



Exploring the value of digital twins for information management in highway asset maintenance

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ABSTRACT

Highway agencies face challenges managing dispersed asset data across maintenance processes and information systems, hindering efficient retrieval of dynamic road information for timely interventions. A Digital Twin (DT)-based Information Management Framework (IMF) offers a promising solution based on a Foundation Data Model, Reference Data Libraries, and Integration Architecture. However, it is currently unclear how DT models of highway infrastructure systems based on a connected data ecosystem can be used in maintenance and how they benefit stakeholders. This paper describes results from a survey exploring DTs' potential in highway maintenance, starting with interviews with 20 experts to understand current processes, followed by a questionnaire survey to identify phases, features, applications, and use cases perceived as important by practitioners for road DTs. 183 responses reveal that DTs are widely deemed useful for asset deterioration prediction, strategy-making for routine maintenance planning, and scenario design for road investigation and repair in project-level maintenance.

1. Introduction

Highway infrastructure plays a vital role in our transportation ecosystem. However, real-world highway assets (e.g., pavements, structures, traffic signs, lighting, guardrails, and drainage) constructed decades ago are deteriorating rapidly, which results in reduced safety, traffic delays, and increased operational costs. The 2021 infrastructure report card released by the American Society of Civil Engineers (ASCE) rates America's road condition at D level and it indicates that 43% of the major roads and highways are in poor or mediocre condition (American Society of Civil Engineers (ASCE), 2023). Consequently, maintaining the ageing road assets becomes increasingly pivotal but challenging, requiring critical decision-making to make right-time maintenance interventions to avoid structural failures and traffic incidences.

High-quality data and functioning information systems are key success factors for maintenance decision-making. Unfortunately, information management (IM) has become an obstacle for highway agencies in efficiently performing maintenance activities. IM refers to a systematic process of data definition, data collection, storage, sharing, and usage of data related to the maintenance and operation of highways (Highways England, 2016). An industry report (E. National Academies of Sciences and Medicine, 2021) that surveys United States (US) departments of transportation (DOT) in 2019 shows that state highway agencies

commonly lack effective solutions for data specification and data management, and there is a lack of interoperability and linkage between existing systems. Highway asset data were collected at various business processes in the past and dispersed in different information systems, which were developed in different historical periods with disparate data definitions and system architectures. Consequently, asset data in the existing database is often inaccurate, incomplete, and incompatible. For example, Utah DOT reported that many asset owners collect data, but there is no single data repository, posing challenges to managing asset inventory (E. National Academies of Sciences and Medicine, 2021). In response, Utah DOT has invested in LIDAR (light detection and ranging) surveys to maintain an up-to-date asset database. Similarly, National Highways that manages the highway network in the UK currently has over 50 database systems and report repositories with some systems storing information on the same asset types (e.g., drainage (Highways, 2023a; Highway Agency, 2009)), but the updating of asset conditions cannot be synchronised across all systems. This made highway practitioners plan their maintenance jobs based on unreliable asset data, causing both economic loss and safety threats.

To mitigate the IM problems around asset data definition, collection, and storage, the highway industry has widely implemented asset management (AM) principles, which represent a systematic coordination of design, construction, operation, and maintenance of infrastructure

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<https://doi.org/10.1016/j.dibe.2025.100614>

Received 26 September 2024; Received in revised form 30 December 2024; Accepted 23 January 2025

Available online 25 January 2025

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assets to realise their life-cycle values (Uddin et al., 2013). Some countries have published standardised highway asset data models, such as OKSTRA and the Asset Data Management Manual (ADMM) (Highways, 2023b). These asset data models have limited software support and require laborious alignment with organisational systems. To enhance data and system integration, highway agencies have started to adopt asset management systems (AMSs) in recent years, such as AASHTOWare (AASHTOWare). These AMSs are geared primarily to conduct network-wide maintenance planning (e.g., project prioritisation) based on condition scores of different road sections. However, the coverage of asset information in current AMSs could be unsatisfactory for some use cases due to uncoordinated data delivery and difficulty integrating heterogeneous files and subsystems. For instance, Ammar et al. (2024) surveyed 30 state DOTs and found only 14 of them that use AMSs to manage ancillary asset data with limited data modelling and analysis capabilities. In terms of asset data collection, paper-based documents, PDF, and drawings mixed with tables and schedules are pervasively used for project delivery (Ammar et al., 2024; Yuan et al., 2017), so information errors and loss can occur when design and construction data flow into AMSs. This also causes the data collected from advanced sensing technologies, such as mobile scanning, cannot be precisely mapped to specific assets or asset components in the operation and maintenance (O&M) phase.

The concept of product lifecycle management (PLM) provides a concrete solution to work out the puzzle of AM of complex highway systems. In the built environment domain, Building Information Modelling (BIM) is the most promising realisation of PLM, which represents a semantic-rich digital model of building products that can be exchanged across the project lifecycle and a variety of engineering software (Eastman et al., 2011). Nowadays, BIM technology has been successfully implemented in the road design and construction phases, such as alignment design (Vignali et al., 2021) and quality control (Han et al., 2023a). Some countries, like Norway, China, and Australia, have published official standards requiring BIM models to be used for road construction delivery, with required asset attributes specified (Naborczyk, 2020). However, traditional AMSs have limited capacity to exchange information with BIM files (Lorvão Antunes et al., 2024), so BIM models are not effectively used, managed, and updated in the operation phase.

The digital twin (DT) concept offers an evolutionary model-based IM approach to addressing the above problems, enabled by the maturity of cloud computing, product modelling technologies (e.g., BIM software ecosystem), Internet of Things (IoT) technologies, and data science (Tao et al., 2018). Grieves (Grieves and Vickers, 2016) first proposed the concept of the DT model in the realm of PLM, which is described as “a set of virtual constructs that fully describes a potential or actual physical product from the micro atomic level to the macro geometric level”. There are three key elements in a twin system: physical space, virtual space, bidirectional data flow between two spaces. The digital system dynamically simulates the physical system, offering values of lifecycle high-fidelity product data integration and data-driven services, such as predictions and model interrogation. In the highway domain, the DT approach transforms static product model files (e.g., Industry Foundation Classes (IFC) (buildingSMART International Ltd, 2019), LandInfra) of infrastructure assets into georeferenced 3D virtual models in cloud services, which will be constantly updated to mirror the dynamic status of physical assets during the asset lifecycle. DT models can be further transferred to contractors as project information models for rehabilitation, renovation, and demolition projects, facilitating seamless lifecycle data exchange and integration. High-fidelity DT models with component-level information, as opposed to vectorized road models in traditional AMSs, can more efficiently combine with IoT technologies to represent road asset status in dynamic 3D environments. The potential applications could be 3D distress modelling for pavement surface monitoring (Dong et al., 2021), design of surface treatments and new layers (Tang et al., 2020), and localisation of underground drainage.

Moreover, the DT-centred information management framework (IMF) (Kendall, 2021) (see Section 2.2 for details) allows DT models governed by asset owners to be shared in a consistent and connected data ecosystem. This helps stakeholders efficiently retrieve information on multiple infrastructure assets and extracts most of the value of data.

To apply the DT approach in highway maintenance, it is necessary to identify its main applications, use cases, and benefits in the road domain. This could aid the development of metamodels, system architectures, and data-user interfaces. However, existing studies on road DTs mostly focus on the creation of DT instances and DT-enabled condition monitoring (Jiang et al., 2022a, 2022b). There is a lack of research on how the highway industry perceives the value of DTs, considering their practical problems and the potential improvements made by DTs. This study is crucial because many details of IM in current practice are confidential within highway organisations, so it is valuable to understand their requirements and expectations for DTs.

In this research, we explore the potential value of road DTs as a new IM approach for highway maintenance based on an industry survey. The authors first interviewed twenty industry experts in the UK highway sector to understand the current highway maintenance processes and the challenges encountered. Subsequently, we conducted a questionnaire survey with experienced practitioners from the highway industry to investigate the potential use cases, benefits, and challenges for DT implementation. In this paper, the term “application” denotes the general area in which we implement the DT, and “use cases” refers to specific scenarios or problems within the application area where the DT provides a solution or improvement.

We highlight the contributions of this research as follows.

- 1) This study reveals the main problems of IM in the highway industry by surveying the existing maintenance processes and their inefficiencies. These findings could motivate the development of a new DT approach for resolving IM-related issues.
- 2) This study shows how the highway industry currently understands the DT concept and how it implements the DT-based approach in this field. The survey reveals in which contexts DT is used to address specific problems.
- 3) This study reveals how industry practitioners commonly perceive the value of road DTs in highway maintenance. The survey results indicate the important features of a road DT, and the use cases depicted by participants demonstrate how users can potentially operate DTs to better perform their maintenance activities and tasks.
- 4) The study reveals the potential challenges for implementing the DT approach in highway organisations considered by industry practitioners. Furthermore, the survey shows highway experts’ views about whether the DT approach will become the standard practice in the future.

We structure the remainder of this paper as follows: Section 2 reviews the existing IM approaches and DT implementations in highway engineering. Section 3 describes the present research methodology. Section 4 presents the results of the interview. Section 5 demonstrates the questionnaire contents and results. Section 6 discusses the survey results by outlining the significance of this research and limitations. Section 7 concludes the research and suggests future research areas.

2. Literature review

2.1. Asset management systems for highway maintenance

Modern AMSs are becoming increasingly complex and contain a broad spectrum of data elements, including inventory, asset condition, material, finance, traffic, weather, and ecological data (Le and David Jeong, 2016). These data elements are normally stored in different database and managed by specific subsystems, like pavement management systems (PMSs), maintenance management systems (MMSs), and

traffic management systems. In the past, different subsystems were developed separately, with their own data collected, stored, used, and updated in a system to support transportation asset management (TAM) use cases (Li, 2018). However, as transportation infrastructure becomes more complex, AMS data may be used differently and be duplicated, necessitating the integration of subsystems.

PMSs and MMSs are the most typical subsystems in highway AMSs (Haas and Hudson, 2015). PMSs involve the collection of pavement data and evaluation of pavement behaviour and performance based on analytical models (Santos and Ferreira, 2013). Currently, nearly all PMSs use geographic information systems (GIS) and global positioning systems (GPS) to manage road asset information with locations, identifications, and attributes (Al-Mansoori et al., 2020). GIS-based PMSs use layers to separate different levels of information (Obaidat et al., 2018) and leverage linear referencing systems (LRS) to describe features (Perrone et al., 2008). However, the nature of 2D data management based on vectors and layers (Escobar et al., 2008) limits the capabilities of PMSs in representing micro-level asset information, such as 3D geometry, asset components, and asset interactions, which could be important in some use cases. For example, 3D models of pavements, structures, and geotechnics could be required to manage the collapse of highway slopes and blockage of carriageways during extreme weather conditions. Unfortunately, different asset systems (e.g., bridges, drainage, road markings) are largely fragmented in current practice (Sassani et al., 2021; Ebbesen, 2021), with the main hurdles arising from heterogeneous network models, LRSs, scales, and the difficulty of mapping linear assets (e.g., pipes) to transportation networks.

MMSs are mainly used by highway engineers to plan and arrange maintenance activities (Chen and Zheng, 2021), which essentially consists of a data module and a decision analysis module (Sarsam, 2016). The data module stores data relevant to the decision-making processes, such as inventory, condition, traffic, finance, activity, and resources (Kerali et al., 2000). The decision analysis module assists in making decisions for activities like programming, budget allocation, and project scheduling (Sun et al., 2020). There are plentiful studies that investigate novel solutions to optimise decisions under specific constraints and objectives (Deshpande et al., 2010). However, the usability of these algorithms is heavily affected by the availability and quality of AMS data (Mohamed et al., 2022). Modern MMSs have started to interface with PMS based on a consistent LRS to improve both maintenance planning and behaviour modelling (Hudson et al., 2011).

Data warehousing and distributed systems are the two main approaches for integrating subsystems within the broader AMS framework (Li, 2018). Data warehousing refers to the process of gathering all information from different sources into a centralised data repository (Oti and Gharaibeh, 2020), which eases retrieval of data in processed formats for ad hoc usage. Highway agencies in different regions, like those in the US, UK, and India, have reported a paradigm shift towards Data-as-a-Service (Highways England, 2016; Krishna et al., 2024), whereas the implementations present challenges due to a highly diverse technology architecture and datasets. State-of-research (Transportation Research Board, 2024) has focused on optimising the enterprise data warehousing strategies, including data aggregation, extract-transform-load, naming, storage, metamodel structure, security, and alignment with standards framework (e.g., IFC). On the other hand, distributed systems contain self-communicable databases to support data sharing, synchronisation, and cross-database queries (Li, 2018). Nonetheless, research and industry articles indicate that AMSs encountered shortages of communications between subsystems (E. National Academies of Sciences and Medicine, 2021; Yuan et al., 2017; Le and David Jeong, 2016; Liu et al., 2024). For example, the Road Directorate in Denmark illustrates that their AMSs are fragmented and technologically obsolete, and there is an urgent need of coherent AMSs for cross-asset financial prioritisation (Ebbesen, 2021). To overcome TAM data interoperability issues, the research community has developed data linkage mechanisms (Yuan et al., 2017) and handover data models (Le

et al., 2018) to transform project documents into AMS database. Le and Jeong (Le and David Jeong, 2016) present an ontology-based method to gather relevant data for decision-making. However, these studies do not substantially solve the data and system integration problems in AMSs.

The critical obstacles for digitalisation of TAM systems and processes stem from several aspects. First, some AMSs have been used for many years, with much sensitive organisational data (e.g., finance) bonded, and their use can be mandated by regulations. Therefore, although existing AMSs fall short in asset data modelling, storage, and acceptance of new technologies (e.g., IoT and sensing technologies (Justo et al., 2021)) and new data (e.g., 3D design models), it is hard to replace old systems. Second, the nature of highway maintenance determines the high diversity and volume of datasets produced and utilised at various processes. Hence, it is prone to data redundancy problems, data silos, and difficulties of handling customised data queries. This suggests that DTs could enhance current practices by: (a) improving the quality and coverage of asset data through the integration of BIM, infrastructure sensing technologies, and artificial intelligence (AI); (b) providing ontological models to represent and deduplicate existing AMS databases; and (c) offering complementary digital systems to streamline dataflows between AMSs and service-oriented platforms for DT applications.

2.2. Product model-based information management

The BIM approach has emerged as a new IM approach in the highway domain to improve asset lifecycle data integration. The core advantages of the BIM approach are twofold: (a) element-wise parametric models can store abundant geometry and semantic information (b) openBIM standards (e.g., IFC, COBIE); allow seamless information exchange between software systems, facilitating product data flow from design to operation phases. Norway's industry is one of the pioneers that adopted the BIM approach for road O&M management. The implementation relies on a common data environment (CDE) called Trimble Quadri, complemented with AgileAssets (Norwegian Public Roads Administration Selects). In academia, existing studies have extended the BIM data models to include new properties such as pavement condition (Bosurgi et al., 2022) and material properties (Oreto et al., 2021a). Additionally, researchers have developed BIM-based workflows for maintenance scheduling (Oreto et al., 2021b), life-cycle assessment (Oreto et al., 2023), and maintenance history management (Cho et al., 2024). These studies show the benefits of BIM in 3D model visualisation, user-friendly interface, and data retrieval. In terms of BIM-AMS integration, Hagedorn et al. (2023) present a BIM-enabled TAM information delivery approach using Information Container for Linked Document Delivery. The Connected Data for Effective Collaboration project (Lorvão Antunes et al., 2024) develops an ontology-based framework to facilitate data interoperability between BIM and AMSs. Although the above efforts have enhanced the integration of BIM and AMS at the semantic level, no product model-based IM framework has been established so far to bolster continuous data updating and governance in the O&M phase. Consequently, highway agencies lack clear guidance to manage road BIM models received from project contractors to maximise their information values (PIARC, 2019).

