HOW CAN DIGITAL TWINS BE USED IN HIGHWAY MAINTENANCE? A QUESTIONNAIRE SURVEY FOR INDUSTRY PRACTITIONERS

Mengtian Yin[1], Varun Kumar Reja[1], Ran Wei[1], Brian Sheil[1], and Ioannis Brilakis[1]
[1]Department of Engineering, University of Cambridge, UK

Abstract

The digital twin (DT) concept can potentially bring about a systematic approach to digitalizing information for road infrastructure systems. However, it is currently unclear how the DT concept can be applied in the highway maintenance domain and what the benefit is. This study conducts a questionnaire survey to explore what industry professionals view as the main obstacles in current practice and what areas of highway maintenance can improve if using a road DT. A total of 183 responses were obtained from highway industry practitioners. The results reveal the main issues in maintenance processes and potential use cases of DTs.

Introduction

Highway infrastructure systems play an essential role in society, the economy, and security. However, with the increasing number of vehicles travelled on the road network, real-world road assets are experiencing rising traffic load and utilization (Sinha, Labi and Agbelie, 2017), causing risks of structural failures. Therefore, maintaining highway assets consistently above a standard level is challenging, requiring a comprehensive acquisition of dynamic road condition data and effective data analytics tools to forecast road states as well as make sound treatment strategies. Unfortunately, highway authorities still heavily rely on manual inspection to assess road condition (Koch *et al.*, 2015) and make treatment plans based on the experience of pavement experts. The entire highway maintenance process may be changed by the newly emerging digital twin (DT) approach, which might enhance data acquisition, integration, analysis, and decision-making in a systematic way.

A DT represents a digital replica of physical assets and processes involved in the built environment lifecycle, enabled by a twin-based system (Brilakis *et al.*, 2019). In the highway maintenance context, DTs provide a detailed virtual model that simulates the behaviour and operations of physical highway infrastructure systems. Based on the dynamic virtual model, DTs bring about a new information management (IM) approach that can potentially improve data interoperability, integration, and analytics. In this way, highway experts may be able to efficiently retrieve useful information from DTs and make more appropriate decisions on maintenance interventions. So far, the DT concept has been widely applied in the fields of aerospace (Li *et al.*, 2021), manufacturing (Kritzinger *et al.*, 2018), and recently gained popularity in building construction (Sacks *et al.*, 2020). However, implementation of DT approach in highway maintenance is still scarce. It is currently unclear how the DT approach can be applied in this area and what actual benefits a DT can provide. Without knowing the purpose of using a DT, it is impractical to build a road DT system with a decisive scope of meta modelling, level of detail (LOD) for model instance generation, and frequency of data updating.

To tackle these issues, this study describes results from a questionnaire survey for highway industry practitioners to understand the main barriers in their professional workflows and the potential improvements that can be realised using a road DT. This questionnaire study is designed based on (a) a state-of-the-art review of DTs in road domain; and (b) interviews of 20 industry experts from the UK National Highways company, which manages England's motorways and major A roads (National Highways, 2021). The survey was further disseminated to highway industry practitioners internationally through different channels, such as email invitations. As a result, 183 valid responses have been obtained from different regions, mainly the UK, China, US, India, and Australia. The survey unveils crucial phases, applications, and use cases that a road DT can potentially take effect on. It also shows how practitioners perceive the challenges of DT deployment in the highway industry.

In the following sections, we first review relevant studies about DTs of road infrastructure. Then, we demonstrate the research methodology before presenting and discussing the survey results. At last, we draw conclusions by summarizing key findings and contributions.

Background research on DTs for road infrastructure

In the planning and design phases, a road DT is mainly used to assess the impacts of new road designs on existing networks and natural environments. Machl et al. (2019) present a DT-based method to assist road planners in assessing design impacts on agricultural core road networks. Jiang et al (2022; 2022a) propose a method to automatically generate DTs of road networks from open map data and use the DT to check the clearance of underpass roads in road widening projects. Jiang et al. (2022b) propose a DT-enabled sustainable urban road planning framework that integrates multi-criteria decision-making and Geographic Information System (GIS), where DTs provide the routes and traffic congestion data.

