tires, and pavement, with the latter being gathered among others through a sensitive top layer of the road surface designed to generate precise data on vehicle loads, positions, speeds, and other parameters. For the digital model of the road, data-driven methods are combined with traditional modelling, simulation, and optimisation techniques to enhance the analysis and prediction capabilities of road infrastructure systems. By collecting and processing data continuously, the Digital Twin Road can provide insights into the current state and future performance of road infrastructure. Additionally, addressing cross-cutting issues such as sustainability and legal and political considerations is crucial to ensure a holistic integration and functionality of the system. This involves, for example, assessing the social and environmental impacts of the materials used in the physical and digital infrastructure, the energy consumption of the sensors, and the overall carbon footprint and equity of the cyber-physical-social system road. Legal and political considerations include the protection of personal data security, as well as broader onto-epistemological questions raised by the Digital Twin Road being employed in decision-making.

The intended use cases of the Digital Twin Road within the CRC/TRR 339 project focus on the optimisation of the road infrastructure. Envisioned is, for instance, preventive maintenance planning by evaluating data on the current road condition and performing predictions of future road states and their durability. Additionally, the Digital Twin Road shall be used for improved design of future roads concerning durability and sustainability based on predictions from digital models investigating different scenarios (road constructions, materials used, predicted traffic, and climatic conditions) to support decision-making processes. Another potential use case is to manage the distribution of the traffic and tire load on the road more effectively. For example, with autonomous trucks, this could be done by prescribing an individual lateral shift to each vehicle within the lane, preventing them from driving exactly over the same location of the road, which would otherwise cause excessive rutting. Of course, a Digital Twin Road could also be envisioned for complete traffic control including all vehicles on a specific road section or even on the road network. However, the latter case is beyond the scope of the CRC/TRR 339 project and would require a huge amount of traffic data, real-time simulations, and possibilities to control the traffic.

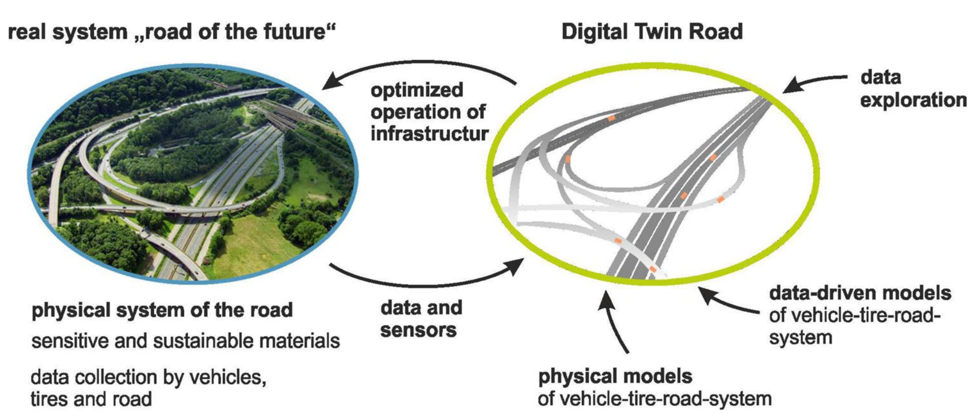

Fig. 2 Cyber-physical system of the road of the future

3 Possible applications of the digital twin of a road

As the number of road users and automated vehicles continues to rise, there is a growing demand for technologies that enable policy makers and engineers to make timely and informed decisions. The digital twin of a road is envisioned to fulfil these requirements, leading to an efficient road operation. The design of the road structure can be viewed as a multi-criteria optimisation problem. The optimisation criteria include material composition, structure geometry, service life, sustainability, among others.

In this section, the multiple possibilities for the application of the digital twin of a road are explored from different perspectives: physical modelling and numerical simulation, data management, sustainability, and law/governance.

3.1 Physical modelling and numerical simulation perspective

Geodesy can accurately represent roadway geometry [41], while materials science characterises the materials used in these roadways [42–45], and computational engineering models their physical behaviour [46–51]. However, researching these domains in isolation limits their benefits. It is the synergies that arise when these fields are integrated into a digital twin [2, 52, 53] that can truly revolutionise roadways throughout their life cycle. Geometric semantic models of the real pavement can be used to simulate different locations of the road network, as they contain all essential geometry and material information. The data structure of these models is designed for fast and automated input into simulation models within the framework of the digital twin. Additional inputs to the digital twin of the road include the position, velocity and magnitude of moving wheel loads from vehicles [54]. With these inputs, simulations can be run in the digital twin, allowing for predictions of pavement response.

Real world data (e.g., strains, temperatures) can be quickly retrieved from sensors embedded within the real counterpart of the digital twin. This data is typically used to verify the accuracy of the digital twin simulations. Any deviations between real-world data and simulations may indicate pavement deterioration, prompting timely maintenance scheduling. Moreover, when physical models are used in digital twin simulations, studying deviations in model parameters can provide insights into the causes of deterioration (e.g., rising groundwater levels or thermally induced softening). Preventive maintenance can then be performed to extend the structure's lifespan.

The enormous potential of the digital twin of the road is particularly evident in long-term analyses, due to the notably longer service life of roads compared to other systems. Long-term predictions from the digital twin enhance understanding of the complex multi-physical processes involved in pavement degradation over its lifespan [55]. These predictions support the identification of areas of the road network that are particularly susceptible to damage (e.g., intersections due to braking and acceleration manoeuvres or rut formation from repeated overruns of heavy wheel loads along the same path). Taking these aspects into consideration in the digital twin, leads to improved prediction of the lifespan of the pavement structures. The digital twin can thus be used as a tool in designing long lasting pavement structures. An overview of a conceptual framework of the digital twin of a road, for the use case of preventive maintenance, is depicted in Fig. 3.

3.2 Data management perspective

This section addresses both the general functionality and implementation approaches, as well as project-specific model alignment, as illustrated in Fig. 3.