DTs can serve as an evolved model-based IM approach that drives a new generation of AMSs. The Centre for Digital Built Britain defines the DT as "a realistic representation of assets, processes, or systems in the built or natural environment" (CDBB, 2020). DTs in the infrastructure O&M phase primarily stand for a digital replica of physical assets (Liu et al., 2024; Lu and Brilakis, 2019), such as roads, bridges, and tunnels. While this concept is similar to the idea of as-is BIM models, the DT concept differs from BIM in its bi-directional data flow between real space and virtual space. This suggests that a DT is also coupled with a twin system, processes, and data-driven models (e.g., optimisation models) to make interventions on the physical assets. The IMF (Kendall, 2021) developed by the UK National Digital Twin (NDT) Programme specifies three

components of a twin system: Foundation Data Model (FDM), Reference Data Library (RDL), and Integration Architecture (IA). FDM is an upper ontology that provides a clear and consistent description of what constitutes the world of DTs by addressing problems like space-time, actuality, and granularity. RDL provides controlled vocabularies with a set of classes and properties to describe domain-specific knowledge, which can be built by reusing existing semantic standards. IA represents a digital system that manages multiple federated DT models and offers protocols for data authorisation, sharing, discovery and retrieval across distributed users and providers.

Even though the traditional AMSs provide digital representations of highway assets in a certain level of detail, infrastructure DTs leverage the product model management processes and provide a high-fidelity, continuously updated digital model, encompassing information like 3D geometry and materials of micro-components. This ensures the information flowed into AMSs can best satisfy TAM needs and offers opportunities for refined management of critical assets (e.g., pavements, structures). Further, a twin system based on FDM, RDL, and IA allows semantically consistent data management of asset systems and data sharing in a connected data ecosystem, which simplifies processes of cross-asset data extraction and analytics.

2.3. Digital twin implementation in road infrastructure

In the planning and design phases, a road DT is primarily used to assess the impacts of new road designs on existing networks and natural environments. Machl et al. (2019) present a DT-based method for supporting road planners to assess design impacts on agricultural road networks, where the DT is a spatiotemporal information model of the cultivated landscape. Jiang et al. (2022b) propose an approach to generate DT instances of existing highways using online map data, including aerial photography, digital surface models, and digital elevation models. Jiang et al. (2022c) further develop a solution to automatically create underpass road DT models. This underpass model is compared with the as-design BIM model to assist in design checking. Furthermore, DTs have also been employed in urban-scale road design. For example, Jiang et al. (2022a) propose a new sustainable urban road planning approach by integrating DT, multi-criteria decision-making framework, and GIS. The road DT incorporates traffic congestion data by querying Google Maps, which is then used to inform plans for new road construction and road widening.

In the road construction phase, the DT is indirectly used to assess the performance of new road materials. Meza et al. (Meza et al., 2021) developed a road DT to examine secondary raw materials (SRM) used in real road construction projects. Manually developed road IFC models are imported into a CDE platform that allows the integration of sensor data installed in various pavement layers. In addition, some existing studies integrate BIM and the IoT for road construction monitoring. For example, Han et al. (2022) propose a BIM-IoT and intelligent compaction (IC)-integrated framework for road compaction quality monitoring and management. Han et al. (2023b) propose a BIM-based quality control and assurance framework that realises real-time construction data integration, visualisation, and analysis based on the analytic hierarchy process approach, artificial neural networks, and genetic algorithms.

In the O&M phase, many studies focus on creating DTs of operating highways, with dissimilar approaches proposed and various data used. Marai et al. (El Marai et al., 2021) propose a DT platform for roads using a 360° camera and IoT sensors. A live stream, GPS location, and measurements of the temperature and humidity are dynamically sent to the DT, with interested objects (e.g., people and vehicles) detected and tracked. Wang et al. (2021) use 3D GIS technology to develop a highway DT, where the computer-generated architecture language is employed to build the road geometric models. Steyn and Broekman (2022) develop a DT prototype of a local road network for dynamic maintenance, which uses LIDAR, unmanned aerial vehicles (UAV), and sensor systems to

capture road geometry, traffic flow data, and road environment data, respectively.

Previous literature has also explored potential applications of road DTs in the O&M phase. Chen et al. (2022) propose a DT-based conceptual framework for road condition prediction that takes historical and real-time data from the whole road lifecycle as inputs and utilises machine learning algorithms to predict future road performance. Yu et al. (2020) propose an approach to highway tunnel pavement performance prediction based on a DT and Multiple Time Series Stacking, where the DT is primarily used to visualize the predictions of performance in a BIM environment. Ye et al. (2020) use an updated Finite Element (FE) model as a DT to identify the root causes of performance concerns for highway bridges, which integrates visual inspection, operational monitoring, and structural testing. Agrawal et al. (2022) take DT deployment on highway maintenance projects as a case study to test their digitalisation framework for organisations. The case study showed that highway experts planned to use DTs to detect defects on pavements, predict future defects, and generate maintenance work orders. By extending the IFC and the Brick ontology (Balaji et al., 2016), Zhu et al. (2023) created an information model for DT-based highway operational risk management, which integrates highway product data, topology data, and sensor data.

2.4. Gaps in knowledge

DTs and twin systems can potentially benefit the highway O&M management. However, there are still some gaps in knowledge in this field.

- 1) There is a lack of in-depth investigation of IM practices and problems for highway maintenance. Existing reports and case studies solely provide simple descriptions like self-assessment scores, but they seldom present details of management, considering different business processes and aspects of IM.
- 2) There is a lack of research exploring the benefits and challenges of applying DTs in highway maintenance from the perspective of industry practitioners. Existing studies focus on the creation of DT models and data analysis, with limited attention to industry opinions regarding the applicability of DTs, considering existing TAM systems and processes.

To fill the above knowledge gaps, the objectives of this work are as follows.

- *Objective 1:* Understand the main pain points in the current practice of highway maintenance. This will be achieved by answering the following research questions (RQ): **RQ1a:** What processes do highway agencies currently follow for road O&M? **RQ1b:** What are the primary inefficiencies in these processes that impede effective highway maintenance?
- *Objective 2:* Explore the potential improvements brought by DTs. This will be achieved by answering the following research questions: **RQ2a:** What are the main phases of highway maintenance that a road DT can take effect? **RQ2b:** What are the main applications and use cases for implementing DTs in highway maintenance? **RQ2c:** What benefits can DTs bring to highway maintenance practices? **RQ2d:** What features of road DTs are perceived as important to realise their values? **RQ2e:** What are the constraints of road DTs in achieving their values?

The scope of this research includes maintaining road assets (e.g., pavement, traffic signs, etc.) in highway infrastructure without covering urban roads or traffic operation management.

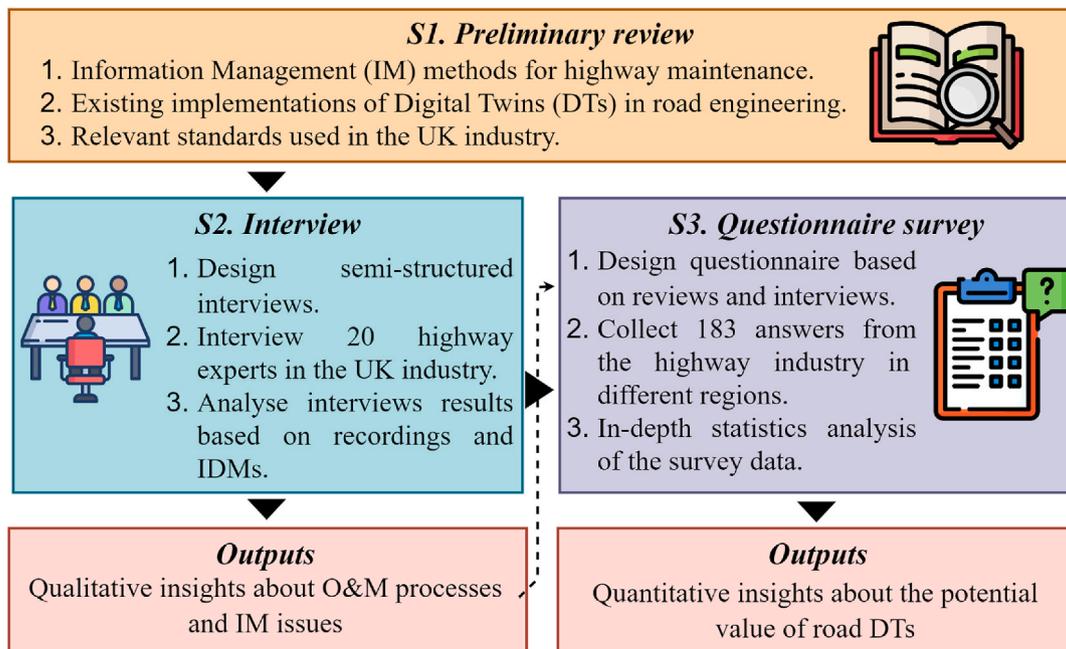


Fig. 1. Research methodology. “S” denotes step.

3. Research methodology

3.1. Data and methods

Fig. 1 outlines the research methodology. The first stage of this study begins with an interview with highway professionals to investigate the inefficiencies of the current IM methods and processes adopted by the industry. Since interviewing worldwide highway agencies is infeasible and uneconomic, we selected the UK industry to conduct an in-depth exploration of IM practices for the following reasons: First, the UK has well-developed infrastructure systems and diverse geographic conditions, offering comprehensive insights into IM issues. Second, the UK industry actively adopts advanced technologies and innovative practices, so it already has comparatively high digitalisation levels for IM. Third, the UK industry has close connections and technological communication with other countries, such as the US and European industries. Hence, the authors interviewed 20 experts who work in different departments of the UK national road agency after we reviewed the highway maintenance standards (for Highways, 2022) used in the UK to understand the basic procedures and data management requirements. We designed semi-structured interviews with a few predetermined questions and other unplanned questions, which allows for great flexibility in gaining detailed insights about the key topics. The interview focuses on the following questions.

- 1) What activities, actors, and data exchanges are involved in your business processes?
- 2) What systems, specifications, platforms, and databases do you use for IM in your professional work related to highway maintenance?
- 3) What are the main decision-making points in your business processes? What are the inputs and outputs of the decisions?
- 4) What are the main challenges and inefficiencies in your professional work?

We employ a qualitative coding approach to systematically categorise and interpret the qualitative data obtained from our participants. Our process involved the following steps.

- 1) Transcription: All interviews were transcribed verbatim to ensure accuracy.
- 2) Thematic Coding: We conducted coding by segregating the transcripts among various themes (e.g., maintenance processes, IM methods) for significant pieces of data.
- 3) Review and Refinement: Themes were reviewed in relation to the questions asked and the entire data set to ensure they accurately reflected the data.
- 4) Documentation: the themes were documented with illustrative quotes from the interviews to provide a comprehensive understanding of the findings. We utilised the Information Delivery Manual (IDM) approach (I.S.O. 29481-1, 2010) to document the existing maintenance processes. IDM was selected because it provides a well-defined process modelling framework, including process maps and exchange requirements, which can denote the hierarchy of maintenance processes, actors, and information exchange.
- 5) Interpretation: Based on the organised codes, the authors analysed the IM-related issues in a group discussion.

In the second stage of this research, a questionnaire survey is used to investigate the value of DTs as a new IM approach in the highway O&M. The questionnaire was designed following the process as follows.

- 1) Decide the required information: (a) is there a consensus in the industry on the issues identified in the previous interviews? (b) how can domain users exploit DT road models to better handle their maintenance-related tasks and solve the existing issues? (c) What barriers to implementing DTs can industry practitioners expect?
- 2) Define the target respondents: this survey intends to collect responses from practitioners in highway organisations whose roles are relevant to the road O&M stage. We identified the main participants based on the conversations during the interview.
- 3) Design the question content: In the questionnaire, we first clarified the definition of the DT concept in the context of highway maintenance and described its functional features. This would help participants who are unfamiliar with the DTs understand the concept and answer questions by relating DTs to their professional work. Based on the literature review and the first-stage interviews, we designed 15 questions in five sections, as described below:

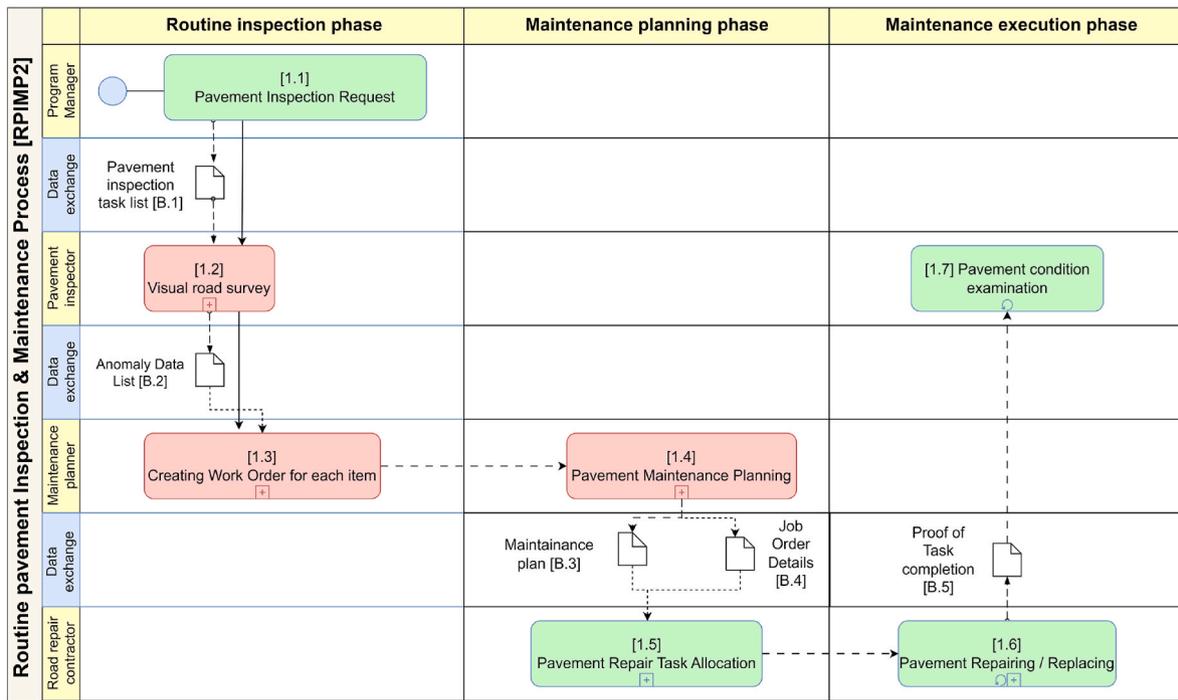


Fig. 2. IDM process map for routine maintenance and reaction. Red block represents the activities that have apparent inefficiencies identified.

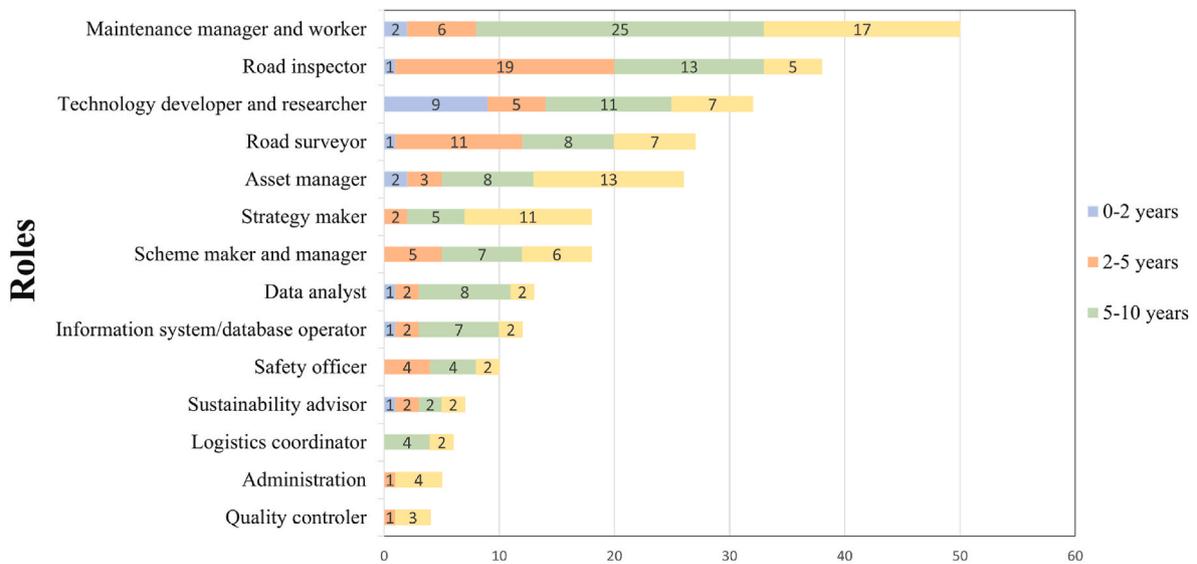


Fig. 3. Respondents' roles in highway maintenance and experience in the highway industry (Questions 1 and 2).