In the road construction phase, the DT is indirectly used to assess the performance of new road materials. Meza et al. (2021) developed a road DT to examine the use of secondary raw materials (SRM) in real road construction projects. Manually developed road Industry Foundation Classes models are imported into a common data environment platform that allows the integration of sensor data installed in various pavement layers. In addition, some existing studies integrate building information models (BIM) and the Internet of Things (IoT) for road construction monitoring, which is close to the concept of DT. For example, Han et al. (2022) propose a BIM-IoT and intelligent compaction (IC)-integrated framework for road compaction quality monitoring and management.

In the operation and maintenance (O&M) phase, many road DTs are created in different ways without a specific purpose. Marai et al. (2021) present a road DT system using a 360° camera and IoT devices. The live stream, GPS location, and measurements of the temperature and humidity are dynamically sent to the DT, with interested objects (e.g., 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 model. Steyn and Broekman (2022) develop a DT prototype of a local road network that uses LIDAR, unmanned aerial vehicles, and sensor systems to capture road geometry, traffic flow data, and road environment data, respectively. In contrast, some studies discuss some potential applications of DT. For instance, Chen et al. (2022) propose a DT-based framework for road condition prediction that inputs historical and real-time data from the whole road lifecycle into machine learning algorithms to predict future road performance. Agrawal et al. (2022) invite highway experts to plan the adoption of DTs to detect pavement defects, predict future defects, and make maintenance work orders.

From the above review, it can be summarized that although there are some implementations of DT in the road maintenance phase, the application scenarios and benefits of DTs have not been systematically explored using surveys of realistic problems encountered by the highway industry. Furthermore, the existing studies primarily focus on DT generation and DT-enabled data analytics, whereas few research has investigated the requirements and challenges for DT implementations considered by the industry practitioners. Understanding the specific use of road DTs and value points could help the highway industry develop DTs as a new IM approach to solve the existing issues.

Research methodology and questionnaire design

Figure 1 shows an overview of the research design. This study first interviewed 20 highway experts from UK National Highways. The objective is to understand existing maintenance processes and the problems that underpin them. The Information Delivery Manual (IDM) (29481-1, 2010) approach is employed to represent different levels of maintenance processes along with the related actors, phases, activities, and data exchange items.

Having documented all relevant existing maintenance processes, the authors analyse the IDM documents to identify any inefficiencies in these processes. Based on the findings, together with the interview conversations and literature review, a questionnaire is designed, covering the following aspects: (a) participant role and experience; (b) barriers in current practices; (c) current use of DT; (d) perceived opportunities of DT; (e) challenges of DT implementation. Most questions are multiple-option questions, where the options come from the authors' findings (e.g., identified inefficiencies) or proposals (e.g., proposed DT applications). The questionnaire also allows participants to input their comments for most questions, in case the predefined options are not within their considerations. The questionnaire form can be accessed through the link: https://forms.gle/Nj7g7BT9D3VHo3x4A .

Finally, we disseminated the questionnaire survey through various channels, such as email invitations, LinkedIn, and Weibo. To allow relevant people to complete this questionnaire, we included prompts in the invitation that state "*the target population is individuals who work 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*".

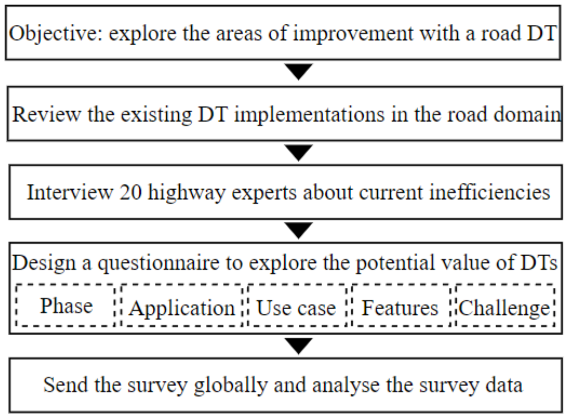

Figure 1. Overview of the research design.