3.2.1 Functionality

A digital twin can provide descriptive, predictive, prospective, prescriptive, and diagnostic functions [56, pp. 29–31]. While a descriptive twin only reflects the current system state, a predictive twin, as described in Sect. 3.1, is used to forecast future states. The concept of digital twin is often closely associated with other concepts, such as the IoT, Big Data, and Machine Learning or AI [57]. IoT devices, such as sensors and actuators, are essential for generating data about the physical world and also offer the ability to interact with it [57, 58]. This data often requires the use of Big

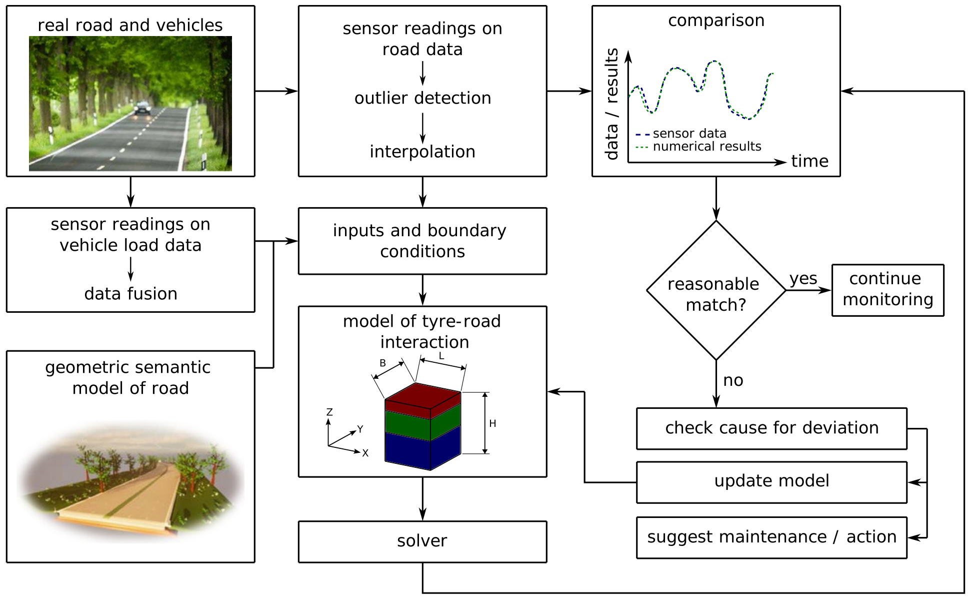

Fig. 3 Flowchart detailing the conceptual framework for the digital twin of a road with the use case of preventive maintenance

Data technologies, [57], which enable the creation and utilisation of numerical models and simulations to represent the physical system's behaviour within the virtual twin, as discussed in Sect. 3.1.

3.2.2 Implementation variety and standard ambiguity

Currently, there is no consensus on the technical implementation of digital twins in general, and particularly for roads [59]. Consequently, a wide range of software architectures [60] and technologies [61] are available for the implementation of a digital twin. Instead of developing a digital twin from scratch, existing platforms and software frameworks—which provide software components and tools for creating a platform—can be utilised [62]. This approach supports the technical realisation of digital twins and can accelerate the overall development process. Therefore, selecting a suitable platform is crucial for the successful implementation of technically complex digital twins of roads. However, many available software solutions for this purpose are closed proprietary platforms, which limit user control over the entire software architecture, posing the risk of a lock-in effect [63]. Using open-source software for a digital twin platform implementation can enhance flexibility through custom development and adjustments, increase interoperability of solutions, and promote the standardisation of the underlying software architecture of digital twins [64, 65]. In the IoT domain, various middleware solutions such as FIWARE, Eclipse Ditto, and SensorThings are particularly suitable for sensor-based applications, although other data can also be integrated.

Especially interesting is FIWARE, an open-source platform that aims to standardise the creation and management of digital twins. It provides a common data model and modular components that facilitate data exchange and real-time analytics. This approach has shown to be successful in many domains [66] including transportation, energy, urban planning, and agriculture. Albeit not useful in laboratory scenarios, FIWARE additionally provides identity management and access control [67], which is highly useful when deploying a digital twin in real-life scenarios.

3.3 Sustainability perspective

The digital twin of a road holds significant promise in revolutionising road infrastructure operation and management, as mentioned in previous sections. Particularly, there is the chance of enhancing sustainability practices in all three dimensions, i.e., environmental, economic, and social. The potential benefits of digital twins of roads can be viewed from two perspectives: the sustainability performance of the road itself (road sustainability perspective) and the methodology used to assess sustainability (methodological perspective). The road perspective encompasses the actual operation of the road. Concerning economic sustainability, research conducted within the CRC/TRR 339 project provides evidence that an average of 45% of the life cycle costs of an asphalt road are associated to maintenance and replacement activities. In this regard, digital twins of roads could lead to more efficient investments by indicating when maintenance, repair, and replacement measures are needed [27, 68]. For instance, the digital twin of a road can provide and manage information related to pavement condition that can be the base to decide whether or not the road needs a particular scheduled or non-scheduled measure. Furthermore, this framework could support more efficient management of construction sites due to the aforementioned measures. In the context of social sustainability, Del Rosario et al. [69] identified the stakeholders workers, local community, society, and consumers (road users) as relevant for the road system. In particular, topics related to the health and safety of workers, local community, and road users are considered of high importance. The digital twin of a road could support early recognition of possible issues with the superstructure and support optimised traffic management [70]. The road authorities could take earlier and better informed decisions, possibly leading to increased road safety and improved social impacts on the aforementioned stakeholder groups. In addition, digital twins can support the simulation and forecast of scenarios [71–73]. In particular, the digital twin of a road could simulate different alternatives for maintenance, repair, and layer replacement in terms of the implemented technology used, intervention time, and influence on traffic, among others. These long-term predictions would decrease the need for resources and effort. Moreover, the digital twin could illustrate possible vulnerable points and potential solutions to emerging risks [74].