- (a) The first section surveys the participants' demographics (Question 1) and predefines several roles as options for Question 2, where the list of roles comes from the involved actors in the developed IDM process maps (see Fig. 2).
- (b) The second section has an open response-option question (Question 3) to gain quantifiable insights about the IM-related problems in current practice. The predefined options come from the commonly addressed issues identified during the thematic coding and interpretation processes in the first-stage interviews.
- (c) The third section studies the industry's adoption of the DT approach. We designed a semi-open question (Question 5) to investigate what IM approaches and relevant technologies are currently used by respondents' organisations, where options

come from the review and interview findings about the systems and tools currently used by highway agencies. An open question (Question 6) follows, allowing participants to describe the context in which they employ DTs.

- (d) The fourth section explores the opportunities for DTs in highway O&M. We determined options for Question 7 by sorting out preliminary phases of highway maintenance processes documented in IDMs. Furthermore, we crafted Questions 8 and 9 to explore the perceived significance of DTs' features and applications. We list several typical features in Question 8 based on the review in Section 2.3, and we further compared current problems (Question 3) and the functional features of DTs with some potential DT applications proposed in Question 9. We also created an open question (Question 10) to efficiently search for

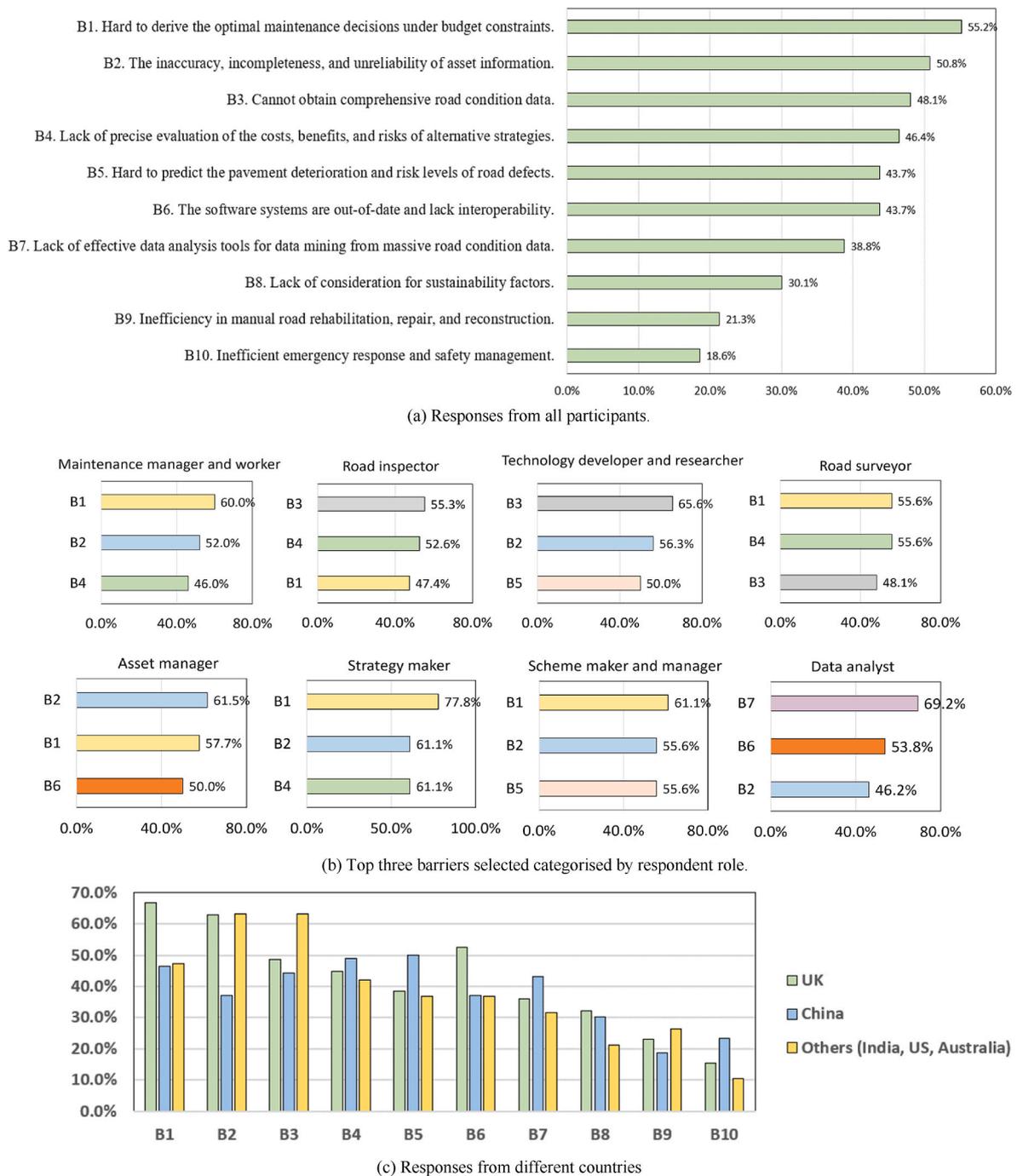


Fig. 4. Responses to Question 3: "What are the main challenges and barriers faced by your organisation in highway maintenance operations?". "B" denotes barrier.

potential use cases, and a semi-open question (Question 11) to understand the benefits of DTs. The predefined options originate from a group discussion based on the shortcomings in the current practice and potential applications of DTs.

- (e) The fifth section mainly involves a semi-open question (Question 12) to investigate the challenges of implementing the DT approach for highway organisations. The predefined options stem from the authors' group discussions, which are based on the interview findings about the systems, specifications, databases, and IM procedures currently adopted by highway agencies.
- 4) Pre-test the questionnaire: five postdoctoral researchers with road engineering expertise were invited to test the survey to evaluate the wording, length, and significance of the questions. The questionnaire form was revised according to their comments.

We determined the required sample size using Taro Yamane's formula based on an assumed 95% confidence level. Given the exploratory nature of this study and the limited pool of potential respondents knowledgeable about DTs, we permitted an 8% margin of error, yielding a minimum required sample size of 157. We adopted a random sampling approach to collect responses from different countries, and we conducted a Chi-Square test for essential questions to identify significant differences in the distribution of responses across different groups, with the null hypothesis that there are no associations. We turned each option of multiple-answer multiple-choice questions (e.g., Question 3) into a binary question because these variables are not mutually exclusive.

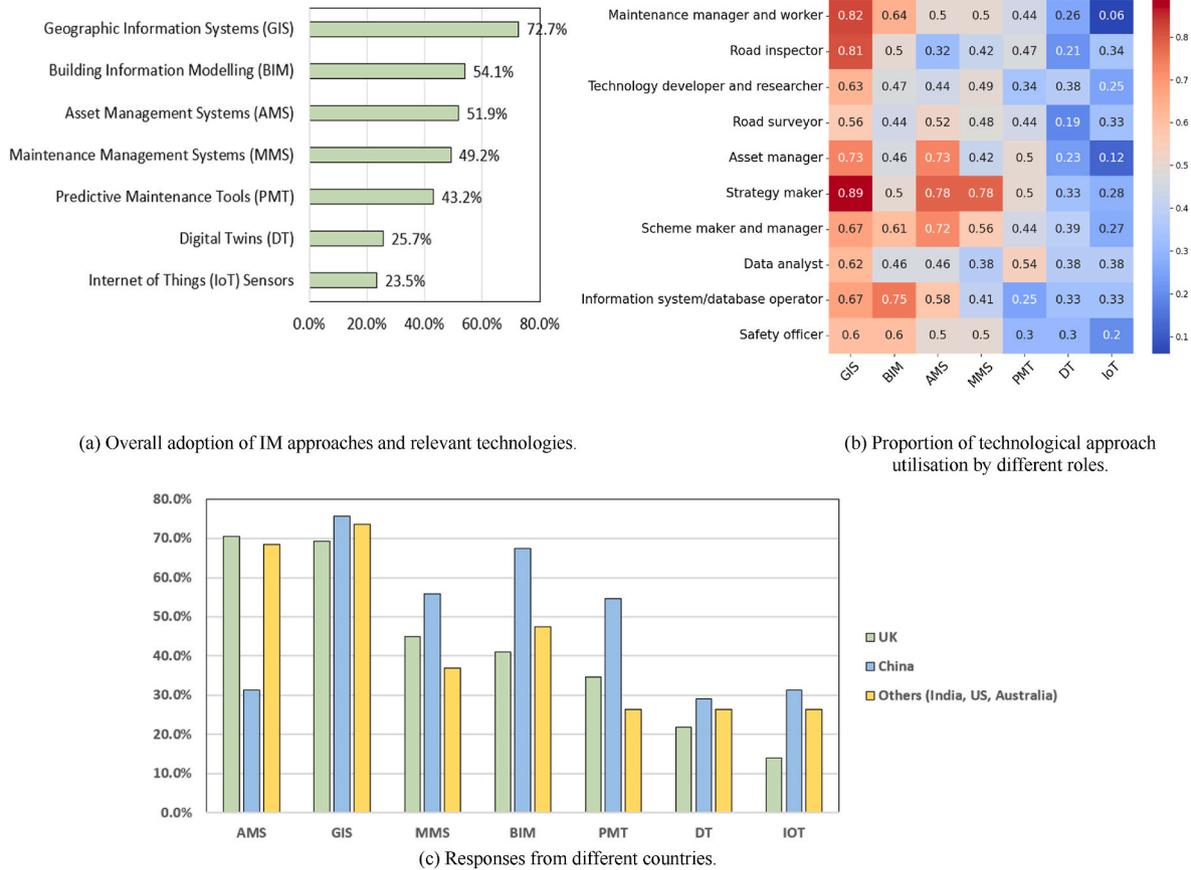


Fig. 5. Responses to Question 5: "Does your organisation currently use digital technologies or solutions for highway maintenance?"

3.2. Assumptions

This research assumes that highway maintenance processes and methods, such as routine maintenance and major maintenance, are generally similar between the UK and other countries. Although the IM procedures are subject to different countries' regulatory frameworks, this research focuses on the IM capabilities and issues driven by technology development, so we assume that the main inefficiencies identified through the interview also exist in the highway industry of other countries and regions. This explains why the questionnaire survey based on interviews with UK agencies is valid to explore the application values of DTs for the highway maintenance domain.

3.3. Activities

The survey stage lasts from October 2023 to November 2023. We first had face-to-face or online interviews with 20 UK highway experts. Their roles include inspector, technical lead, data scientist, service delivery manager, routine maintenance manager, scheme developer, network planner, network surveyor, standard developer, and asset manager. Each interview ranged from 1 to 2 h, depending on how thoroughly the discussion topics were covered. We began by introducing the research project and its objectives to the interviewee, followed by asking specific questions.

For the second-stage survey, we disseminated the questionnaire through various channels, such as email invitations and LinkedIn. The survey was collected in approximately a month's time, with over 500 email invitations. Several highway agencies helped spread the survey internally and to their contractor companies. To attract relevant people to complete this questionnaire, we gave prompts in the invitation that stated: "The target population for the survey is practitioners in the highway

industry, especially in the following areas: (a) road survey and inspection; (b) road maintenance; (c) information system/database operation; (d) strategy making and research innovation; (e) asset management; and (f) safety management." Consequently, a total of 215 responses were received from different regions, with 32 determined to be invalid (e.g., leaving all questions blank). The remaining 183 valid responses include 77 responses from the UK, 86 responses from China, 12 responses from India, 6 responses from the US, and 2 responses from Australia. The 85 responses from the UK, US, and Australia reflect the perspectives of industry practitioners in developed countries, which manage a significant amount of aging road infrastructure. Notably, the UK data includes responses from practitioners who work across multiple European countries. In contrast, the 98 responses from China and India represent, to some extent, typical developing countries with more newly constructed roads. While the results are predominantly from respondents in the UK and Chinese industries and do not cover a broader range of countries and regions, the collected data provide valuable insights to address the research questions RQ2a-e. This is because our goal is to explore functional features and technological applications of DTs recognised as beneficial by experienced highway practitioners, rather than to identify differences in industry maturity across countries. Since regional factors can influence the distribution of responses, we compare answers from the UK and China in Section 5 to illustrate disparities between typical developed and developing regions.

4. Interview of highway professionals

4.1. Existing maintenance processes

Based on the interviews, we generally broke down the UK's highway maintenance processes into seven interconnected levels, each with

Table 1

Selected answers for Question 6: “Briefly describe the context or project where digital twins were/are utilised.” The number in parentheses denotes how many times the case was mentioned by respondents; * denotes that the case was mentioned by some respondents who did not select “Digital twins” in Question 5, but not all; underlines denote that the case was mentioned only by respondents who did not select “Digital twins” in Question 5.

Category	Context of DT adoption
Maintenance planning	Decision-support tools to assess maintenance needs*(5), behaviour modelling of road assets (4), real-time pavement condition monitoring*(6), <u>predictive maintenance</u> (4), dynamic visualisation of road conditions (4), data-driven decision-making (1), <u>optimise maintenance plans</u> (1), fleet composition analysis (1), BIM-GIS-IoT-based maintenance management system (2)
Asset data management	AIM creation (3), asset management platform (2), road condition information storage (2), <u>GIS-based utility management</u> (1), locating and georeferencing assets (1)
Road survey	<u>Digital information systems integrating surveys, digital designs, and as-built data</u> (1), BIM generation from point clouds (1)
Road design and renovation	<u>Clash detection</u> (1), <u>measurement of road sections</u> (2), future road planning (1)
Road repair and construction	<u>Construction planning</u> (1), <u>job sequencing</u> (1), site monitoring* (2), <u>improve safety of workers and machinery</u> (1), <u>building structures</u> (1), 3D visualisation of maintenance projects (3), <u>construction process simulation</u> (1)
Operation management	Budgetary analysis (1), <u>operational monitoring</u> (1), <u>process improvement</u> (1), inventory management (1), training and education (1), <u>DBFO (design, building, finance, operate) life-cycle management</u> (2), procurement *(2), sharing road conditions and maintenance information with stakeholders (1)
Traffic management	Safety analysis (2), <u>traffic flow monitoring</u> (3), <u>transportation system monitoring</u> (1), real-time data analysis with IoT and dashboard *(2), accident visualisation and retrospective*(2), <u>positioning of highway participants</u> (1), formulate traffic emergency evacuation plans *(3), autonomous vehicles (3), driver behaviour analysis (1)
Environment	Environment modelling*(2), <u>weather condition monitoring</u> (1), environment analysis (1), real-time weather detection of the highway environment (1), refined weather forecast (1), flood risk analysis (1), energy reduction (1)

distinct data flows, which can be described as follows.