Survey results and discussion

Overview

The survey data collection period covers approximately 40 days, from October to November in 2023. The number of email invitations is over 500. As a result, 183 valid responses have been obtained as valid samples for data analysis. This sample size enables a 95% confidence level with an 8% margin of error for the survey results, as calculated using Slovin's formula (Tejada and Punzalan, 2012). Given the exploratory nature of this study and the limited pool of respondents, these parameters can be deemed appropriate.

Table 1 shows the demographics of all respondents. Maintenance managers and engineers (27.9%), road inspectors (20.8), and technology developers (19.1%) occupy the largest proportions, probably because this topic gains interest from these groups. It is worth noting that some respondents selected multiple roles in this survey.

Table 1: Demographics of the 183 respondents.

Roles	Proportion
Road surveyor	14.2%
Road inspector	20.8%
Maintenance manager and engineer	27.9%
Scheme maker	10.4%
Asset manager	14.2%
Technology developer	19.1%
Network-level strategy maker	11.5%

In terms of participants' experience in the industry, 34.4% of participants have 5-10 years of working experience. People who have worked for over 10 years account for 32.8%. In comparison, practitioners who have started their careers (0-2 years) and have 2-5 years' experience make up 9% and 24%, respectively.

Main barriers in current practice

Figure 1 presents the responses from the participants regarding question 3, which is about selecting the main barriers faced by their organization in highway maintenance. It shows that "*hard to derive optimal maintenance decisions under budget constraints*" is the most selected choice (55.2%), which implies that the main limitation for the highway industry is still budget constraints. In this situation, practitioners must carefully evaluate the impacts of different decisions and prioritize the importance of different tasks, which is difficult to achieve due to several reasons. First, as the ranked second (50.8%) choice points out, much of the asset information stored in the existing maintenance management systems (MMS) and asset management systems (AMS) is inaccurate, incomplete, and unreliable, especially for old and underground assets (e.g., electricity). Second, it is still difficult to obtain comprehensive road condition data, which is also acknowledged as the third barrier. If maintenance planners do not know what happens on the entire road network, it is difficult to make 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. This is because most existing decision-support tools can only optimize short-term plans with controllable factors rather than forecasting long-term, multi-year network evolution with uncertainties incorporated.

Some respondents also identified specific problems they faced. For example, two answers illustrate that there is a lack of "*consistent operational approach*" and "*maintenance strategy based on needs*". These problems relate to other written answers that demonstrate a lack of knowledge of how asset handover works and the complexity of the data specifications of the current asset systems. The barriers occur because an increasing number of highway authorities are adopting asset information models (AIM) for managing highway assets, but maintenance people do not know how to use these asset data in their professional work. For example, the National Highways publishes an Asset Data Management Manual (ADMM) (National Highways, 2023) as their data handover specifications for all road construction projects, but they currently use another system with disparate data schemas to schedule routine maintenance.

Apart from the asset data usage problem, other written answers mention some challenges in lack of skilled workforce, lack of trust in analytical processes, communication with stakeholders, inefficient contract preparation, and difficulty obtaining road data without traffic disruption.

Current use of relevant technologies

In this survey, we also investigate the IM approaches and technologies adopted by highway organizations in the current practice. In the questionnaire, we first clarify what a DT is in the highway maintenance context: "*a digital replica of the physical highway system, encompassing road infrastructure assets, traffic elements, environmental factors, and more*." Afterward, the fourth question first surveys the participants' familiarity with the DT concept. As a result, 63.9% of participants responded