The digital twin of a road also poses a great potential for the assessment of the sustainability performance of roads using sustainability assessment methods such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Social Life Cycle Assessment (S-LCA), and Life Cycle Sustainability Assessment (LCSA) (methodological perspective). One key aspect concerns the typical process of conducting sustainability assessments. In general, the results of sustainability assessments provide us with a snapshot of the performance at a certain point in time. Traditional LCA studies usually omit time-related information by aggregating environmental data at different times [75]. However, roads are highly dynamic due to the changing flow of vehicles through the years or the cyclic maintenance and repair activities involving different materials, equipment, staff, and other resources. Furthermore, roads have a very long lifespan, expanding over several decades, which poses modelling issues for LCSA practitioners [76]. Due to its static approach, the traditional sustainability assessment of a road may possess a high degree of uncertainty. The digital twin of a road provides a digital representation that is constantly updated, which is particularly relevant when assessing the sustainability performance of the use stage of a road [8, 71, 72]. This dynamic approach connects to the ability of the digital to collect data in real-time, allowing for a constant evaluation and monitoring of the sustainability performance of the road [8].

Another possible methodological benefit is a faster, more efficient comparison of estimated or secondary data with real-time and primary data [71]. In particular, the gap between the data used and outcomes obtained in an LCA or LCC carried out during the planning or design stage of the road (planned performance) versus those performed after construction / during operation (actual performance) can be better understood [77]. Moreover, through the digital twin of the road high-quality primary data can be obtained [72, 77–80]. In the particular case of roads this could imply more reliable data for additional vehicle emissions due to deterioration of the road, routine maintenance activities, leachate, among others.

Another possibility offered by the digital twin lies in the automation of LCSA steps. The Life Cycle Inventory (LCI) is one of the most challenging, time- and resource-consuming phases in LCSA of roads. The LCI could be made more accurate through the automation of data collection from sensors. Furthermore, the digital twin can automatise the calculation of the environmental impacts based on LCI data. Some studies have demonstrated the potential benefits of using a digital twin framework for sustainability assessment. An example is provided by Oreto et al. [81], who integrated LCA on a digital twin road model based on Building Information Modelling (BIM), focusing on automated LCA calculations and the bidirectional information exchange between the BIM platform and the LCA tool. Another notable example is by [82], who developed a digital twin-based method for estimating embodied carbon of buildings with automatic data exchange.

Finally, the digital twin of a road could enable the access and combination of more data sources by incorporating environmental data from generic databases or Environmental Product Declarations (EPD) to characterise the environmental performance of road pavement and sensor materials. For example, [8] used the latter as the data source for a digital twin of a building.

3.4 Legal perspective

Digital twins of road systems have the potential to support the implementation of the European Commission's 2020 Data Strategy concerning mobility data, as well as the 2020 Sustainable and Smart Mobility Strategy, a component of the European Green Deal [83]. Both strategies emphasise the importance of data and digital technologies in creating a more sustainable and safer transport system. More specifically, the Sustainable and Smart Mobility Strategy advocates for deploying smart digital solutions and intelligent transport systems (ITS) necessitating the collection, processing, and utilisation of vast amounts of data. In line with this, the European Commission's Data Strategy envisions the creation of a European Mobility Data Space, a decentralised infrastructure and governance framework facilitating federated sharing and use of transport-related data across the EU. However, the potential of digitalisation to transform the European mobility system, as envisioned by the European Commission and embedded in the EU's policy and legislative framework, remains uncertain. Critics contend that the European Green Deal's focus on digital technologies reflects the "new digital spirit of green capitalism," ultimately amounting to "an exercise in necropolitics" [84, p. 186], [85, p. 2].

Central to the European policy and legal framework concerning mobility is the development and implementation of interoperable, harmonised, and continuous Cooperative Intelligent Transport Systems (C-ITS) across all EU Member States [86–88]. C-ITS enable communication among vehicles, infrastructure, and other road users, facilitating cooperative decision-making and coordination. These systems provide the foundational communication and data infrastructure that underpin advanced CCAM. Given that C-ITS fundamentally rely on the availability and accessibility of mobility data, the C-ITS Directive mandates EU Member States to make certain information accessible in a digital, machine-readable format for C-ITS applications and services [88, Art. 6a].

Embracing the credo that more data use and data sharing is desirable, the European Commission's Data Strategy, along with the EU's legislative framework for data processing, incorporate several measures and initiatives to increase the (re) use and sharing of data [89]. This is considered particularly important in the realm of mobility. Mobility data, considered to provide "important benefits for society, the environment and the economy," has been designated as "high-value" under the 2019 Open Data Directive, with the 2022 Implementing Act on High-Value Datasets mandating that publicly held digital datasets on transport networks be freely available [90, Art. 2(10)], [91, Annex]. Additionally, the recently adopted EU Data Act requires certain data holders, including vehicle manufacturers, to share generated data with the users or third-party 'data recipients' upon request by the user [92, Art. 4, Art. 5].

However, as highlighted in the expert report "Towards a common European mobility data space," the successful creation of C-ITS necessitates data sharing beyond mandated requirements [93, p. 7]. Digital twins could support the creation of C-ITS by providing accurate, precise, real-time data essential for decision-making and operational purposes. Digital twins generate and process real-time data about physical road networks and infrastructures, serving as a centralised repository for all road and traffic data. This integration of information from multiple sources could provide more comprehensive and coherent datasets, enhancing overall data access and exchange for C-ITS.

Furthermore, digital twins could facilitate the digitalisation of traffic law(s), transforming the way they are enforced and communicated in an era of fully automated vehicles. By integrating traffic laws and regulations into a digital twin framework, authorities could ensure that all relevant rules are up-to-date and accurately reflected in real-time. Traffic regulations, such as speed limits, no-parking zones, and temporary road closures, could be updated and communicated with the support of the digital twin infrastructure. This would ensure that drivers, autonomous vehicles, and traffic management systems have access to the most current legal requirements. The digitalisation of traffic laws is particularly crucial for autonomous vehicles, which rely on precise and current data to navigate safely and legally. Digital twins could thus facilitate the translation of the legal framework for autonomous driving systems, enabling real-time traffic governance.