- 1) Organisation-level strategy making: Senior managers, engineers, and chief scientists in highway authorities make top-level strategies for resource allocation, maintenance standards, technical roadmaps, and others that target the whole network. Decision-makers often need to gather data from different departments and systems to make evidence-based strategies.
- 2) Network-level survey: The highway agencies carry out annual condition surveys for the whole road network, including visual condition surveys, structural condition surveys, and skid resistance surveys. Interviewees informed us that they generated detailed defect maps using image processing algorithms. However, due to the network database’s limited storage capacity, they only hand over several indexes (e.g., rutting index) for road sections. The raw survey datasets are sometimes requested by other processes, such as routine maintenance.
- 3) Network-level planning: Network strategy makers receive the network survey results and plan maintenance schemes for the road network in the following years. They have a tool to prioritise and programme all schemes based on factors like asset age, risk levels, and budget constraints. The UK agency currently stores network survey data in pavement asset management system (P-AMS) (Highways, 2023c) and exports Excel sheets to gather relevant data for network planners.

- 4) Scheme (project)-level survey and treatment: Scheme makers develop detailed plans for comprehensive road investigation (e.g., coring) and treatment for each maintenance scheme. They receive a list of Excel sheets exported from P-AMS that contain detailed scheme descriptions and make decisions by viewing network survey data across many sheets, construction data in P-AMS, and other different systems to retrieve traffic, flooding, incident, and historical maintenance information.
- 5) Routine and reactive maintenance: the UK industry currently use a nationwide system, Confirm (Highway Agency, 2009), to manage asset information and arrange work orders for this level of maintenance. Experienced engineers determine cyclic maintenance frequencies for different asset classes every year based on their local knowledge. For reactive maintenance, road inspectors regularly drive through the entire network to check for abnormal road conditions, such as pavement distress, vegetation overgrowth, and blocked drains. They upload defect reports with notes and photos to Confirm through a tablet.
- 6) Emergency response: if any emergencies occur (e.g., traffic accidents), maintenance planners make a 24-h response to arrange for engineering teams to repair assets in case any chained accidents happen rapidly. The IM for emergency response is also based on Confirm and follows similar patterns of routine maintenance.
- 7) Maintenance for extreme weather: a service that provides salt and snow removal in winter and responds to other extreme weather conditions (e.g., storms). The relevant teams currently use separate systems called Severe Weather Information System (SWIS) and WebTRIS to monitor weather and traffic flows, respectively.

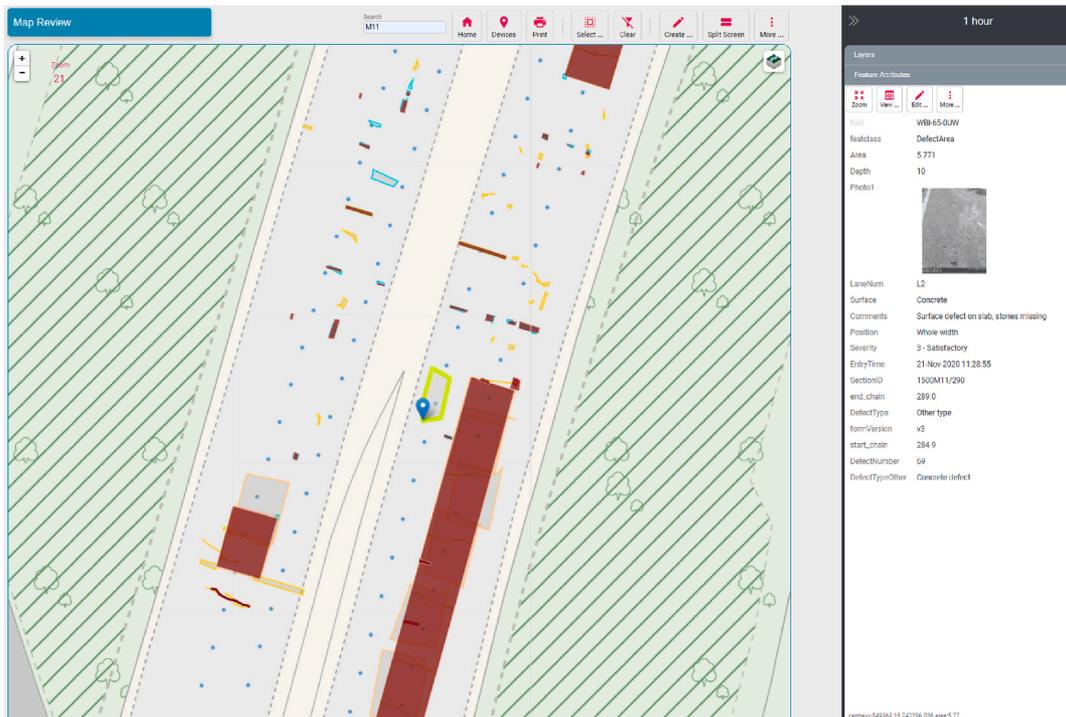
There are other professional maintenance processes for non-pavement assets, such as condition surveys for drainage and structural integrity inspections for lighting, each utilizing different data systems, like the Geotechnical & Drainage Management Service (Highways, 2023a) for drainage assets. We have developed the corresponding IDMs for the above maintenance processes and related information models. Fig. 2 shows an example of the process map for routine maintenance, including the activities (rectangular blocks in the pool), actors (vertical rows), phases (horizontal rows), and data exchange (file symbols in the pool).

4.2. IM-related issues

Problems in the existing processes were identified through talks with the highway experts and analysis of the IDMs. In Fig. 2, the routine maintenance case, three activities (represented by red blocks) are presently being carried out inefficiently. First, the visual road survey (1.2) is carried out purely based on visual observations, which is tedious and laborious. Second, when road inspectors create work orders on tablets (1.3), it is difficult to properly assess the risk level of defects due to the shortage of data (e.g., traffic flow) and analytical tools. Third, the prioritisation in the maintenance planning process (1.4) are primarily based on the experience of senior maintenance planners, which could be biased and suboptimal. Moreover, an interviewee complained that the Confirm system only allows sending work orders for each individual asset rather than a group of assets, which is inefficient for managing a large number of assets in the network.

Through group discussions, we summarise the IM-related issues in the current practice as follows.

- Data definition: Different systems currently use incompatible data models and data libraries to define asset information for the highway network. For example, the UK road agency used ADMM (Highways, 2023b) as the data specification for P-AMS, but Confirm has disparate data schemas, georeferencing methods, and attribute definitions. An interviewee commented: “We took much time to prepare multiple sets of data handover for construction project delivery due to the



(a) Precise representation of defects identified by AIs and repair areas.



(b) 3D model for viewing road asset geometry and conditions.

Fig. 6. An example of the existing adoption of road DTs: K-portal (KOREC, 2024).

misalignment between data models". Furthermore, Confirm system has been criticised about its poor asset classification and insufficient attribution for decision-making of maintenance frequencies.

- Data collection: the biggest issue is that the highway agency does not know what assets currently exist in the huge network. The data of many old assets in the network is incomplete, inaccurate, and poorly maintained. Much of the data is distributed in heterogeneous files, such as CAD drawings and paper documents. Maintenance history was often recorded in free texts without providing details about what really happened. For this reason, the UK road agency made the

decision in 2015 to abandon the old asset inventory database and use mobile scanning to recollect the asset data, which is also problematic till now. In terms of condition monitoring, the current ways to obtain pavement condition data heavily rely on costly intrusive techniques. Moreover, the existing inspection processes still have room for improvement. An interviewee said: "It would be helpful to have a large-scale digital survey to pick up risky regions in a huge network for prioritised inspection in routine maintenance".

- Data storage and integration: the data for the same asset is often stored in different places by staff from different teams and from

Table 2

Responses to Question 7: "In which phases of highway maintenance do you see that digital twins can take effect?"; bold numbers denote the most selected answer for each category of respondents; "P" denotes phase.

Phase	Overall	Scheme maker and manager	Road surveyor	Road inspector	Maintenance manager and worker	Asset manager	Quality controller
P1. Scheme making and prioritisation	80.9%	88.9%	70.4%	84.2%	84.0%	92.3%	75.0%
P2. Road assessment	66.7%	72.0%	70.7%	60.5%	68.0%	57.7%	50.0%
P3. Maintenance planning	74.3%	83.3%	77.8%	63.5%	72.0%	96.2%	75.0%
P4. Maintenance execution	59.0%	61.1%	66.7%	60.5%	60.0%	38.5%	25.0%
P5. Quality assurance and control	54.1%	50.0%	44.4%	52.6%	58.0%	50.0%	50.0%
None of above	1.0%	0.0%	0; 0%	2.0%	0.0%	0.0%	0.0%

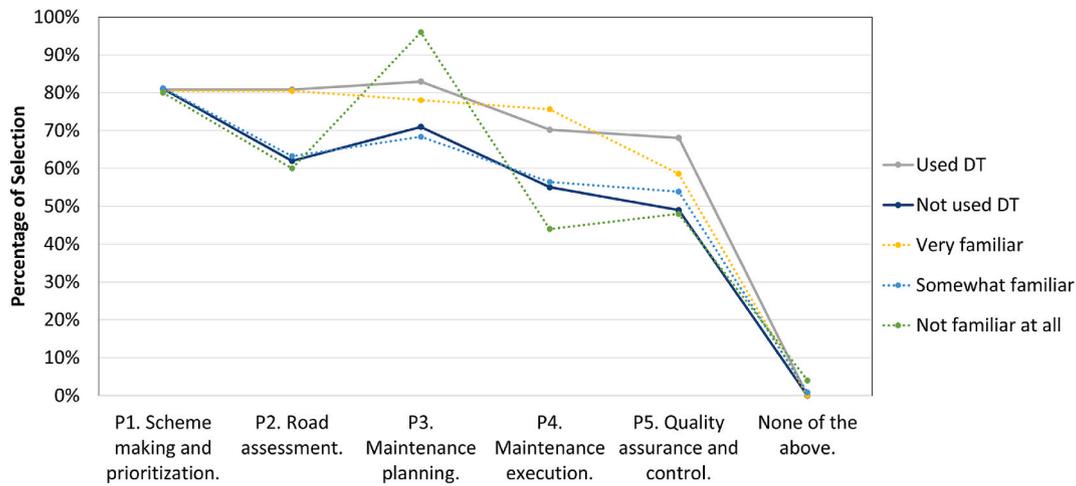


Fig. 7. Presentation of responses to Question 7 based on classification of maturity levels (solid lines) and user familiarity of DTs (dot lines).

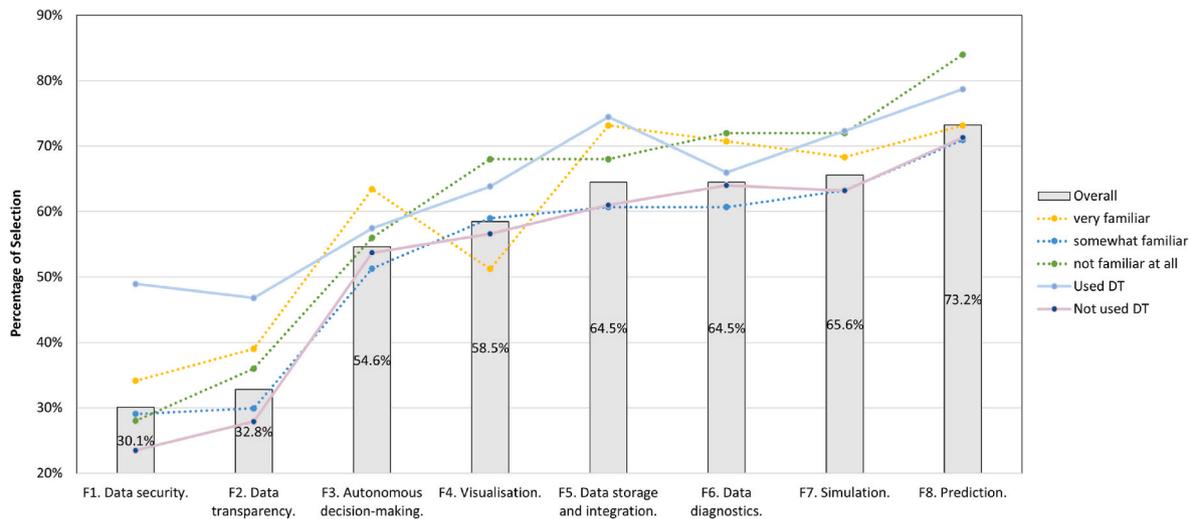


Fig. 8. Responses to Question 8: "What features of a digital twin system do you perceive are important in highway maintenance?"; "F" denotes feature.

various levels of maintenance processes. Different datasets are often conflicting with each other, and there is a lack of timely synchronisation of asset data across systems. Due to data errors, there were instances where engineering teams received instructions to maintain non-existent assets on the network. Integrating these datasets is challenging due to semantic interoperability issues. A data scientist commented that: "we have an interoperability issue between different network models". Furthermore, system fragmentation leads to inefficient coordination between different teams when they aim to maximise outputs during a road closure.

- Data sharing: although both internal and external users could apply for accounts to access different systems from the cyber security team, many old systems do not provide APIs to enable interactions and dataflows between software components. Moreover, there is a lack of a discovery protocol to flexibly retrieve information on the entire highway system. An inspector told us that they do not have effective ways to know the asset interventions made by other engineering teams, which negatively influences their maintenance activities for the same assets.

Table 3

Responses to Question 8; F denotes features. F1-8 are described in Fig. 8. Bold numbers denote the most selected answer for each category of respondents.

Roles	F1	F2	F3	F4	F5	F6	F7	F8
Road surveyor	37.0%	25.9%	44.4%	55.6%	48.1%	70.4%	59.3%	77.8%
Road inspector	31.6%	28.9%	55.3%	44.7%	55.3%	57.9%	63.2%	57.9%
Maintenance manager and worker	28.0%	30.0%	46.0%	52.0%	70.0%	60.0%	60.0%	68.0%
Scheme maker and manager	44.4%	22.2%	55.6%	50.0%	72.2%	77.8%	66.7%	77.8%
Administration	20.0%	40.0%	60.0%	20.0%	80.0%	80.0%	20.0%	60.0%
Logistics coordinator	16.7%	0.0%	83.3%	33.3%	16.7%	83.3%	50.0%	100.0%
Sustainability advisor	28.6%	42.9%	42.9%	71.4%	42.9%	42.9%	85.7%	85.7%
Information system/database operator	33.3%	25.0%	83.3%	41.7%	83.3%	75.0%	66.7%	83.3%
Data analyst	38.5%	23.1%	46.2%	30.8%	69.2%	84.6%	53.8%	76.9%
Asset manager	26.9%	30.8%	50.0%	73.1%	61.5%	53.8%	76.9%	76.9%
Safety officer	30.0%	10.0%	30.0%	40.0%	30.0%	60.0%	60.0%	70.0%
Strategy maker	44.4%	44.4%	61.1%	66.7%	61.1%	83.3%	72.2%	94.4%
Technology developer and researcher	32.3%	29.0%	64.5%	67.7%	80.6%	80.6%	71.0%	77.4%
Quality controller	0.0%	25.0%	50.0%	75.0%	50.0%	75.0%	75.0%	50.0%