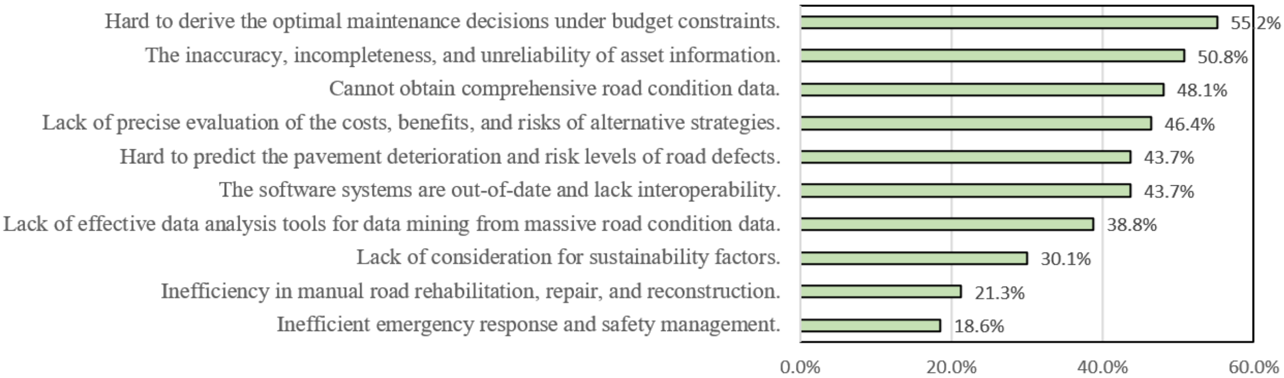

Figure 1. Responses to Question 3: "What are the main challenges and barriers faced by your organization in highway maintenance operations?"

"somewhat familiar," and 22.4% of participants chose "very familiar". In contrast, only 13.7% of participants acknowledge that they are not familiar with DTs at all.

The fifth question sought to clarify what technological approaches are currently used by participants' organizations. As shown in Figure 2, GIS is the most used technology for highway maintenance, which is intuitive because nearly all highway assets should be georeferenced in large road networks. Moreover, it was found that BIM approach is increasingly used in the road engineering domain (54.1% of participants). How to best use the road BIM files from the design and construction phases in the maintenance phase requires further studies. One potential solution is to make BIM models exchangeable with twin-based systems to realise their maximum value. In addition to the predefined options, participants also mention drone-based real-time data collection techniques and material deterioration models.

The sixth question aims to explore the contexts and projects in which highway organizations adopt DT technology and how it is used. From the answers obtained, it was found that most applications of DTs are 3D visualization to assist maintenance planners in making decisions. However, there are some noteworthy other applications, as listed in Table 2.

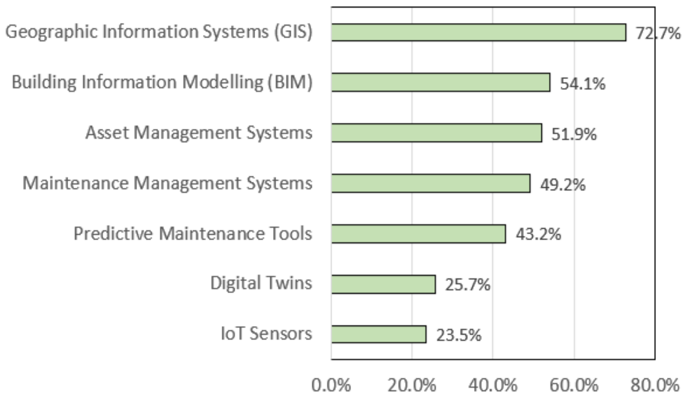

Figure 2. Responses to Question 5: "Does your organization currently use digital technologies or solutions for highway maintenance? "

Table 2: Selected answers for Question 6: "briefly describe the context or project where digital twins were/are utilized."

Current use of DT in organizations
1. Behavior/deterioration modeling of road assets.
2. Combining survey and as-built data for digital design.
3. Decision-support tools to predict maintenance needs.
4. Analysis of budget, safety, environment, flood risk, driver behavior, and fleet composition.
5. Comprehensive data storage with road asset definition, road construction, and condition data.
6. Measurement of complex road segments.
7. Real-time weather detection of the highway environment and refined weather forecast.
8. Emergency response and traffic jam management.
9. Supporting the development of autonomous vehicles.
10. Education and training.