In addition to operational benefits, digital twins of roads could support strategic planning and policymaking. By analysing the data provided by digital twins, policymakers can gain insights into traffic patterns, infrastructure usage, and mobility trends. This information can be used to make decisions on infrastructure investments, urban planning, and environmental policies aimed at reducing emissions and promoting sustainable mobility. The potential of digital twins of roads to lead to more socially and environmentally sustainable policy and planning decisions, however, hinges on their specific design and the data they do and do not generate and integrate.

4 Issues and challenges of the digital twin of a road and possible solution approaches

As demonstrated in Sect. 3, the digital twin of a road could open a multitude of possibilities in different fields, while improving the performance and functionality of the future road system. However, such a disruptive framework poses barriers that need to be addressed. In this section, the challenges associated to the digital twin of a road are discussed.

4.1 Physical modelling and numerical simulation perspective

While the framework of the digital twin of the road for the use case of preventive maintenance, shown in Fig. 3, seems straightforward to be implemented, each individual component is associated with a set of challenges, that must be overcome in order to ensure reliable and smooth functioning of the digital twin. There are several inputs that need to be provided to the digital twin, for example, the loading from the wheels, geometry of the pavement section and boundary conditions from the environment (e.g., thermal conditions of the pavement, existing damage like potholes, cracks or ruts, moisture levels, among others). Most of the data to be used as input for the digital twin is collected by sensors placed on the road. The sensors are typically quite varied and collect data for different aspects of the structure. Hence, they require some form of sensor data fusion [94] to provide the required inputs in a meaningful and systematic manner. The raw data from sensors is also known to possess outliers and can be discontinuous. This necessitates data processing to remove outliers [95] and interpolate for missing values [96] before it can be used as input to the digital twin. The sensors are additionally associated with a degree of uncertainty [97] in terms of sensor location and the obtained readings. Another aspect worth considering is the deterioration of the sensors themselves over time due to environmental effects, or flaws in the manufacturing process. Often, the sensors are located such that it would be inconvenient to extract and replace damaged or faulty sensors. Sufficient care must, therefore, be taken to choose robust and resilient sensors that also offer a degree of redundancy in case of malfunctions, i.e., if a sensor fails, there should be some technology (extra sensors) to ensure the continuous collection of data. Additionally, with technological progress, the sensors currently employed in the real counterpart of the digital twin may become obsolete in the future. This also needs to be taken into consideration.

With the input data at hand, appropriate physics-based numerical models can be applied and solved. Each model has certain domain-specific assumptions about the involved physical phenomena. Therefore, the choice of such models is not trivial, and requires discernment by experts [98]. While simpler models are numerically easier to solve, the results they yield may not capture reality very well. Hence, a balance must be struck, such that the chosen models produce sufficiently accurate results, while also not being overly complex. Numerical solution technologies that enable the consideration of more complex models, while also reducing the required computational effort [46–48, 55] are vital to the digital twin, as these would enable fast and accurate simulations. Another direction worth exploring is the use of AI as a replacement for such complex physics based models [99]. Care must then be taken to ensure that these AI-based models produce physically meaningful results. Physics-based retraining or re-calibration techniques must be employed in case these models produce erroneous results, to ensure the accuracy of the digital twin. Further, the computation of these models can be performed on high-performance computing (HPC) clusters to enable a further reduction in the computation time. However, the use of such HPCs necessitates higher energy consumption and must be carefully considered [100].

Expert knowledge is required in each of the different domains involved to ascertain whether the results produced by the numerical calculations are in agreement with reality. Additionally, there could be cases where the parameters required for the models to match reality may not be unique or may not exist. In such cases, expert analysis is required to ensure optimal model parameters can be found and used.

Further, the implementation / deployment of the digital twin concept as a continuous system for all the roads in the network is not to be expected within short time, due to the costs (financial, environmental and temporal) associated. Therefore, a more realistic approach would be to identify key points in the road network which are then 'twinned' on a priority basis. These key points could include intersections where the vehicles perform a lot of acceleration and braking manoeuvres, or sections that have a history of requiring higher frequency of maintenance, or sections that have higher accident incidence rates, for instance. Data from the sensors embedded in these sections could provide valuable insights and enable engineers to put forth safer and more sustainable designs. Restrictions that would arise by just a partial coverage would depend strongly on the specific use-case of the digital twin. However, by connecting and interpolating the data from 'twinned' key points, an overall picture of the status of the road network can be gleaned. Additionally, data on the roads between the key points can be gathered from sensors that are integrated in the vehicles and, thus, continuously available. This strategically distributed (federated) implementation [101] would theoretically offer most of the benefits of continuously twinning the entire road network, while being considerably more cost effective. This distributed implementation is of course only possible, given a sufficient density of the key points. Therefore, it needs to be developed in a systematic and phased manner.

Moreover, if such a digital twin of the road is to be successfully implemented, the final hurdle to be overcome is the issue of societal trust. The ability of the predictions from the digital twin to convince the engineers, policymakers and road users depends on how explainable and understandable they are [102]. Therefore, abundant caution, and checking these predictions must become standard practice.

4.2 Data management perspective

The vision of a digital twin application as proposed in the CRC/TRR 339 is characterised at both the model and data levels by the continuous adjustment of the predictive models when there is a significant deviation between the prediction and the measured value. Therefore, it is necessary to account for (1) the errors of the sensors or the data they generate, (2) the errors of the underlying models, and (3) the errors of data from other sources, integrating these into the calculation of the deviation between the physical and digital twins through an appropriate error calculation in the system.

The road sensor system is designed to capture the condition of the pavement and utilise model matching for predicting road conditions. For this purpose, a system for storing sensor data and middle-ware from the IoT domain can be employed. Nevertheless, for predictive purposes, stream processing is not required; rather, the storage of historical data—time series—is necessary since simulations must be based on original data rather than aggregated time series data, making their storage indispensable.