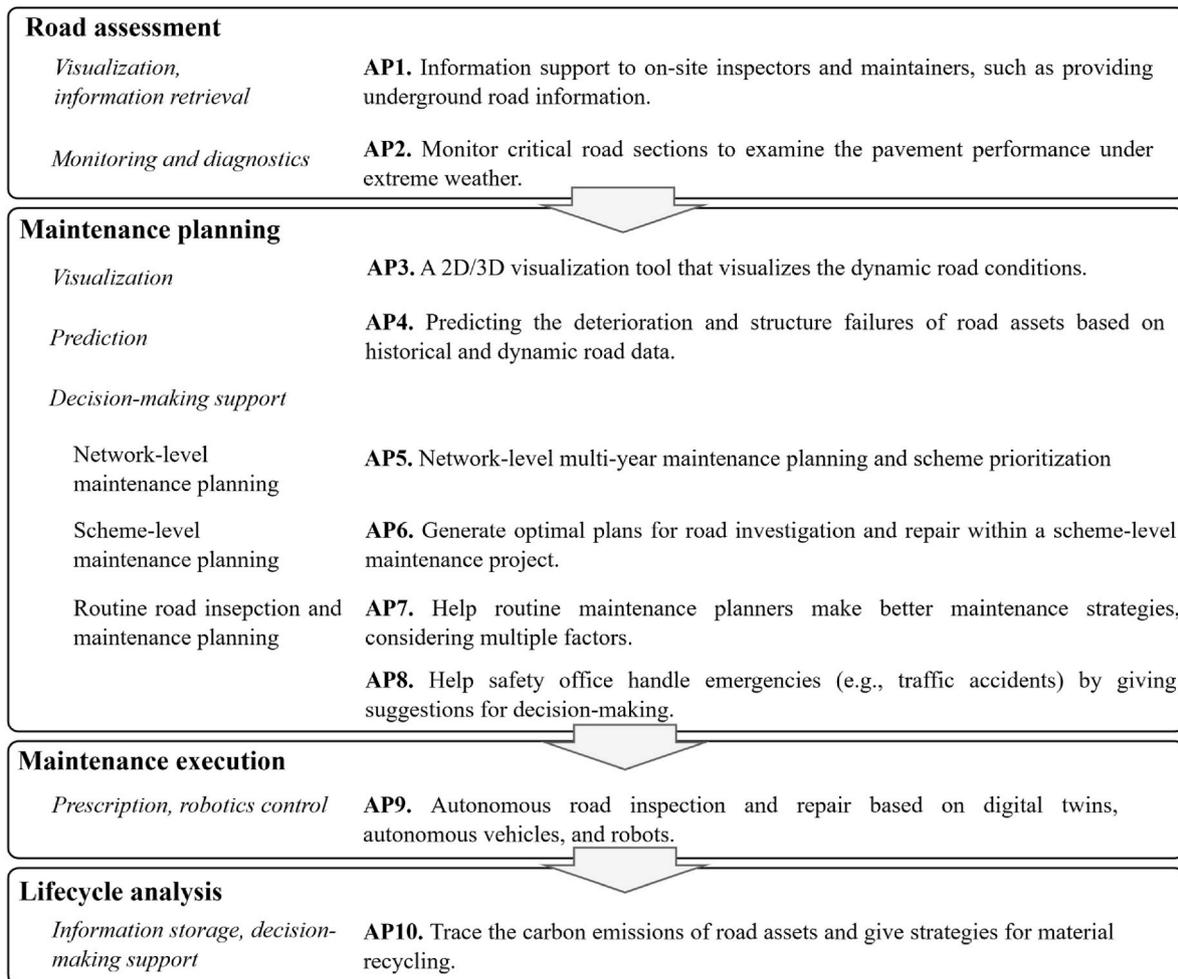


Fig. 9. Proposed DT applications for Question 9: "Which of the below digital twin-based applications do you perceive are important and valuable in highway maintenance?"; AP denotes application.

- Data usage: decision-makers, such as scheme developers, often need to switch back and forth between different systems and files to obtain the required information. There is a lack of unified data environments for flexibly querying and performing data analytics. Furthermore, most decision-making processes are based on the experience of highway experts. In comparison, data-driven approaches are not commonly used due to the limited quality, quantity, and integration of AMS data.

5. Questionnaire survey results

5.1. Demographics

The initial two questions survey the respondents' roles and experiences within the highway industry. Fig. 3 presents the results for all 183 participants. Notably, 46 individuals indicated involvement in multiple roles, and most participants possess 5–10 years (34.4%) or over 10 years (32.8%) working experience. By contrast, a mere 9% reported 0–2 years

Table 4

Responses to Question 9; AP denotes application. AP1-10 are described in Fig. 9. Bold numbers denote the most selected answer for each category of respondents.

Roles	AP1	AP2	AP3	AP4	AP5	AP6	AP7	AP8	AP9	AP10
Road surveyor	70.4%	22.2%	51.9%	66.7%	48.1%	63.0%	70.4%	40.7%	40.7%	33.3%
Road inspector	60.5%	28.9%	57.9%	63.2%	34.2%	57.9%	63.2%	36.8%	47.4%	28.9%
Maintenance manager and worker	46.0%	40.0%	68.0%	74.0%	46.0%	64.0%	60.0%	34.0%	58.0%	28.0%
Scheme maker and manager	44.4%	50.0%	66.7%	83.3%	61.1%	83.3%	72.2%	33.3%	66.7%	38.9%
Administration	40.0%	40.0%	20.0%	80.0%	20.0%	60.0%	60.0%	40.0%	20.0%	40.0%
Logistics coordinator	66.7%	50.0%	50.0%	83.3%	83.3%	66.7%	66.7%	33.3%	16.7%	33.3%
Sustainability advisor	42.9%	28.6%	71.4%	71.4%	57.1%	57.1%	57.1%	0.0%	28.6%	28.6%
Information system/database operator	41.7%	25.0%	58.3%	83.3%	66.7%	50.0%	66.7%	25.0%	50.0%	41.7%
Data analyst	46.2%	15.4%	46.2%	69.2%	46.2%	69.2%	38.5%	23.1%	46.2%	30.8%
Asset manager	65.4%	23.1%	46.2%	73.1%	57.7%	61.5%	84.6%	11.5%	23.1%	19.2%
Safety officer	70.0%	30.0%	30.0%	60.0%	60.0%	70.0%	80.0%	30.0%	20.0%	20.0%
Strategy maker	66.7%	50.0%	55.6%	83.3%	66.7%	83.3%	77.8%	22.2%	50.0%	38.9%
Technology developer and researcher	71.9%	56.2%	65.6%	90.6%	59.4%	71.9%	71.9%	9.4%	65.6%	50.0%
Quality controller	50.0%	50.0%	50.0%	25.0%	75.0%	50.0%	100.0%	0.0%	50.0%	0.0%
Overall	59.6%	37.7%	57.4%	73.2%	51.4%	61.2%	67.2%	21.9%	47%	37.2%

of experience in highway maintenance, highlighting that this survey predominantly captures insights from professional practitioners who have diverse engagement in various processes in this field.

Among all participants, maintenance managers and engineers account for the largest proportion (27.3%). Technology developers and researchers make up 17.5% of all participants. Road surveyors and inspectors occupy 14.8% and 20.8%, respectively. A noteworthy 9.8% of respondents are responsible for strategy making, such as network planning, budget allocation, and standard development, and most of them have over 10 years of working experience, aligning with their positions as senior managers and engineers. Furthermore, a small number of participants are involved in specific roles: six in logistics coordination, four in administration, and three in quality control. Apart from the roles outlined in Figs. 3 and 8.7% of participants selected “other” and wrote down their own positions, such as “*service delivery manager*”, “*contractor*”, and “*consultant*”. We aligned some of these answers with the predefined options when they are semantically close, such as “*asset data manager*” and “*asset manager*”.

5.2. Barriers in current practice

The third question allows participants to select the main challenges faced by their organisations in highway maintenance. Fig. 4 (a) presents the overall responses for Question 3, which reveal that “*hard to derive optimal maintenance decisions under budget constraints*” (B1) was the most popular choice (55.2%), implying that the main limitation for the highway industry is budget constraints. Thus, practitioners must carefully evaluate road conditions and prioritise different maintenance tasks, which are difficult to achieve due to several reasons. First, as the ranked second (50.8%) choice (B2) indicates, much asset information stored in the existing database systems is inaccurate, incomplete, and unreliable, especially for old and underground assets. Second, it is still difficult to obtain comprehensive road condition data using existing data capture techniques, which is also acknowledged as the third barrier (B3). If maintenance planners do not know what happens on the entire road network, it is difficult to make perfectly informed decisions. Furthermore, 46.4% of participants agree that there is a lack of precise evaluation of the costs, benefits, and risks of alternative strategies (B4).

Fig. 4 (b) shows the top three selections, this time binned into the respondent’s role. The results demonstrate that maintenance planners, strategy makers, and scheme makers treat B1 as the biggest challenge, showing that they struggle to come to the best decisions when making maintenance strategies. In comparison, B2 was the top choice for asset managers, which implies that it is still difficult for them to gather complete and accurate life-cycle asset information. Responses from data analysts reveal a need for advanced data science models to mine information from massive road data. Furthermore, they note that the software systems utilised by their organisations are out-of-date and lack

data interoperability. Fig. 4 (c) shows the differences in challenges between different regions. The UK participants highlight the problems of poor asset data quality and outdated information systems. Comparatively, the Chinese industry is less concerned about these issues, likely due to the management of newer roads with new data systems. This implies that IM for highway maintenance is increasingly difficult for highway organisations with the accumulation of data and legacy systems. Finally, the Chi-Square test indicates that there is no significant difference (p -value >0.05) between different roles, showing that highway practitioners are largely in agreement with the primary difficulties with the existing maintenance procedures. Overall, the results align with the interview findings and previous reviews of the other countries’ industries, showing the need for effective and future-proofing IM approaches.

Some respondents also identified specific problems in their professional work. For example, two answers indicate that there is a lack of a “*consistent operational approach*” and “*maintenance strategy based on needs*”. These problems relate to other written answers that state “*a lack of knowledge of how asset handover works*” and “*the complexity of the data specifications of the current asset systems*”. These problems are due to an increasing number of highway authorities adopting asset information models (AIMs) for managing highway assets, even though maintenance staff do not know how to use these asset data in their professional work. Written answers also mention other challenges, including (a) a lack of skilled workforce, (b) a lack of trust in analytical processes, (c) poor communication between stakeholders, (d) inefficient work planning and contract preparation, (e) reluctance to embrace new technologies and systems; and (f) difficulty obtaining road data without traffic disruption.

5.3. Understanding and current use of DTs in highway maintenance

In the third section of the questionnaire (Questions 4–6), we study how DTs and relevant digital technologies are utilised in current practice. Question 4 surveys the participants’ awareness of the DT concept by asking: “*How familiar are you and your organisation with the concept of digital twins and applications in infrastructure management?*”. 63.9% and 22.4% of participants responded “*somewhat familiar*” and “*very familiar*” respectively. In contrast, only 13.7% of participants acknowledged that they were not familiar with DTs at all.

The fifth question sought to clarify what IM approaches and supporting technologies are currently used by participants’ organisations. Fig. 5 (a) presents the results for overall usage, which is further categorised according to the participants’ roles in Fig. 5 (b) and countries in Fig. 5 (c). GIS is the most widely used technology (72.7% of participants) in highway maintenance because nearly all highway assets should be georeferenced in road networks. Moreover, it was found that the BIM approach is increasingly used for IM in the road engineering domain (54.1% of participants). Fig. 5 (b) shows that information system

Table 5

Responses for Question 10: “Please describe the potential use cases of digital twins in highway maintenance that you believe hold significant promise”; the number in the bracket denotes the number of times this case has been mentioned.

Processes and users	DT use cases in highway maintenance
Network-level strategy making (<i>strategy makers</i>)	Countrywide roadworks strategy (1), targeted spending based on all factors, including complaints and insurance claims (1), enabling decisions based upon whole life value rather than solely capital or whole life cost (1), lifecycle planning (1), rank road conditions across networks (1), prescribe future designs & built outcomes that impact maintenance (1), visualisation of service provided, risks, opportunities, and benefits (e.g., environmental net gains) (2), lifecycle cost analysis (1), simulate the impacts of natural hazards on road networks (1).
Scheme making (<i>scheme makers and managers</i>)	Data-driven strategic planning for schemes (1), prioritise maintenance schemes and categorically determine evidence and risk (3), traffic control and flow analysis for planning road development schemes (1), scheme optimisation based on budgets (1), scenario simulation and planning (6), execution and installation of maintenance programmes (1), optimisation of materials and design (3), measurement of complex road sections (1), network survey data analysis (2).
Road survey and inspection (<i>road surveyors and road inspectors</i>)	Automated (human-free) road inspections (5), live highway monitoring (e.g., traffic and pavement structure conditions) (10), highlight underground drainage defects (1), monitor the asset under extreme weather conditions (3), AI video analysis of asset condition, asset audits, asset changes (1), abnormal detection and early warning of road damage and dangers (8), use videos and meteorological sensors to monitor road sections that are prone to collapse, fractures, vibrations (2), condition data sharing from road users (1), a visualisation platform where the spatial axis can be manipulated to efficiently position to any location to inspect highways with cameras (1)
Asset information management (<i>asset managers, information system/database operators</i>)	Maintain and update asset record (location, condition and interventions delivered) (4), single-source-truth asset attribution (1), asset data collection for newly constructed highways (1), long-term data storage in a central repository (2), detailed incident tracking to understand real-world risks on the network and comparing with asset condition (4), store, correlate, and usefully present disparate data sources to inform decision making (1), provide standard platform and ruleset so that assets with differing attributes and conditions can be compared and prioritised (1), evaluation of year-on-year maintenance information (1), understanding interaction between different asset classes to help aid predictive modelling for best asset interventions taking account of whole life asset management (1), transform how existing maintainers access and use data to make timely decisions (1), a unified map that provides compliant asset information for maintenance (1)

Table 5 (continued)

Processes and users	DT use cases in highway maintenance
Maintenance planning (<i>maintenance planners and managers, data analysts</i>)	Risk-based proactive maintenance (5), data-driven maintenance planning (1), predict maintenance need (e.g., how often to do asphalt on road deck) (5), calculate costs and risks and understand what budgets will be required in the future when decisions not to treat an asset are made (1), understand asset performance/condition and align works to suit and improve (4), optimal planning based on multiple factors (5), scheduling for replacement of pavement/electricity systems (1), asset behaviour modelling and prediction (6), a colour coordination system to understand which roads will next require maintenance based on condition data (1), understand how much maintenance can be done based on a budget (1), maintenance suggestions in troubled areas (1), instruction of emergency repair and prioritisation of repair based on pavement condition (8), visualize past inspections and maintenance activities with a pin to assets, and then predict the future maintenance interventions (2), 3D modelling of asset performance over time to support decision-making (6), provide multiple maintenance strategies (3), optimise maintenance plans for natural hazards (2)
Maintenance execution (<i>maintenance engineers, workers, contractors, safety officers</i>)	Data for autonomous cars/machines for snow-ploughing the road (1), data for autonomous marking/painting on the road (the white strips/lines) (1), end-to-end maintenance process generation (3), understanding 3rd party productivity risks to site works e.g., PROW (Public Right of Way) or ecology (1), understanding 3rd party safety risks including where to park, traffic levels, works access (2), optimise CAV routing for maintenance and wear (1), progress monitoring of repair, construction, or demolition (7), risk prediction based on traffic data and accident records (1), automatic road repair (1)
Operations management (<i>administration, logistics coordinators</i>)	Complete asset information (e.g., lightbulb, guardrail) provision for procurement (1), education and training (1), operations monitoring (1), provide insights for capital purchase decisions (1), 3D visualisation platform for integrated operation management (1)
Carbon reduction for sustainability (<i>sustainability advisors, strategy makers</i>)	Accurate carbon and lifecycle assessment (1), provide circular economy materials inventory information (1), carbon emission capture (1), monitor material usage (1)

operators, maintenance managers, and scheme makers selected the BIM solution the most. Fig. 5 (c) illustrates that the UK industry has a lower adoption rate of the BIM approach than others, and it widely relies on AMs. From interviews, we found that many highway experts are still unclear about how to use the road BIM files in the maintenance phase. In terms of MMS, Fig. 5 (b) suggests that high-level strategy makers might have a higher percentage of utilisation than scheme makers and maintenance managers, probably because network-level MMS are necessary for strategy makers to make multi-year development plans.