As can be seen from the above table, some highway organizations have started to leverage the rich data in digital twins for behaviour prediction, road renovation, maintenance need estimation, and multi-factor analysis for maintenance planning. Moreover, it is worth noting that the integration of road DTs and connected autonomous vehicles (CAV) has the potential to create huge benefits for both the highway industry and the automotive industry: on one hand, the road DT can provide high-fidelity data about road conditions, providing better navigation to CAVs to avoid dangerous road defects (e.g., potholes). On the other hand, the rich data collected from CAVs driving on the network, such as images and sensing data (e.g., temperature, roughness), can be used to update the road DT in real time, which could overcome the critical problems regarding the DT data collection for the huge road network.

Potential use cases of road DT

This section of the questionnaire aims to understand how highway industry practitioners perceive the opportunities for DTs in highway maintenance. Specifically, we try to identify (a) important phases for applying DT; (b) important features that a road DT must have to take effect; (c) valuable applications of road DTs; (d) potential use cases; and (e) main benefits of road DTs.

Based on our interview, the process of highway maintenance can be generally divided into five stages:

- *Scheme making and prioritization*: experienced engineers receive annual network-level survey data and make maintenance schemes for a specific road section. All schemes must be prioritized based on severity levels.
- *Road assessment*: road inspectors physically arrive at road sites to inspect road defects. Various techniques can be used to investigate the deterioration of pavements, such as coring, deflectograph, and ground penetration radar (GPR).
- *Maintenance planning*: based on the results of inspections, maintenance planners make treatment plans with consideration of budgets, costs, labour, and risk level.
- *Maintenance execution*: based on the maintenance plans, contractors of highway authorities conduct road repair and rehabilitation using both humans and machines.
- *Quality assurance and control*: the process of quality inspection to ensure that the maintenance work reaches the required standard.

Table 3 presents the results of Question 7, showing that the stage of *Scheme making and prioritization* is the most commonly agreed phase in which a road DT can take effect. This might be because the DT can be used to check road conditions in 3D views and simulate the effects of different strategies. In addition, *Maintenance planning* is also a popular response (74.3%). By contrast, fewer participants recognize that a DT can be useful in the phases of *Maintenance execution* and *Quality assurance and control*, suggesting that the DT alone may not be useful in fieldwork that involves mainly manual work. Finally, some participants also wrote answers, such as operational planning and control, long-term investment optimization, and maintaining inventory data for soft estate assets. One answer demonstrates that the DT can enable new intelligence-led proactive maintenance that could totally change the existing processes.

Table 3: Responses to Question 7: "In which phases of highway maintenance do you see that digital twins can take effect?"

Phase	Count	Proportion
Scheme making and prioritization	148	80.9%
Road assessment	122	66.7%
Maintenance planning	136	74.3%
Maintenance execution	108	59%
Quality assurance and control	99	54.1%
None of above	2	1%

Question 8 was designed to investigate what features of road DTs are perceived as important for industry practitioners in highway maintenance. From the literature review, we summarize several key features of DTs: data transparency, data security, autonomous decision-making, prediction, simulation, data diagnostics, visualization, and data storage and integration. In the domain-specific context, we provide explanations for the following features in the questionnaire:

- Data diagnostics: identify the anomalies, risks, and their causes in the condition data.
- Simulation: simulate the operations of alternative strategies and assess their effects.
- Prediction: predict future states of roads, such as deterioration and structural failure.
- Autonomous decision-making: generate suggestions to decision-makers based on performance indicators.

Figure 3 presents the results for Question 8. As can be seen, prediction and simulation are two of the most important functional features that a road DT is expected to have. In comparison, fewer participants selected the feature of autonomous decision-making (54.6%). This implies 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. Furthermore, Figure 3 shows that the features of data transparency and data security 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. In contrast, system architects and DT developers might consider these two features to be crucial.

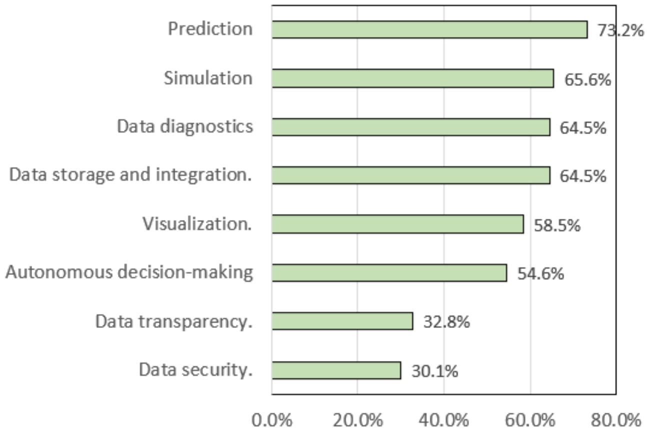

Figure 3. Responses to Question 8: "What features of a digital twin system do you perceive are important in highway maintenance?"