Two extreme approaches are conceivable: In the first case, all the sensor data of the physical twin would be processed completely, at maximum frequency, and highest granularity. This approach, referred to as full downstream, would be agnostic and indifferent to the data requirements of the models, and thus, inefficient for the overall system, potentially causing a temporal lag between the physical and digital models. The other extreme would be a full upstream approach, where the entire data processing logic for matching the twins is executed directly at the sensors (edge computing) of the physical system (road). However, this would require the results of the models to be disaggregated and transmitted back to the sensors. Sensors are rarely capable of processing complex queries due to limited computing resources and power constraints. This implies that an appropriate compromise in terms of cost, processing time, and other factors, must be found in the form of a complex, distributed sensor-fog-cloud infrastructure. The critical question then becomes how to identify such a compromise in a given setting involving workload, software, and hardware.

Moreover, not only the sensory processing may induce difficult decision making. As already proposed, models like FIWARE provide a modern solution to building digital twins to virtually any system, while being open-source. However, the development of a digital twin of the road system does not start from a fully informed perspective. Since this development is multi-faceted and include interdisciplinary collaboration, many new insights are gained throughout the project itself. This agile development, properly displayed by our prototyping methodology, does not work inherently well with a huge system like FIWARE. In fact, first prototypes occur between small interdisciplinary groups and evolve simple modelling of faced challenges using fast and easily typed languages like Python. In those small case scenarios, issues can be solved and tested fast. However, for deployment and incorporation of multiple interdisciplinary tasks, simple modelling may fail. Finding the sweet spot between efficient prototyping and incorporating large scale models like FIWARE while keeping development agility is thus another major question to investigate.

4.3 Sustainability perspective

Similar to the possible applications of digital twins of roads, sustainability-related challenges can also be addressed from two perspectives, as proposed in Sect. 3.3 the road sustainability and methodological perspectives. In particular, the discussion in this Section covers aspects related to social acceptance and criticality, as well as the implementation of life-cycle-based methods, such as LCSA, LCA, and S-LCA, in the context of digital twins of roads.

Regarding road sustainability, social acceptance by different stakeholders could present a major issue. In particular, users of the real twin might present concerns for their data privacy due to the number and nature of sensors used [103, 104]. The privacy-related concerns regarding the digital twin are highly connected to possible misuse of personal data, as reported in various studies [105–107]. The S-LCA methodology provides an structured approach which can encompass the assessment of social impacts related user privacy in digital systems. Notably, the sub-category "consumer privacy" defined in the S-LCA Methodological Sheets of the United Nations Environment Programme (UNEP) addresses aspects such as the robustness of privacy protection measures, the effectiveness of data protection systems, as well as the frequency of privacy-related incidents, including complaints about data breaches or loss within a defined time frame [108]. Another consideration is whether policymakers and technical staff trust the data and predictions provided by the digital twin, and whether they are willing to base their decisions on it. Furthermore, due to the large number of stakeholders related to digital twins of roads (e.g., infrastructure managers, traffic managers, policymakers, road service providers, and road users), governance issues may arise [79, 109]. In this context, stakeholder engagement is crucial for the enhancement of the social acceptance of digital twins of roads since it promotes transparency and trust. Effective stakeholder involvement could ensure that multiple perspectives and requirements are represented within the development and deployment of these systems. In particular, methods such as one-on-one interviews, focus groups, and surveys could be used to foster engagement [110].

Digital twins of roads offer the potential for a more efficient road operation through the integration of sensors, antennas, and IT equipment. These technologies often rely on critical raw materials (CRMs). According to the European

Commission, CRMs are non-energy, non-agricultural raw materials critical for the economy of the European Union (EU) [111]. Examples of CRMs, as defined by the EU, used in digital technologies are cobalt, gallium, graphite, and rare earth elements [112]. In the particular case of the digital twin road as envisioned by the CRC/TRR 339 project, a sensitive surface layer gathers and generates data based on vehicle loads, positions, and speeds. This layer is composed of graphene, polymethylmethacrylate (PMMA), filler, and copper electrodes. A criticality assessment of the raw materials of the sensitive surface layer using the ESSENZ method [113] revealed graphite (as the raw material for graphene) and copper as the most critical raw materials, with hotspots related to political stability of the countries where these materials are sourced from, concentration of reserves and production, trade barriers, among other socio-economic aspects, as shown in Fig. 4.

Moreover, the production and transport of CRMs materials can have considerable impacts on the environment and human health [114–118]. For the example of the sensitive surface layer it is estimated that the production of 1 kg of the aforementioned composite (considering raw material extraction, transport, and mixing process) leads to a Global Warming Potential of around 60 kg CO_2 eq. As a reference, the production of 1 kg of surface layer asphalt with polymer-modified bitumen can amount up to 0.09 kg CO_2 eq. [119]. Furthermore, concerns have been raised about the environmental impacts of the digital twin operation due to high energy demand [104, 120]. These factors collectively undermine the sustainability performance of the digital twin of a road. Nevertheless, it should be highlighted that there is a general lack of concrete information surrounding the environmental performance of digital twin infrastructure. In this context, a partial implementation of the digital twins of roads may offer some benefits. Specifically, the strategic design and placement of sensors, such as the sensitive surface layer, at key locations like intersections or near highway exits could reduce resource use and data processing demands. This approach would not only minimise environmental impacts and the use of critical resources, but also potentially lower life cycle costs, while maintaining a reasonable level of representativeness.

One major challenge in sustainability assessment is the lack of standardised frameworks for digital twin and LCSA, which hinders their combined use in decision-making [72]. This lack of standardisation can lead to unreliable or false outcomes, resulting in poor decision-making. Since roads are considered part of the critical infrastructure, poor decision-making could negatively affect the global and local environment, society, and the economy in general.