From the perspective of DTs, Fig. 5 shows that 25.7% of respondents claimed that their organisations had adopted the DT approach for IM. Scheme makers, technology developers, and data analysts are the three groups that selected this option the most (39%, 38%, and 38%,

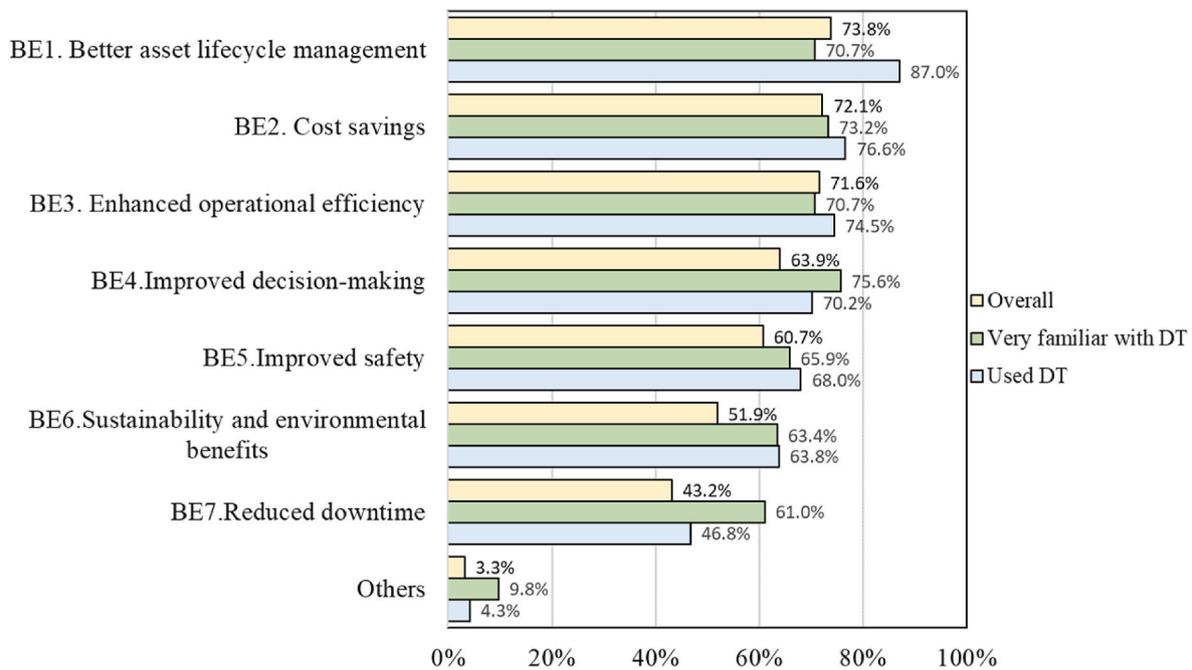


Fig. 10. Responses for the Question 11: "Please select the potential benefits you expect digital twins to bring to highway maintenance." "BE" denotes benefit.

Table 6

Responses to Question 11; BE denotes benefits. BE1-7 are described in Fig. 10. Bold numbers denote the most selected answer for each category of respondents.

Roles	BE1	BE2	BE3	BE4	BE5	BE6	BE7
Road surveyor	85.2%	77.8%	81.5%	40.7%	74.1%	37.0%	33.3%
Road inspector	71.1%	71.1%	60.5%	42.1%	71.1%	42.1%	42.1%
Maintenance manager and worker	72.0%	70.0%	66.0%	48.0%	58.0%	60.0%	40.0%
Scheme maker and manager	72.2%	50.0%	66.7%	72.2%	61.1%	38.9%	44.4%
Administration	60.0%	60.0%	80.0%	60.0%	40.0%	40.0%	20.0%
Logistics coordinator	83.3%	100.0%	100.0%	33.3%	50.0%	50.0%	66.7%
Sustainability advisor	71.4%	85.7%	71.4%	71.4%	71.4%	71.4%	42.9%
Information system/database operator	83.3%	58.3%	58.3%	66.7%	58.3%	58.3%	50.0%
Data analyst	46.2%	69.2%	61.5%	76.9%	69.2%	61.5%	38.5%
Asset manager	80.8%	65.4%	88.5%	84.6%	65.4%	53.8%	23.1%
Safety officer	70.0%	80.0%	90.0%	40.0%	70.0%	20.0%	20.0%
Strategy maker	83.3%	61.1%	77.8%	88.9%	72.2%	44.4%	38.9%
Technology developer and researcher	80.6%	77.4%	67.7%	80.6%	77.4%	54.8%	54.8%
Quality controller	75.0%	75.0%	100.0%	100.0%	50.0%	50.0%	50.0%

respectively). Interestingly, IoT sensors, an important component for updating road DTs, have only a 23.5% selection rate.

The sixth question took a step forward to explore the contexts and projects in which highway organisations use DTs. We found that some respondents answered this question even if they did not select "Digital twins" in Question 5, meaning that their organisations might use similar solutions or plan to use DTs. The responses are summarised in Table 1, with key phrases extracted from respondents' written answers.

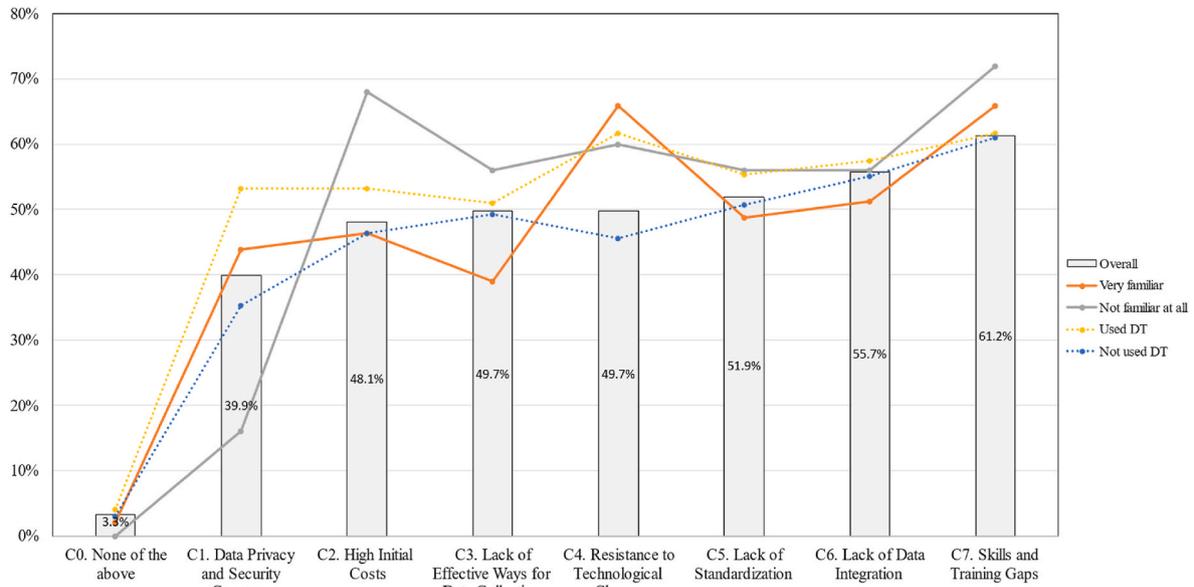
From Table 1, we found that the existing road DT implementations are mainly used for visualisation (9 cases), asset data management (8 cases), traffic analysis (8 cases), and highway environment analysis (6 cases), all of which are technically feasible and beneficial to current practice. Moreover, the results show that highway organisations have planned to leverage the rich data in DTs for advanced applications, such as predicting future maintenance needs, but these have not been fully realised. To delve into details of existing DT adoption, we arranged a video meeting with one of the known respondents who answered this question. The respondent introduced a DT system called K-portal from the KOREC group (KOREC and K, 2024) currently used by their department for concrete pavement maintenance. This system has periodical multi-modal data collection (e.g., point clouds, images, and ground penetration radar) and uses AI models to automatically segment

point clouds and detect defects. Users can retrieve defect and repair information based on data entry time (see Fig. 6(a)) and view realistic 3D road models for maintenance design (see Fig. 6(b)). According to the respondent, the main advantages of this road DT over traditional AMSS can be summarised as (a) realistic representation of assets and defects, especially shapes and geospatial locations; (b) higher automation in condition assessment; and (c) better integration of multi-modal reality capture data and retrieval of time-stamped information.

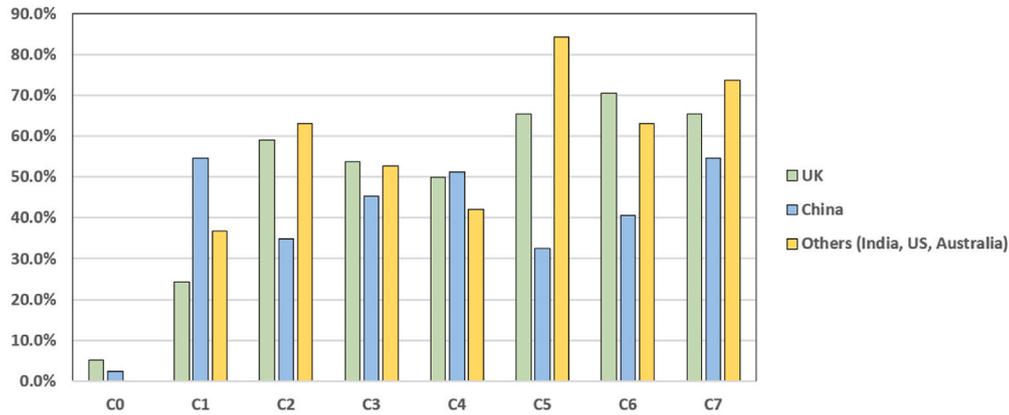
5.4. Perceived opportunities for DTs in highway maintenance

In this section, we identify how highway industry practitioners perceive (a) important phases for applying DTs, (b) essential features that a road DT must have to take effect, (c) valuable applications of road DTs, (d) potential use cases of road DTs, and (e) the main benefits of road DTs.

The seventh question explores which stage of road O&M a DT can influence the most, where we focus on the bottom-level processes that involve inspection and treatment activities. Hence, we divide the process of highway maintenance into five phases: (a) *Scheme making and prioritisation*: develop and prioritise maintenance schemes for the next few years; (b) *Road assessment*: inspectors physically arrive at road sites



(a) Overall responses.



(b) Responses from different countries.

Fig. 11. Responses to Question 12: "Please select the primary challenges or barriers you foresee in implementing digital twins for highway maintenance." "C" denotes challenge.

to inspect road defects with various techniques, such as coring; (c) *Maintenance planning*: maintenance planners evaluate inspection results and make treatment plans; (d) *Maintenance execution*: contractors conduct road repair and rehabilitation using both humans and machines; (e) *Quality assurance and control*: the process of quality inspection to ensure that the maintenance work reaches the required standard.

Table 2 presents the results of Question 7, including overall responses and opinions from the main participants for each phase. The results show that P1 is the phase in which a road DT can have the most influence. This might be because this phase has a profound impact on budget allocation, and a DT is expected to simulate the effects of different strategies. In addition, P3 is also a popular response (74.3%) and is particularly favoured by asset managers (96.2%), probably because asset managers have a strong interest in exploiting rich asset information stored in DTs to improve the maintenance planning process. By contrast, fewer participants recognise that a DT can be useful in P4 (59%) and P5 (54.1%), suggesting that practitioners think that the DT can create more value for office work with digital systems than for fieldwork with physical roads. It is worth noting that there is no significant association between responses and roles, according to the Chi-Square test. This means that practitioners commonly agree that DT

models are more useful for decision-making in the early planning stages.

This research further analyses the difference in responses from participants whose organisations have used DT or not (based on Question 5). As shown in Fig. 7, participants who have used DTs chose P3 (83%) the most. We also studied how respondents with disparate knowledge levels of DTs answered this question based on the answers to Question 4. Fig. 7 demonstrates that participants who claimed "Very familiar" made very similar responses to participants who have used DT, with a Pearson correlation of 98.7%. In addition, some participants wrote other answers: "investment", "operational planning", "maintaining inventory data for soft assets", and "new intelligence-led proactive maintenance processes".

The eighth question was designed to investigate what features of road DTs are perceived as important for industry practitioners in highway maintenance. We summarise several key features of DTs from the literature review: data transparency, data security, autonomous decision-making, prediction, simulation, data diagnostics, visualisation, and data storage and integration. In the domain-specific context, we provide explanations for the following features and how they would work in practice.

Table 7
Written answers for Question 12 about the challenges of DT implementation.

Roles of respondent	Other challenges of road DT implementation
Road surveyor and inspector	<ul style="list-style-type: none"> Lack of political understanding of the urgency. Difficult to check the quality of the gathered data.
Maintenance manager	<ul style="list-style-type: none"> Silo mentality: different sectors or organisations involved in highway maintenance operate independently and without much coordination or information sharing.
Quality controller	<ul style="list-style-type: none"> Encompass experts' knowledge on the roads in the digital twins.
Technology developer and researcher	<ul style="list-style-type: none"> Technical integration of emerging technologies. This is a leadership challenge. Everything else has been solved and is waiting for deployment. The DT data obtained from existing databases may have poor levels of accuracy.
Strategy maker	<ul style="list-style-type: none"> Maintain DTs whose technology and data structure constantly adapt to new system/technology. Manage huge asset data and regularly amend its format or system. The costs of creating and maintaining DTs may exceed the values they create. Lack of trust in analytical processes.
Asset manager	<ul style="list-style-type: none"> Lack of understanding of the impact of change and consistent approaches to implementation. Procurement of the DT systems and meshing with the existing maintenance systems.

- **Data diagnostics:** identify the anomalies, risks, and their causes in the condition data. By using IoT sensors installed at roadsides, vehicles, or UAVs, real-time data can flow into DTs and be interpreted by suitable fault detection algorithms, such as computer vision models for pothole detection (Chen et al., 2024).
- **Simulation:** simulate the operations of alternative strategies and assess the effects of such strategies. Simulation environments can be developed in twin systems for maintenance planning and design, coupling asset degradation models (Haas and Hudson, 2015), risk assessment models (Alberti and Fiori, 2019), and cost models.
- **Prediction:** predict future states of roads, such as deterioration and structural failure. Existing DT technical frameworks, such as (Chen et al., 2022), can achieve this feature by using historical and real-time data for deterioration prediction based on statistical models (e.g., Gaussian process regression (Zhang et al., 2024)) or deep learning algorithms.
- **Autonomous decision-making:** automatic generation of decisions based on performance indicators. This suggests DTs can receive sensing data, perform data analytics, and send instructions without human intervention, which may be realised using an agent-based framework (Xu et al., 2024) to model interactions between DTs, infrastructures, sensors, and humans.

Fig. 8 and Table 3 present the overall and categorised results for Question 8. As can be seen, F8 (73.2%) and F7 (65.6%) are two of the most selected functional features by all participants. However, participants who are very familiar with DTs and have used DTs also value the

features of F5 with selection rates of 73.2% and 74.5%, respectively, and Table 3 shows that these respondents include many maintenance planners, scheme makers, information system operators, and technology developers. This suggests that these practitioners who work with digital systems expect a twin system that can better store and integrate complicated asset data. In comparison, fewer participants selected F3 (54.6%), especially relevant roles like maintenance planners, scheme makers, and strategy makers, meaning that industry practitioners tend to make decisions on their own based on the intermediate results from DT-enabled simulation and prediction rather than leaving them entirely with DTs. F4 was mainly selected by participants who have little knowledge of the DT concept, as they simply understand DTs as a 3D visualisation platform. Fig. 8 also shows that F2 and F1 are the least chosen (32.8% and 30.1%), suggesting that industry practitioners care more about the practical functions that a DT could bring about. Finally, the Chi-Square test shows that maturity levels are significantly related to options F1 and F4, and roles are strongly associated with F8.

The subsequent question (Question 9) asked the participants to select applications of road DTs that they think are valuable. As presented in Fig. 9, we proposed ten potential applications of road DTs at various levels of road maintenance processes, where DTs can perform different functions (e.g., diagnostics and predictions). Although existing AMSS cover some applications (e.g., AP5) to some extent, DTs' model-based IM approach might enhance current practices by improving data integration, visualisation, data retrieval, and analytics. The corresponding results are presented in Table 4. The most popular DT application (73.2%) among all respondents is asset deterioration prediction (AP4). In essence, deterioration prediction is a longstanding research problem in the field of highway maintenance. The role of DTs is to be the data holder of historical and real-time road condition data, road construction data (e.g., material), traffic data, and environment data, which support behaviour models to forecast future states of road assets.