The subsequent question is about the application of road DTs. Based on the review and interview, the authors list several applications for road DTs, and the participants are asked to make selections of applications that they think are valuable. The result of Question 9 is presented in Figure 3. The most chosen DT application (73.2%) is *Predicting the deterioration and structure failures of road assets based on historical and dynamic road data*. In essence, deterioration prediction is a longstanding research problem in the field of highway maintenance. The role of DTs in this task is to be the data holder of historical and real-time road condition data, road construction data (e.g., material), traffic data, and climate data. The prediction of deterioration and failure depends on analytical models that process these DT data and predict the future states of pavements and other assets.

The second-ranked application is *Helping routine maintenance planners make better maintenance strategies, considering multiple factors*. From our interview, routine maintenance and reaction is one of the crucial processes to ensure the operation of the UK highway infrastructure, in which road inspectors drive on the entire network every week to visually check abnormal conditions. Maintenance planners have trouble making the best decisions in prioritizing the repair of the damaged assets and sending work orders that can minimize costs and risks. Therefore, a DT can be used to help maintenance planners make sound strategies in consideration of multiple factors. For instance, a DT may provide cost information for an asset or estimate the risks of the observed defects in association with the traffic environment. The third-ranked application is *Generating optimal plans for road investigation and repair within a* *scheme-level maintenance project.* The UK highway authorities use scheme-level road investigation and maintenance as a key strategy to systematically repair, rehabilitate, or reconstruct road sections. Within a maintenance scheme, scheme makers gather different kinds of survey data and then use their knowledge and experience to determine the treatment strategies. A road DT could aid in the creation of optimized treatment plans with less bias due to human experiences.

Question 10 is an open question that asks participants to describe at least two use cases of DTs that are valuable for highway maintenance. A total of 125 written responses were obtained. While some answers overlap with the applications listed in Question 9, many responses provide valuable insights from the viewpoints of highway experts. Table 4 presents 10 selected answers.

Table 4: Selected answers for Question 10: "Please describe the potential use cases of digital twins in highway maintenance that you believe hold significant promise."

Potential use cases of DT for highway maintenance
1. Supporting risk-based proactive maintenance and automated, human-free road inspection.
2. Live highway monitoring (traffic and pavement structure conditions) to generate instructions for emergency repair and prioritization of repair.
3. Improve predictability of maintenance need, simplicity of maintaining, and up-to-date asset record (location, condition and interventions delivered)
4. Provide data for autonomous cars/machines for snow-plowing the road; provide data for autonomous marking/paining on the road.
5. Data from inspections and maintenance activities is visualized and pinned to the asset to show it "service" history current condition and is then used to predict future maintenance interventions.
6. Understanding 3rd party productivity risks to site works e.g., PROW (Public Right of Way) or ecology; understanding 3rd party safety risks including where to park, traffic levels, works access.
7. Providing detailed incident tracking to understand real-world risks on the network and comparing with asset condition; CAV routing for maintenance and wear.
8. Highlight underground drainage defects.
9. Understanding interaction between different asset classes to help aid intelligence-led predictive modelling for best asset interventions taking account of whole life asset management.
10. Prescribing future designs and built outcomes that impact maintenance.

By analysing the collected responses, some use cases of road DTs can be realized in the short term, while others can only be achieved in a long-term period (over 10 years). For the former, the feasible use cases include integration of highway asset information with a single source of truth, visualization of inspection and maintenance activities, and decision-making for maintenance interventions. For the latter, predicting future states of roads and proactive maintenance may require the collection of road condition data and maintenance records over many years to develop usable deterioration models and approaches for risk-based predictive maintenance.