Another identified challenge relates to data. The data granularity needed can vary depending on the assessed sustainability dimension and system boundaries, complicating the assessment [8]. One of the implementation barriers in sustainability assessment is related to inconsistent data in terms of formats and quality [77]. To assess the environmental dimension, some approaches exist in which the environmental data is standardised and verified, and certain levels of quality have to be met in order to be considered reliable [121]. Some examples are EPD and Product Environmental Footprint (PEF). However, these formats are not yet widespread in the road construction and digital technology sectors. A similar format, the Social Product Declaration (SPD), exists, but it is still in its infancy in terms of application [122, 123]. In the case of the economic dimension, no standard format is available. Moreover, until now, no standardised format links sustainability-related data of all three pillars, although proposals have been made [124]. In this regard, standardised formats that provide holistic sustainability-related data for digital twins of roads are needed. However, even if such data formats are available for the three sustainability dimensions, the primary and real-time data collected by the digital

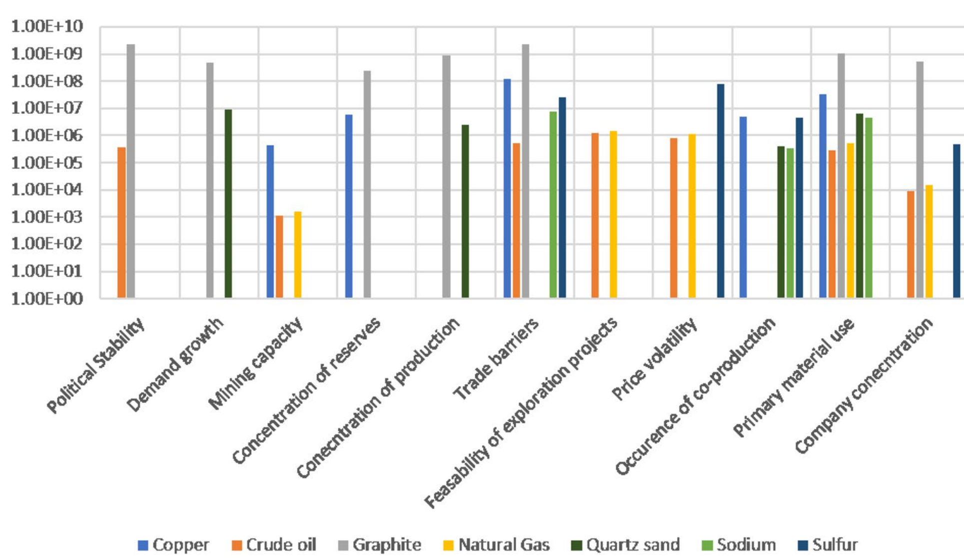

Fig. 4 Criticality assessment results for socio-economic availability applying the ESSENZ method on raw materials of the sensitive surface layer

must be processed (e.g., aggregated, converted) before being linked to the corresponding datasets [71]. Furthermore, the main assumptions behind the datasets (e.g., Product Category Rules for EPDs or Product Environmental Footprint Category Rules for PEF) must be revised to ensure compatibility.

Another related issue concerns the consideration of the three pillars of sustainability. Although, LCA provided the basis for LCC and S-LCA, the combination of the three methods within LCSA still presents issues that could result in challenges regarding model interoperability [79]. For instance, it is often not possible to define identical system boundaries when assessing all three dimensions [125], this is often due to the perspective from which the assessment is done (relevant for LCC and S-LCA). This particular aspect could generate issues connected to the type of data format needed for the digital twin of a road since each dimension presents different requirements. Moreover, particularly social data represents a great challenge [77, 79]. For the social dimension, there is not yet a unified set of indicators and impact pathways to determine the social impacts of roads or digital twins. However, some of the already addressed challenges make clear that such a set of indicators should consider the topics of data privacy and social acceptance.

The consideration of several criteria and data of different nature renders the interpretation of results challenging [9, 69]. Therefore, appropriate analysis methods should be chosen. Another challenge regarding interpretation is connected to a lack of benchmarks against which the results of the sustainability assessments can be compared. Moreover, since the three pillars of sustainability are being considered throughout the whole life cycle of the digital twin of the road, trade-offs among sustainability dimensions and life cycle stages can occur, as well as dependencies between dimensions [77]. These trade-offs and dependencies must not only be fully understood but consistent measures on how to deal with them must be defined to enable a correct interpretation of the sustainability performance outcomes.

4.4 Legal perspective

The creation of a digital twin of the road requires the generation and integration of vast amounts of data. What kinds of data are being generated and integrated (including third party data) depends on the purpose and the specific design of the digital twin. If the digital twin is used exclusively for the purpose of predictive maintenance of pavements, it is imaginable that all the data that is generated and integrated could be considered non-personal data. That is, if the digital twin only processes data on vehicle positions, velocity, and wheel loads generated by the sensitive surface layer for which it is "reasonably likely" that it cannot be linked to an identifiable person since the infrastructure does not communicate with vehicles and the digital twin does not integrate vehicle data, it is not subject to the EU General Data Protection Regulation (GDPR). However, vehicles and road users (through, e.g., smartphones) themselves produce vast amounts of data, which poses an increased risk that the data generated by the digital twin can be linked to an identifiable person. Whether or not this data should be considered personal data is still subject to debate with some scholars arguing that this question is a matter of risk assessment [126, 127], while others argue that the distinction between personal and non-personal data should be abandoned [128].

Furthermore, many advanced functions and purposes of digital twins, as envisioned by the Digital Twin Road CRC/TRR 339 project, require the integration of vehicle data, thus, requiring the processing of data considered personal data according to Art. 4 (1) of the GDPR [129]. For instance, intelligent, road-preserving trajectory planning aimed at extending pavement lifespan—a preventive maintenance application foreseen by the CRC/TRR 339 – necessitates communication between vehicles and road infrastructure. Consequently, a core focus of the CRC/TRR 339 is the cooperative fusion of sensor data. Specifically, one of the tasks of the digital twin(s) envisioned by CRC/TRR 339 focuses on integrating data from vehicle sensors (such as GPS positions, speeds, and wheel loads) with data from infrastructure sensors (such as road conditions and vehicle positions, load, and velocity sensed by a sensitive surface layer of the pavement). This data is georeferenced, enabling precise mapping of sensor data to physical locations on the road network. Such integration supports dynamic and predictive models that are considered essential for effective preventive maintenance. To elaborate, the precise georeferencing of sensor data allows for detailed mapping of vehicle trajectories and load distributions, facilitating the identification of potential stress points and wear patterns on the pavement. This information is considered vital for planning maintenance activities and optimising road usage to extend pavement lifespan. Thus, creating digital twins of roads will likely involve processing personal data.