Table 4 illustrates that highway practitioners with varying jobs exhibit distinct preferences for these applications, and the Chi-Square test reveals the significant differences (p-value <0.05) between various roles in the choice of options AP2, AP3, and AP4. In detail, road surveyors and road inspectors commonly perceive AP1 (on-site information support) as valuable DT applications, with selection rates of 70.4% and 60.5%, respectively. This implies that a mobile app can potentially be developed on smart devices to help fieldworkers view and retrieve road information stored in DTs. Strategy makers and scheme makers highly recognise the value of AP6 (generate plans for maintenance schemes), with a selection rate of 83.3%. This might be because scheme makers in current practice must spare efforts gathering information from different systems and then use their experience to determine the treatment strategies. Therefore, a potential application of road DTs could be a decision-support system for scheme-level maintenance projects, which could aid in the creation of optimised treatment plans with less bias. Table 4 also highlights that asset managers generally prefer AP7 (routine maintenance planning) because asset information is very useful in making treatment strategies for individual assets in this process. This suggests that an application can be built on top of DTs to

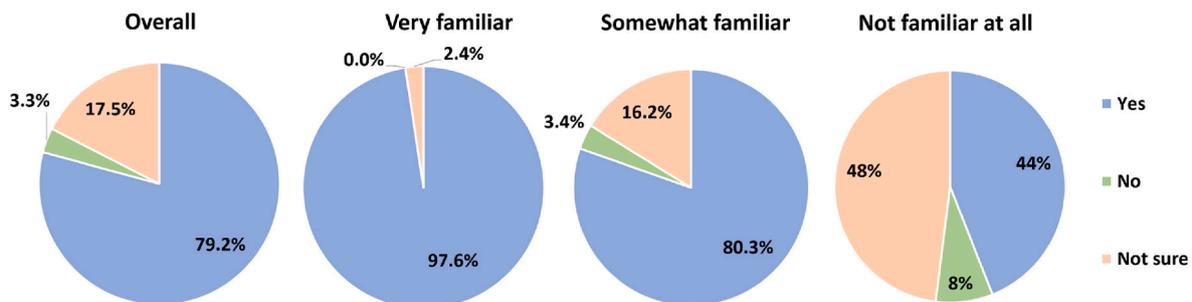


Fig. 12. Responses to Question 13: "Do you believe that digital twins will become a standard practice in the highway maintenance sector in the future?"

effectively exploit AIMS to make trustworthy decisions in prioritising the repair of the damaged assets and arranging work orders that can minimise costs and risks.

Question 10 is an open question that asks participants to describe at least two use cases of DTs that are beneficial for highway maintenance. A total of 125 written answers were obtained. We classified all these responses according to the processes and merged the overlapped cases. Table 5 lists 71 use cases for road DTs that industry professionals have described. These use cases involve various maintenance procedures and various user types.

By analysing the collected responses, some use cases of road DTs are directly related to asset data management, which forms a foundation for other service-oriented use cases. Respondents expressed the need for a twin system that can efficiently receive new highway data, provide unified data reference libraries, dynamically update, and integrate multiple asset classes, all of which can link to the existing IM issues presented in Section 2.1 and Section 4.2. Regarding service-oriented use cases, many written answers show the potential of using high-fidelity product models, such as measurement of complex road sections and 3D modelling of asset performance. However, their realisation also depends on the technical feasibility and organisational acceptance of change. For example, the real-time updating of road DTs requires the development of IoT and infrastructure sensing technologies, as well as the installation of sensors across the network. Furthermore, predicting the future states of roads and proactive maintenance may require long-term data collection to develop deterioration models and data-driven approaches for predictive maintenance.

The last question (Question 11) in this section allows participants to select the potential benefits of DTs in highway maintenance. The overall and categorised results are presented in Fig. 10 and Table 6, respectively. BE1 was the most popular response (87%) amongst respondents across a variety of roles and whose organisations have used DTs. This shows that the main advantage of the DT-based IM approach is to enhance asset lifecycle data integration and management based on product models, consistent data libraries, and connected data ecosystems. On the other hand, participants who claimed a high level of familiarity with DTs selected BE4 (76.6%) the most, and Table 6 shows that BE4 is widely chosen by scheme makers, data analysts, and strategy makers. It suggests that these participants commonly have higher expectations of DT capabilities. Chi-Square test indicates significant associations between (a) options BE4, BE5, BE6, BE7 and participants' previous use of DTs; (b) options BE3, BE6, BE7 and participants' familiarity with DTs; and (c) options BE4, BE7 and roles. Some respondents also mentioned other benefits, such as "improved service to customers", "take the friction out of collaboration across complex communities of specialists", and "improved automation in decision-making".

5.5. Perceived challenges of DT implementation

In the last section of the questionnaire, we study the potential challenges of implementing DTs for highway organisations. As presented in Fig. 11 (a), the responses for Question 12 show that the top three selected challenges of DT implementation are C7 (61.2% selected), C6 (55.7% selected), and C5 (51.9% selected). The results suggest that training and education for highway practitioners to use the new DT-based IM approach and twin systems will be a primary issue because they are accustomed to existing tools. Hence, the design of user-friendly interfaces and process instructions are important to reduce training costs and user reluctance. The second-ranked challenge (C6) stems from several aspects. First, the connection of the new twin system with existing AMS and databases is difficult, requiring significant manual alignment between data schemas. It is challenging to update the old asset data based on new information requirements (e.g., new attributes) for DTs, which would introduce missing or mismatched information. Third, designing a data schema (FDM and RDL) for road DT that has sufficient coverage and scalability is itself an intricate task. This also

relates to the third ranked challenge (C5) as a well-defined data standard is crucial, for instance, creation and data sharing between connected DTs. Further, we found that respondents who are very familiar with DTs and whose organisations have used DTs commonly chose C4, whereas participants who have less knowledge of DTs consider C2 a key issue. Fig. 11 (b) shows that the barriers to DT implementation vary between different countries, depending on local organisations, policies, and other factors.

As shown in Table 7, respondents from different roles also comment on other potential difficulties for implementing DTs in the highway industry, which can be summarised into engineering and management aspects. From the perspective of engineering, devising and maintaining DTs that are futureproofed to future technological changes and data expansion is challenging. From the perspective of management, there is a lack of understanding of the actual benefits and costs of DTs, with clear cases demonstrated, making it challenging to convince policymakers and senior corporate managers to adopt DTs.

Question 13 asked respondents whether they believe that DTs would become the standard practice in the future highway industry. As presented in Fig. 12, 79.2% of the 183 respondents chose *yes*, and 17.5% chose *not sure*. Although the overall responses are optimistic, there might be a sampling bias for this question because respondents to this survey may generally have an interest in this topic. Fig. 12 also shows that there is a strong belief that DTs will dominate the standard practice in the future (97.6%) among participants who are very familiar with DTs. In comparison, participants who are unfamiliar with DTs are more sceptical about DTs, with 48% responding that they are *not sure*. Furthermore, 89.4% of participants whose organisations have used DTs selected *yes*, showing that they are generally positive about the future of DTs after they have attempted to implement DTs in real-world cases.

The fourteenth question asks respondents when they anticipate that DTs can be widely adopted in the industry. As a result, most of the participants were selected *within the next 3–5 years* (45.6%). In addition, 31.1% of participants chose *more than 5 years*, and 11.5% chose *within 1–2 years*.

The last question (Question 15) in this survey is stated as follows: "Could you please provide any additional comments or insights concerning a road digital twin for highway maintenance?". Regarding the data analytics process, a comment suggests that data must be manipulated by human elements to ensure decisions are fit for purpose, meet customer needs, and are affordable. In addition, trust is recognised as a key factor in the data analysis, so behaviour science should be incorporated into DT development. In terms of DT implementation, it is recommended that it start at a low maturity level with partial benefits realised. Moreover, it must provide value and not be an additional cost to already constrained budgets.

6. Discussion

6.1. Findings and implications

The findings of this study answered the research questions as follows.

- 1) The study identifies six levels of primary maintenance processes in the UK highway authority and the main IM problems that impede these processes, including data model incompatibility, system fragmentation, insufficient attributions, data redundancy, and lack of digitalisation of old data. The results of questionnaire survey reveal three challenges that highway practitioners consider more critical than others: the complexity of making optimal maintenance decisions within budget constraints, the poor quality of asset inventory information, and the difficulty in obtaining comprehensive and timely information about road conditions (answered RQ1a-b).
- 2) The value points addressed by the current DT implementations are mostly around visualisation, asset data management, traffic analysis, and environment analysis. This survey further indicates that industry

practitioners widely recognised that DTs can be especially valuable in phases of scheme development and maintenance planning, where DTs can be potentially used for asset deterioration prediction (73.2%), strategy-making for routine maintenance (67.2%), and plan optimisation for scheme-level road investigation and treatment (61.2%). We also got 71 use cases from participants, including 11 about using DTs to enhance the AMS database, 9 about automating road inspections, and the rest depicting how users can interact with DTs in different processes with the aid of better data and systems. According to highway experts, the main benefits of DTs are better lifecycle asset management, lower costs, and higher operational efficiency (answered RQ2a-c).

- 3) The survey results reveal that the most crucial functional features of DTs for highway maintenance are prediction, scenario simulation, and abnormal diagnostics. We also identified the primary constraints for realising the value of road DTs, including (a) skills and training gaps, (b) lack of data integration, and (c) lack of standardisation (answered RQ2d-e).

The outcomes of this research could provide valuable insights for practice in the design and implementation of road DTs. Specifically, we now have a better understanding of the current IM practices and issues within the broader highway TAM processes, and the resulting inefficiencies in highway maintenance. This helps the industry develop DTs in a proper pathway that can best complement the existing AMS architectures. The survey results suggest that the implementation of road DTs can begin with the most selected applications and use cases (e.g., scenario simulation for scheme-level maintenance planning), accompanied by the development of appropriate system components (hardware, software, and processes) to address existing obstacles. For example, shallow road furniture data in AMSs entails a DT to capture more geometry and condition data for making hybrid maintenance schemes. The findings of this research pave the way for DT researchers and developers to adopt DTs in highway maintenance domain and scientifically evaluate the actual cost and returns. Highway organisations could then effectively make strategies for DT development based on the technical feasibility and cost-benefit analysis, thereby benefiting our society by improving the efficiency, safety, and sustainability of highway network operations.

6.2. Limitations

The limitations of this study are acknowledged as follows.

- 1) We conducted the interview for the UK national road agency experts only, and the questionnaire was designed primarily according to the state of practices in the UK. However, the situations and pain points in highway maintenance may differ between countries, so the questionnaire may not fully cover all critical problems for the whole industry. As a result, the statistics for Question 3 may be biased because participants must manually input answers in text boxes when they need to describe other important problems.
- 2) Although the questionnaire survey with 183 answers can provide quantifiable insights for this explorative research, the sample size is still relatively small to yield accurate results with a low margin of error. Most of the survey results come from the UK and China industries, which can be less representative from a global industry perspective. Industry experts from other regions, such as Europe and North America, might highlight different use cases for Question 5. Furthermore, we conducted an in-depth analysis of the survey results by separating participants' roles in this study. However, the number of participants for some roles (e.g., quality controller) are small, causing less statistical significance in the interpretation of the results.
- 3) We found that some respondents who claimed that they have used DTs or understood DTs still confuse DTs with classical 2D GIS-based

AMSs. This causes some application scenarios collected in Questions 9 and 10 to overlap with the existing AMS functions.

- 4) Some written responses, such as use case descriptions, for the questionnaire survey are too general to understand their exact meanings. Therefore, we will conduct another round of interviews with industry experts to verify the details of the collected use cases in a future study.

7. Conclusions

Maintaining highway assets at the standard service level is essential to guaranteeing road network efficiency and safety. Digital twins (DTs) have the potential to be applied in highway maintenance to manage the dispersed information sets and improve the existing processes based on dynamically updating virtual road models. This paper has presented a survey for highway industry practitioners to identify the main barriers in the current practice and the potential value of DTs in this field. We first interviewed 20 highway experts in the UK industry to understand the existing maintenance processes and the inefficiencies related to information management. We subsequently designed a questionnaire based on those interviews, addressing the following questions: (a) the main obstacles in current practice; (b) how the industry understands and currently uses DTs; (c) the perceived opportunities of DTs in highway maintenance; and (d) the perceived challenges of DT implementations. The questionnaire was then disseminated to gain insights from a wide range of industry practitioners, with 183 valid responses obtained from professionals across different roles in the highway domain. The results highlight the adoption phases, functional features, applications, and use cases of road DTs, which are widely regarded as important by industry practitioners. The survey also reveals the barriers to DT implementation that concern practitioners, as well as the acceptance rate regarding whether DTs will become the standard practice in the highway industry.

In the future work, a DT prototype will be developed based on the findings of this survey to evaluate the feasibility and effectiveness of various use scenarios. We will conduct some real-world case studies and perform a systematic cost-benefit analysis to evaluate the return on investment of DT adoption, assisting decision-makers in highway agencies in developing appropriate strategies for investing in DTs.

CRedit authorship contribution statement

Mengtian Yin: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Varun Kumar Reja:** Writing – original draft, Visualization, Resources, Methodology, Investigation, Data curation. **Ran Wei:** Writing – review & editing, Supervision, Data curation. **Ioannis Brilakis:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Brian Sheil:** Writing – review & editing, Supervision. **Federico Perrotta:** Writing – review & editing, Supervision. **Alix Marie d'Avigneau:** Validation, Formal analysis. **Linjun Lu:** Resources, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Varun Kumar Reja reports financial support was provided by European Commission. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101034337. We wish to thank Dr.

George Economides, Dr. Pieter Pauwels, Dr. Stefano Cavazzi, Dr. Matt Peck, Yogesh Patel, Katrin Johannesdottir, and Simon Hayton for their contributions to this paper.

Appendix A

This study received ethical approval from the Ethics Review Committee, Department of Engineering, University of Cambridge, UK, for the research project titled 'Exploring the Minimum Viable Product (MVP) of a Digital Twin for Road Inspection and Maintenance' (Protocol No. 321), ensuring compliance with ethical standards for the questionnaires and interviews conducted as part of the research.

The information about the study to the participant, the participation consent form, and the questionnaire form used in this research can be accessed via the link: <https://forms.gle/Nj7gBT9D3VHo3x4A>.

Data availability

Data will be made available on request.