The last question (Question 11) in this section allows participants to select the potential benefits of DTs in highway maintenance. The results are presented in Figure 5. Better asset lifecycle management, cost savings, enhanced operational efficiency, and improved decision-making are recognized as the main benefits that digital twins can bring to the field of highway maintenance. It suggests that a road digital twin should incorporate asset management principles to facilitate better operational and maintenance planning. Hence, a DT not only serves as a data hub to store and integrate road data but also provides processes and workflows for lifecycle management, from data collection and data updating to the usage of asset data.

Perceived challenges of DT implementation

In the previous section of the questionnaire, the potential use cases and benefits of road DT are studied. However, it is also important to be aware of the challenges of adopting DT approach for highway organizations to better understand which use cases can be implemented in the short term and which use cases require long-term investment and development, thus deriving a reasonable technical roadmap for DT standardization, development, and promotion. Therefore, the last section of the questionnaire investigates the difficulties perceived by

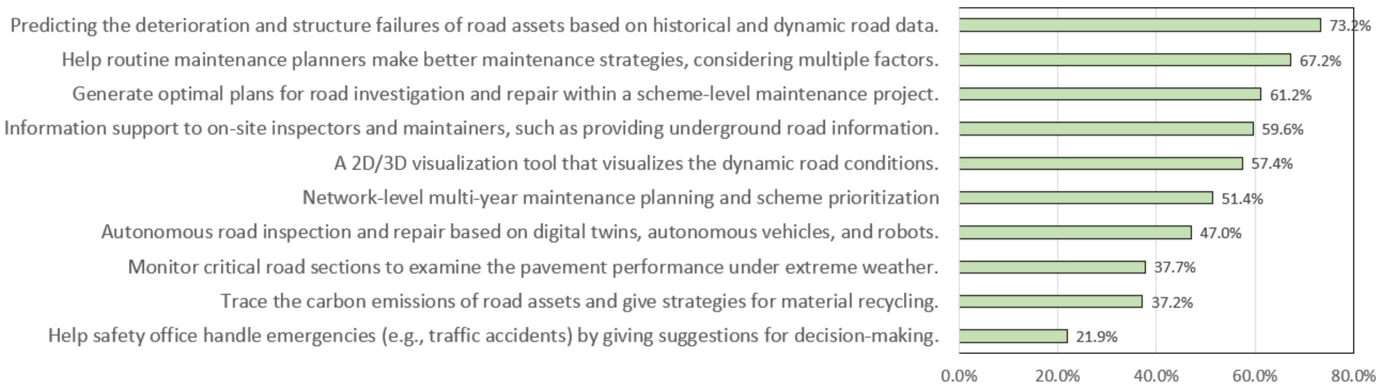

Figure 4. Responses for the Question 9: "Which of the below digital twin-based applications do you perceive are important and valuable in highway maintenance?"

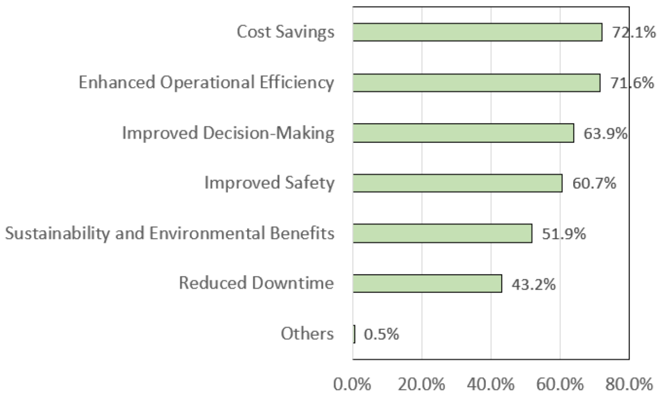

Figure 5. Responses for the Question 11: "Please select the potential benefits you expect digital twins to bring to highway maintenance."

industry practitioners when it comes to implementing DTs for their organizations.