Insofar as personal data is processed, digital twins of roads must comply with the principles and rules set out by the GDPR. Art. 5(1) GDPR mandates that the processing of personal data must be lawful, fair, and transparent and in accordance with data protection principles such as data minimisation, accuracy, as well as integrity and confidentiality. Importantly, for processing to be lawful, it must meet at least one of the legal bases set out in Art. 6 GDPR, such as explicit consent, a legal obligation, or public interest. Since it is unclear whether it could be technically feasible to obtain explicit consent, the lawfulness of the processing would most likely have to be grounded in a legal obligation or the public interest; both of which require a legal basis either in Union or in Member State law (Art 6 (2) GDPR).

The recently adopted C-ITS Directive (EU) 2023/2661 not only introduced an obligation for Member States to provide certain types of ITS data, but also set out to provide a legal basis for the processing of certain types of personal data [130]. According to its Art. 10, personal data can be lawfully processed "insofar as it is necessary for the performance of ITS applications, services and actions identified in Annex I of this Directive with a view to ensuring road safety or security, and enhanced traffic, mobility or incident management" [88, Art. 10(1)]. The C-ITS Directive can, however, only provide a legal basis insofar as the specifications adopted as Commission delegated acts specify "the categories of those data and provide for appropriate personal data protection safeguards" [88, Art. 10(2)]. So far, no such delegated act has been adopted.

Thus, at this point the processing of personal data by digital twins of roads could only be considered lawful if the competent legislative body of the Member State establishes a legal basis under domestic law (for instance, no such legal basis currently exists in German law). Such a law should clearly set out the categories of personal data and the purposes of its processing. It should further reflect the GDPR principles. This includes the principle of data minimisation, limiting the processing to 'what is necessary in relation to the purposes' (Art. 5(1)(c) GDPR), the principle of 'storage limitation,' limiting the storage of personal data to the period necessary to achieve the purpose (Art. 5(1)(e) GDPR), and the principle of 'integrity and confidentiality' (Art. 5(1)(f) GDPR), requiring appropriate technical and organisational security measures. Furthermore, the implementation of digital twins of roads that process personal data will likely require a Data Protection Impact Assessment. Given that it involves "new technologies" (Art. 35(1) GDPR), the "large-scale processing" of personal data (GDPR Recital 91), as well as the "systematic monitoring of a publicly accessible area on a large scale" (Art. 35(3)(c) GDPR), the implementation of digital twins of roads "is likely to result in a high risk to the rights and freedoms of natural persons" (Art. 35(1) GDPR). While such a Data Protection Impact Assessment must be carried out "prior to the processing" (Art. 35(1) GDPR), a first iteration should already take place prior to the adoption of the law.

Such an assessment could also establish technical and organisational data protection measures, including design requirements for implementing data protection by design and by default (Art. 25 GDPR). The technical measures should address a variety of concerns regarding data protection, privacy, and security including measures to ensure secure data storage in edge devices, access controls, and location privacy protection. Location privacy protection is crucial to prevent unauthorised tracking of user devices by untrusted service providers or attackers in edge computing environments. The recently updated ETSI specification 103 836-6-1 (V2.1.1) relies on pseudonym change—assigning "temporary pseudonyms instead of constant identifiers"—to limit such risks [131, p. 29]. However, even pseudonymisation with proper management (appropriate changing scheme, utilisation of automatically generated IPv6 interfaces) has severe limitations, with the risks being higher the more data is available [132]. One study found that if the number of observation points is high enough and if certain information from vehicle-to-everything communication is available (e.g., length and width of the vehicle), tracking of 80% of vehicles was possible [133].

The design and implementation of digital twins of roads also raises concerns about surveillance and the commodification of personal data. By continuously collecting real-time data, such a digital twin risks creating a surveillance infrastructure where data about users' behaviours and movements could be exploited beyond its intended purpose. Data-driven systems, while ostensibly designed to enhance efficiency and equity, often reinforce existing social inequities and exacerbate vulnerabilities. In the context of the digital twin of a road, the real-time collection and analysis of road infrastructure and its integration with road user and vehicle data could disproportionately impact marginalised communities, who may already be subject to heightened surveillance and control. These populations could face increased scrutiny and policing based on the patterns detected in their movements. Moreover, even when data is initially generated to improve public services, there is a risk that it will be repurposed for monitoring and punitive measures. This reinforces the necessity of critically examining who controls the data, how it is used, and clearly delimiting the purposes of the processing of personal data. Furthermore, the vast amounts of data collected can be used to predict and influence user behaviour, subtly steering decisions and actions. This form of "soft" control raises significant ethical concerns about the erosion of individual agency and the potential for manipulation [134–136].

Beyond the protection of personal data, digital twins of roads raise questions regarding their onto-epistemological impacts. Critical data studies emphasise that data is never neutral; it is imbued with the values and biases of those who collect, manage, and interpret it. Specifically, when digital twins are used as the foundation for decision-making in sustainable design, predictive maintenance, efficient operation and sustainable decommissioning, what data is included or excluded is of crucial political relevance. The data collection processes within the digital twin of a road might privilege certain types of data or perspectives, potentially marginalising others. For example, the emphasis on environmental and economic data might overshadow social dimensions, particularly those aspects that are harder to quantify, such as community impacts and social equity. Questions that arise include: who controls the digital infrastructure and the data that is generated and integrated? Who decides what data is generated and integrated? Who makes decisions about its use and how are such decisions made?