References

- AASHTOWare, (n.d.), <https://www.aashtoware.org/>.
- Agrawal, A., Fischer, M., Singh, V., 2022. Digital twin: from concept to practice. *J. Manag. Eng.* 38, 1–13. [https://doi.org/10.1061/\(asce\)me.1943-5479.0001034](https://doi.org/10.1061/(asce)me.1943-5479.0001034).
- Al-Mansoori, T., Abdalkadhum, A., Al-Husainy, A.S., 2020. A GIS-Enhanced pavement management system: a case study in Iraq. *J. Eng. Sci. Technol.* 15, 2639–2648.
- Alberti, S., Fiori, F., 2019. Integrating risk assessment into pavement management systems. *J. Infrastruct. Syst.* 25, 1–21. [https://doi.org/10.1061/\(asce\)is.1943-555x.0000472](https://doi.org/10.1061/(asce)is.1943-555x.0000472).
- American Society of Civil Engineers (ASCE), 2023. 2021 report card for America's infrastructure - roads. <https://infrastructurereportcard.org/cat-item/roads-infrastructure/>.
- Ammar, A., Maier, F., Pratt, W.S., Richard, E., Dadi, G., 2024. Practical application of digital twins for transportation asset data management: case example of a safety hardware asset. *Transport. Res. Rec.* 2678, 114–130. <https://doi.org/10.1177/03611981241231804>.
- Balaji, B., Bhattacharya, A., Fierro, G., Gao, J., Gluck, J., Hong, D., Johansen, A., Koh, J., Ploennigs, J., Agarwal, Y., 2016. Brick: towards a unified metadata schema for buildings. In: *Proc. 3rd ACM Int. Conf. Syst. Energy-Efficient Built Environ.*, pp. 41–50.
- Bosurgi, G., Pellegrino, O., Sollazzo, G., 2022. Pavement condition information modelling in an I-BIM environment. *Int. J. Pavement Eng.* 23, 4803–4818. <https://doi.org/10.1080/10298436.2021.1978442>.
- buildingSMART International Ltd, 2019. Industry foundation classes (IFC). <https://technical.buildingsmart.org/standards/ifc/>.
- CDBB, 2020. The Approach to Delivering a National Digital Twin for the United Kingdom, vol. 20. https://www.cdbb.cam.ac.uk/files/approach_summaryreport_final.pdf.
- Chen, W., Zheng, M., 2021. Multi-objective optimization for pavement maintenance and rehabilitation decision-making: a critical review and future directions. *Autom. ConStruct.* 130, 103840. <https://doi.org/10.1016/j.autcon.2021.103840>.
- Chen, K., Eskandari Torbaghan, M., Chu, M., Zhang, L., Garcia-Hernández, A., 2022. Identifying the most suitable machine learning approach for a road digital twin. *Proc. Inst. Civ. Eng. Infrastruct. Constr.* 174, 88–101.
- Chen, J., Chan, I., Brilakis, I., 2024. Shifting research from defect detection to defect modeling in computer vision-based structural health monitoring. *Autom. ConStruct.* 164, 105481.
- Cho, J., Kim, C., Song, Y., Kang, J., Yeon, J., 2024. Lumped record management method using BIM and dynamo for spalling maintenance. *Autom. ConStruct.* 160, 105324.
- Deshpande, V.P., Damjanovic, I.D., Gardoni, P., 2010. Reliability-based optimization models for scheduling pavement rehabilitation. *Comput. Civ. Infrastruct. Eng.* 25, 227–237.
- Dong, J., Meng, W., Liu, Y., Ti, J., 2021. A framework of pavement management system based on IoT and big data. *Adv. Eng. Inf.* 47, 101226. <https://doi.org/10.1016/j.aei.2020.101226>.
- E. National Academies of Sciences and Medicine, 2021. *Guidebook for Data and Information Systems for Transportation Asset Management*.
- Eastman, C.C.M.C., Eastman, C.C.M.C., Teicholz, P., Sacks, R., Liston, K., 2011. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, second ed. John Wiley & Sons, Hoboken.
- Ebbesen, M., 2021. Data-driven asset management on the state roads of Denmark, *Bridg. Maintenance, Safety*. In: *Manag. Life-Cycle Sustain. Innov. - Proc. 10th Int. Conf. Bridg. Maintenance, Saf. Manag. IABMAS 2020*, pp. 3215–3219. <https://doi.org/10.1201/9780429279119-436>.
- El Marai, O., Taleb, T., Song, J., 2021. Roads infrastructure digital twin: a step toward smarter cities realization. *IEEE Netw.* 35, 136–143. <https://doi.org/10.1109/MNET.011.2000398>.
- Escobar, F., Hunter, G., Bishop, I., Zerger, A., 2008. *Introduction to GIS*. Dep. Geomatics, Univ. Melbourne. Available Online <http://www.sli.unimelb.edu.au/Gisweb/>. (Accessed 2 April 2008).
- for Highways, S., 2022. CS 230 - pavement maintenance assessment procedure. <https://www.standardsforhighways.co.uk/search/5c21c19f-4292-4764-86f6-bbb51df313e0>.
- Grieves, M., Vickers, J., 2016. Origins of the digital twin concept, *Florida Inst. Technol.* 8, 3–20.
- Haas, R., Hudson, W.R., 2015. *Pavement Asset Management*. John Wiley & Sons.
- Hagedorn, P., Liu, L., König, M., Hajdin, R., Blumenfeld, T., Stöckner, M., Billmaier, M., Grossauer, K., Gavin, K., 2023. BIM-enabled infrastructure asset management using information containers and semantic web. *J. Comput. Civ. Eng.* 37, 4022041.
- Han, T., Ma, T., Fang, Z., Zhang, Y., Han, C., 2022. A BIM-IoT and intelligent compaction integrated framework for advanced road compaction quality monitoring and management. *Comput. Electr. Eng.* 100, 107981. <https://doi.org/10.1016/j.compeleceng.2022.107981>.
- Han, C., Han, T., Ma, T., Tong, Z., Wang, S., Hei, T., 2023a. End-to-end BIM-based optimization for dual-objective road alignment design with driving safety and construction cost efficiency. *Autom. ConStruct.* 151. <https://doi.org/10.1016/j.autcon.2023.104884>.
- Han, C., Han, T., Ma, T., Tong, Z., Wang, S., 2023b. A BIM-based framework for road construction quality control and quality assurance. *Int. J. Pavement Eng.* 24. <https://doi.org/10.1080/10298436.2023.2209903>.
- Highway Agency, 2009. *Network management manual*. https://assets.publishing.service.gov.uk/media/5a8000cf40f0b62302690edd/nmm_part_Composit_0_9.pdf.
- Highways, National, 2023a. Gdms - geotechnical & drainage management service. <https://gdms.assetia.cloud/home>.
- Highways, National, 2023b. *Asset Data Management Manual (ADMM) and other management and maintenance guides*. <https://nationalhighways.co.uk/suppliers/design-standards-and-specifications/admm-and-other-management-and-maintenance-guides/>.
- Highways, National, 2023c. The new National Highways pavement asset management system has successfully launched. <https://www.highwaysindustry.com/the-new-national-highways-pavement-asset-management-system-has-successfully-launched/>.
- Highways England, 2016. *Information management and technology strategy*. https://assets.publishing.service.gov.uk/media/5a7fffb40f0b62302690e77/Information_Management_and_Technology_Strategy.pdf.
- Hudson, S.W., Strauss, K., Perrone, E., Pilon, C., Hudson, W.R., 2011. Improving PMS by simultaneous integration with MMS. In: *Eighth Int. Conf. Manag. Pavement Assets/FugroFederal Highw. Adm. ChileCAF-Banco Desarro. Am. Lat. I.S.O. 29481-1*, 2010. *Building Information Modeling—Information Delivery Manual—Part 1: Methodology and Format*.
- Jiang, F., Ma, L., Broyd, T., Chen, W., Luo, H., 2022a. Digital twin enabled sustainable urban road planning. *Sustain. Cities Soc.* 78, 103645.
- Jiang, F., Ma, L., Broyd, T., Chen, W., Luo, H., 2022b. Building digital twins of existing highways using map data based on engineering expertise. *Autom. ConStruct.* 134. <https://doi.org/10.1016/j.autcon.2021.104081>.
- Jiang, F., Ma, L., Broyd, T., Chen, K., Luo, H., 2022c. Underpass clearance checking in highway widening projects using digital twins. *Autom. ConStruct.* 141, 104406. <https://doi.org/10.1016/j.autcon.2022.104406>.
- Justo, A., Soilán, M., Sánchez-Rodríguez, A., Riveiro, B., 2021. Scan-to-BIM for the infrastructure domain: generation of IFC-complaint models of road infrastructure assets and semantics using 3D point cloud data. *Autom. ConStruct.* 127. <https://doi.org/10.1016/j.autcon.2021.103703>.
- Kendall, J., 2021. *National Digital Twin: Integration Architecture Pattern and Principles*. Kerala, H.G.R., Odoki, J.B., Stannard, E.E., 2000. *Overview of HDM-4*. *Highw. Dev. Manag. Ser. Vol. One*. World Road Assoc. PIARC. World Bank, Washington, DC, USA.
- KOREC, 2024. K-Portal. <https://kportal.k-matic.com/live/>, 2024.
- KOREC, K-Portal. <https://kportal.k-matic.com/live/>, 2024.
- Krishna, C.M., Ruikar, K., Jha, K.N., 2024. Revolutionising Indian Highway Projects: Unleashing the Power of Data Integration with Cutting-Edge Data Lake.
- Le, T., David Jeong, H., 2016. Interlinking life-cycle data spaces to support decision making in highway asset management. *Autom. ConStruct.* 64, 54–64. <https://doi.org/10.1016/j.autcon.2015.12.016>.
- Le, T., Le, C., David Jeong, H., 2018. Lifecycle data modeling to support transferring project-oriented data to asset-oriented systems in transportation projects. *J. Manag. Eng.* 34, 1–13. [https://doi.org/10.1061/\(asce\)me.1943-5479.0000620](https://doi.org/10.1061/(asce)me.1943-5479.0000620).
- Li, Z., 2018. *Transportation Asset Management: Methodology and Applications*. CRC Press.
- Liu, L., Zeng, N., Liu, Y., Han, D., König, M., 2024. Multi-domain data integration and management for enhancing service-oriented digital twin for infrastructure operation and maintenance. *Dev. Built Environ.* 18. <https://doi.org/10.1016/j.dibe.2024.100475>.
- Lorvão Antunes, A., Barateiro, J., Marecos, V., Petrović, J., Cardoso, E., 2024. Ontology-based BIM-AMS integration in European highways. *Intell. Syst. with Appl.* 22. <https://doi.org/10.1016/j.iswa.2024.200366>.
- Lu, R., Brilakis, I., 2019. Digital twinning of existing reinforced concrete bridges from labelled point clusters. *Autom. ConStruct.* 105, 102837. <https://doi.org/10.1016/j.autcon.2019.102837>.
- Machl, T., Donaubaue, A., Kolbe, T.H., 2019. Planning agricultural core road networks based on a digital twin of the cultivated landscape. *J. Digit. Landsc. Arch.* 4, 316–327.
- Meza, S., Mauko Pranjić, A., Vezočnik, R., Osmokrović, I., Lenart, S., 2021. Digital twins and road construction using secondary raw materials. *J. Adv. Transport.* 2021, 1–12.

- Mohamed, A.S., Xiao, F., Hettiarachchi, C., 2022. Project level management decisions in construction and rehabilitation of flexible pavements. *Autom. Construct.* 133, 104035.
- Naborczyk, K., 2020. BIM requirements in Norway – part 1 – statens vegvesen. <https://bimcorner.com/bim-requirements-in-norway-part-1-svv/>.
- Norwegian Public Roads Administration Selects Trimble for Asset Lifecycle Management, (n.d.). <https://www.prnewswire.com/news-releases/norwegian-public-roads-administration-selects-trimble-for-asset-lifecycle-management-301717319.html>.
- Obaidat, M.T., Ghuzlan, K.A., Bara'W, A.-M., 2018. Integration of geographic information system (GIS) and PAVER system toward efficient pavement maintenance management system (PMMS). *Jordan J. Civ. Eng.* 12.
- Oreto, C., Biancardo, S.A., Viscione, N., Veropalumbo, R., Russo, F., 2021a. Road pavement information modeling through maintenance scenario evaluation. *J. Adv. Transport.* 2021. <https://doi.org/10.1155/2021/8823117>.
- Oreto, C., Massotti, L., Biancardo, S.A., Veropalumbo, R., Viscione, N., Russo, F., 2021b. Bim-based pavement management tool for scheduling urban road maintenance. *Infrastructure* 6. <https://doi.org/10.3390/infrastructures6110148>.
- Oreto, C., Biancardo, S.A., Abbondati, F., Veropalumbo, R., 2023. Leveraging infrastructure BIM for life-cycle-based sustainable road pavement management. *Materials* 16, 1047.
- Oti, I.C., Gharaibeh, N.G., 2020. A note on assessment of transportation infrastructure data management practices, public work. *Manag. Policy.* 25, 132–150.
- Perrone, E., Mastin, N., McKittrick Jr., R., Wu, J., 2008. Using LRS change transactions generated externally to maintain data integrity in the pavement management system in North Carolina. In: Seventh Int. Conf. Manag. Pavement Assets/Transportation Res. Board/Alberta Infrastruct. Transp. Canada/Federal Highw. Adm.. Citeseer.
- PIARC, 2019. Innovative approaches to asset management - technical report. <https://www.piarc.org/en/order-library/31221-en-InnovativeApproachestoAssetManagement-TechnicalReport>.
- Santos, J., Ferreira, A., 2013. Life-cycle cost analysis system for pavement management at project level. *Int. J. Pavement Eng.* 14, 71–84.
- Sarsam, S.I., 2016. Pavement maintenance management system : a review. *Trends Transp. Eng. Appl.* 3, 19–30. https://www.researchgate.net/profile/Saad-Sarsam/publication/307976894_Pavement_Maintenance_Management_System_A_Review/links/57dbd02808ae5292a3790296/Pavement-Maintenance-Management-System-A-Review.pdf.
- Sassani, A., Smadi, O., Hawkins, N., 2021. Developing pavement marking management systems: a theoretical model framework based on the experiences of the US transportation agencies. *Infrastructure* 6, 1–32. <https://doi.org/10.3390/infrastructures6020018>.
- Steyn, W.J., Broekman, A., 2022. Development of a digital twin of a local road network: a case study. *J. Test. Eval.* 50, 20210043. <https://doi.org/10.1520/jte20210043>.
- Sun, Y., Hu, M., Zhou, W., Xu, W., 2020. Multiobjective optimization for pavement network maintenance and rehabilitation programming: a case study in Shanghai, China. *Math. Probl Eng.* 2020, 1–11.
- Tang, F., Ma, T., Zhang, J., Guan, Y., Chen, L., 2020. Integrating three-dimensional road design and pavement structure analysis based on BIM. *Autom. Construct.* 113, 103152. <https://doi.org/10.1016/j.autcon.2020.103152>.
- Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., Sui, F., 2018. Digital twin-driven product design, manufacturing and service with big data. *Int. J. Adv. Manuf. Technol.* 94, 3563–3576. <https://doi.org/10.1007/s00170-017-0233-1>.
- Transportation Research Board, 2024. Transportation enterprise data warehouse implementation guide. <https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=5358>.
- Uddin, W., Hudson, W.R., Haas, R.C.G., 2013. Public Infrastructure Asset Management. No Title.
- Vignali, V., Acerra, E.M., Lantieri, C., Di Vincenzo, F., Piacentini, G., Pancaldi, S., 2021. Building information Modelling (BIM) application for an existing road infrastructure. *Autom. Construct.* 128, 103752. <https://doi.org/10.1016/j.autcon.2021.103752>.
- Wang, S., Zhang, F., Qin, T., 2021. Research on the construction of highway traffic digital twin system based on 3D GIS technology. In: *J. Phys. Conf. Ser. IOP Publishing*, 42045.
- Xu, L., Mak, S., Minaricova, M., Brintrup, A., 2024. On implementing autonomous supply chains: a multi-agent system approach. *Comput. Ind.* 161, 104120.
- Ye, S., Lai, X., Bartoli, I., Aktan, A.E., 2020. Technology for condition and performance evaluation of highway bridges. *J. Civ. Struct. Heal. Monit.* 10, 573–594.
- Yu, G., Zhang, S., Hu, M., Wang, Y.K., 2020. Prediction of highway tunnel pavement performance based on digital twin and multiple time series stacking. *Adv. Civ. Eng.* 2020, 1–21.
- Yuan, C., McClure, T., Cai, H., Dunston, P.S., 2017. Life-cycle approach to collecting, managing, and sharing transportation infrastructure asset data. *J. Construct. Eng. Manag.* 143. [https://doi.org/10.1061/\(asce\)co.1943-7862.0001288](https://doi.org/10.1061/(asce)co.1943-7862.0001288).
- Zhang, Y., d'Avigneau, A.M., Hadjidemetriou, G.M., de Silva, L., Girolami, M., Brilakis, I., 2024. Bayesian dynamic modelling for probabilistic prediction of pavement condition. *Eng. Appl. Artif. Intell.* 133, 108637.
- Zhu, B., Hou, F., Feng, T., Li, T., Song, C., 2023. An information model for highway operational risk management based on the IFC-Brick schema. *Int. J. Transp. Sci. Technol.* 12, 878–890. <https://doi.org/10.1016/j.ijtst.2022.12.004>.