As presented in Figure 6, the responses for Question 12 show that the top 3 challenges of DT implementation are (a) skills and training gaps (61.2% selected); (b) lack of data integration (55.7% selected); and (c) lack of standardization (51.9% selected). It suggests that training and education for highway practitioners to use new DT technologies and systems will be a significant issue because they become accustomed to the existing tools (e.g., GIS). Hence, the design of user-friendly human-DT interfaces is important to reduce the negative impacts of training costs and user reluctance towards new technologies.

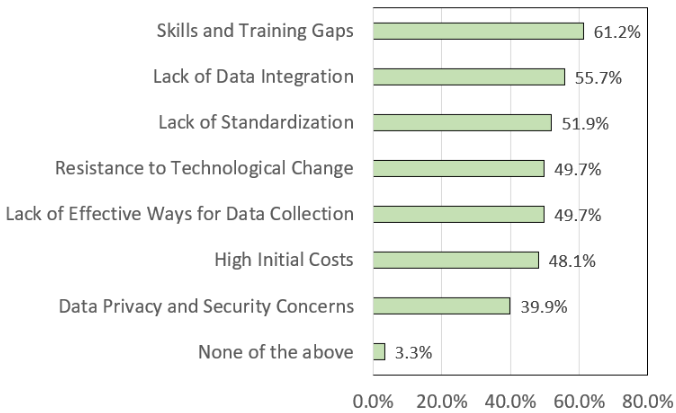

Figure 6. Responses to Question 12: "Please select the primary challenges or barriers you foresee in implementing digital twins for highway maintenance."

The challenge of data integration stems from several aspects. First, the connection of the new DT system with the existing systems and databases used by highway organizations is difficult, requiring a heavy workload of manual alignment between different data schemas. Second, when the road DT has new data requirements about road construction and condition, it is challenging to update the old asset data according to the new requirements, which would induce much missing or mismatched information. Third, designing a data schema for road DT that has sufficient interoperability and scalability is itself an intricate task. This also relates to the 3rd-ranked challenge: lack of standardization. A well-defined data standard is crucial for DT instance creation and information exchange between different DTs.

Apart from the options shown in Figure 6, some respondents also input other problems for implementing DTs in the highway industry, as shown in Table 5.

Table 5: Selected written answers about the challenges of DT implementation.

Other challenges of road DT implementation
1. Lack of political understanding of the urgency.
2. Silo mentality: different sectors or organizations involved in highway maintenance operate independently and without much coordination or information sharing.
3. Technical integration of emerging technologies.
4. Leadership challenge.
5. The cost of maintaining DTs may exceed the values they create.
6. Lack of trust in the analytical processes
7. The DT data obtained from existing databases may have poor levels of accuracy.
8. Procurement of the DT systems and meshing with the existing maintenance systems.

From the above table, policy support, coordination between organizations, and cost estimation for maintaining DTs are also issues for implementing DTs in the highway industry.

Conclusions

Maintaining highway assets at the required service level is critical to ensuring the efficiency and safety of road networks. The digital twin (DT) concept has the potential to be applied in highway maintenance and improves existing processes based on dynamically updating digital road models. This paper presented a questionnaire survey for highway industry practitioners to identify the main barriers in current practice and potential use cases of DTs in this field. The questionnaire was designed based on previous interviews with highway experts in the UK industry, and it was then disseminated globally, with 183 responses obtained from professionals across different roles in the highway industry.

The findings reveal a consensus on the main inefficiencies in highway maintenance: the complexity of making optimal maintenance decisions under constraints, the poor quality of asset inventory information, and the difficulty of acquiring comprehensive road condition data. The survey also indicates that the DT can be potentially used for deterioration prediction, maintenance planning, and scheme development, taking advantage of its well-structured, dynamically updated road asset information in cyberspace.

This study contributes to the knowledge of how industry practitioners perceive the prospects and challenges of road DT in highway maintenance, which provides valuable insights for the design and implementation of road DTs. The results of this survey can be effectively used by academia and industry to develop a purpose-driven approach for applying DTs in the highway maintenance field, where the most valuable use cases with fewer technical and managerial challenges could be implemented first and DTs can be progressively improved to realise more application values. In future work, the survey data will be further analysed based on the roles and experiences of participants.

Acknowledgments

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