This is pertinent even if a digital twin's sole purpose is to enhance the operation and maintenance of pavements. For example, does the digital twin generate and integrate data on noise and light pollution, on non-human animal crossings, and geo-referenced GHG emissions? Should it generate and integrate data about road users such as race, gender, and socio-economic status? How might these considerations change if the digital twin supports traffic management and the development of C-ITS? Incorporating such diverse and inclusive datasets into digital twins of roads highlights the political and ethical dimensions of these technologies. If digital twins prioritise data on vehicular traffic flows and infrastructure conditions while neglecting noise pollution or non-human animal crossings, they reinforce a narrow perspective on road management that centers on efficiency and economic gain over broader environmental and social considerations. This selective data inclusion could lead to decisions that prioritise car-centric infrastructure improvements, marginalising the needs and safety of pedestrians, cyclists, and wildlife. The political implications of such decisions are significant, as they shape urban and rural landscapes in ways that reflect and perpetuate existing power dynamics and societal values. However, integrating socio-economic data such as race, gender, and income levels into digital twins poses even more ethical challenges related to privacy, surveillance, and potential discrimination. While such data can enhance equity in road management by identifying and addressing disparities in infrastructure quality and safety, it also risks reinforcing biases if not handled with care. Therefore, the decision to include or exclude specific types of data is not merely a technical one but a deeply political act that shapes whose voices and experiences are considered in road management.

Moreover, when digital twins support traffic management and the development of C-ITS, the stakes are even higher. These systems promise to optimise traffic flow, reduce congestion, and enhance road safety through real-time data integration and predictive analysis. However, the focus on optimising traffic can lead to a technocratic approach that overlooks the lived experiences of road users. For example, prioritising data that facilitates rapid vehicle movement might neglect the needs of non-motorised road users or fail to account for the social and environmental impacts of increased traffic volumes. Additionally, the development of C-ITS involves significant investments in digital infrastructure, raising questions about who benefits from these advancements and who bears the costs.

The use of digital twins for decision and policy-making in road management thus risks creating an illusion of objectivity and comprehensiveness, masking the value-laden choices and biases embedded in data collection and interpretation. The creation of more data and the increasing reliance on data-driven governance are premised on the promise of data to be 'objective.' Data along with scientific procedures allow for, what Daston and Galison call, "mechanical objectivity" [137]. At the very least, data are seen as more objective than humans, who are inherently subjective and biased. Unexamined, this belief in the promise of 'more data' can, as Lisa Gitelman and Virginia Jackson (2013, p. 3) put it, "become a faith in their neutrality and autonomy, their objectivity."

Ascribing 'objectivity' to data has far-reaching impacts. As Frank Pasquale (2015, p. 40) points out, "[b]ias can embed itself in other self-reinforcing cycles based on ostensibly 'objective' data." This depoliticisation of inherently political decisions can obscure critical factors such as community impact, historical context, and local knowledge, leading to policies that may not reflect the diverse needs and priorities of all stakeholders. As such, it is crucial for policymakers and planners to critically engage with the data practices underlying digital twins, ensuring that they are transparent, inclusive, and aligned with broader social and environmental justice goals. In other words, the deployment of digital twins in road management and C-ITS development must be approached with a critical awareness of their onto-epistemological impacts. That is, if we acknowledge that being and knowing are always already entangled, the choices about what data to collect, how to interpret it, and what to do with it shape not just what we know, but also what we consider to be real or important [138]. Decisions about what data to collect, how to interpret it, and what actions to take based on it are not neutral; they reflect and perpetuate particular worldviews, priorities, and power structures. The development and implementation of digital twins thus requires us to recognise and address these political dimensions.

5 Conclusions

This contribution examined potential applications and inherent challenges involved in developing and implementing a digital twin for roads. Considering the aspects of physical modelling and numerical simulations, data management, legal frameworks, and sustainability assessments, digital twins ostensibly offer significant benefits in the context of road infrastructure management. These possible benefits include the ability to conduct long-term analyses to accurately predict pavement deterioration and enhance preventive maintenance strategies. Such capabilities could lead to extended pavement lifespan, improved road safety through the early identification of vulnerable areas, and the development of long-lasting, resilient road structures. Moreover, the digital twin's capacity to forecast future states and generate real-time data allows for continuous monitoring, which could lead to more resource-efficient maintenance planning and improved sustainability performance assessments.

The integration of digital twins into road management also aligns with broader European strategies that emphasise the role of data and digital technologies in building a more sustainable and safer transportation system. By supporting the implementation of C-ITS, digital twins could support the digitalisation of traffic law and contribute to strategic policymaking. They could also bolster EU's sustainability goals by enabling more accurate sustainability assessments through high-quality, real-time data.

However, several significant challenges concerning digital twins were identified that need to be addressed. On the technical side, the integration of various sensors requires advanced sensor data fusion techniques, and issues such as data outliers, sensor errors, and effects of the weather on sensors introduce uncertainties. Ensuring the right choice of numerical models and reducing computational effort without compromising accuracy is another critical challenge. Additionally, data security is of utmost importance for digital twin of roads and and requires future research focusing on aspects such as safeguarding sensitive information or protecting data integrity. Finally, the development of digital twins demands a high level of expertise.

In addition to these technical challenges, social and ethical considerations play a crucial role in the adoption of digital twins. Data privacy concerns, particularly the potential use of personal data or the linking of generated data to individuals, raise important questions about the handling of data and the impacts on the users of the system. There is also the risk of disproportionate impacts on marginalised communities, who may be subject to heightened surveillance or exclusion. Furthermore, a possible focus on efficiency and economic parameters may lead to biased systems, in which environmental and social impacts are disregarded.

Finally, while digital twins could generate numerous benefits in terms of road infrastructure management, sustainability, and policymaking, their successful implementation will require addressing various challenges. Through interdisciplinary research and collaboration, the CRC/TRR 339 project attempts to contribute to identify and address these hurdles, advancing the digital twin concept application in the context of road infrastructure.

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Code availability Not applicable.

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Declarations

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