UNIVERSITY OF CAMBRIDGE

European Commission

FUTUREROADS PROGRAMME

2021 - 2026 PROGRAMME SUMMARY

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FOREWORD

What a journey it has been. The FUTUREROADS Fellowships programme is gracefully coming to its end date, having accomplished far more than the original team ever could have imagined. The programme started with a simple premise: Whether we like it or not, roads are the most critical part of our transportation infrastructure, and responsible for most people and freight movement in every country. Yet, while the vehicles that drive on the roads have advanced significantly over the last 50 years, the underlying infrastructure that supports them has not. How can we therefore expect future, modern, autonomous, electrified vehicles to reach their full potential when they drive over roads that were designed with, constructed with, and still maintained with, frameworks and methods that were devised before even seat belts were a standard feature?

FUTUREROADS set out to answer this question by decomposing it to key research challenges, and on their basis, recruiting individual fellows supported by a large network of infrastructure companies to attempt to address them. And addressing they did. The outcomes of the programme are diverse and far reaching. They have been disseminated in a large variety of output formats (conference papers, journal papers, reports, presentations, seminars, etc.) to reach both academia and industry worldwide, and have resulted in three very successful cohorts of fellows, most of which are now already assistant or even full professors at universities around the world and continue to work with the same industry organisations that supported their projects, or work at senior positions in these organisations.

I invite you to read this report carefully. There is a treasure trove of content in it that will be eye opening to the reader. The latest research in Digital Twins, Data Science, Smart Materials, Sustainability, and Automation and Robotics for roads is explained in here.

Finally, I wish to thank all the sponsors, their representatives, the fellows, the supervisors, and management team of FUTUREROADS for their amazing contributions to the programme. I want to especially thank our Senior Project Manager, Dr Nevena Vajdic, for organising and compiling this report supported by Ms Mai Nguyen. All of you played a crucial role to the success of the programme.

Professor Ioannis Brilakis, PhD CEng MICE
Laing O'Rourke Professor of Civil & Information Engineering
Principal Investigator, Digital Roads of the Future Initiative
Director, Construction Information Technology Laboratory
Hans Fischer Senior Fellow of the TUM Institute for Advanced Study

MESSAGES

FROM ACADEMIC LEADS

Prof Ioannis Brilakis
Digital Twins Academic Lead
Laing O'Rourke Professor of Civil and Information Engineering,
Director of the Construction IT Lab
University of Cambridge

DIGITAL TWINS

The most strategic and timely worry of the construction sector these days is the AI transition. New AI tools quickly dominate the market every year, or even every few months. All of us have started to be strongly reliant on them for our personal lives. So it is only reasonable for the sector to ask how they could use these capabilities for their work. In some ways they can; but when the answers are hidden in their own proprietary information or that of their clients and suppliers, AI tools are not able to help them.

Digital Twins are the answer to this problem. They are synonymous to holistic information management that allows secure access across systems for the purpose of answering questions that we could not answer before. Below you will find many examples of research towards this aim. They include methods for planning, designing, constructing, maintaining, and operating Digital Twins for the benefit of the lifecycle of the physical road assets.

SMART MATERIALS

Construction and infrastructure materials are significant carbon emitters and a major cost in construction repair and maintenance projects. As a result they have taken centre stage in the industry’s endeavours to reduce cost and carbon. This has created significant challenges given the sector’s conservative nature and insufficient government expenditure and the need to continue to deliver reliability and safety.

The smart materials programme within FUTUREROADS covered the three themes of decarbonisation, digitalisation and environmental protection. The projects included the exploration of low carbon cements, binders and concrete, investigating pavement solutions for enhanced road safety in extreme weather, enhancement of commercial pavement performance inspection approaches and the use of machine learning approaches for exploring the correlations between the parameters that impact pavement performance. The strong and direct collaboration with the industry partners was instrumental in shaping the direction of the research and ensuring its direct commercial relevance.

Prof Abir Al-Tabbaa
Smart Materials Academic Lead
Professor of Civil and Environmental Engineering,
Head & Director, EPSRC CDT in Future Infrastructure and Built Environment,
University of Cambridge

MESSAGES
FROM ACADEMIC LEADS

Ass Prof Kristen MacAskill
Sustainability Academic Lead
Assistant Professor, Environment and Sustainable Development,
University of Cambridge

SUSTAINABILITY

Sustainability serves as a unifying thread throughout the FUTUREROADS programme, connecting research across digitisation, mobility, materials and resilience. Establishing sustainability as a theme in its own right created space for broader, systems-oriented thinking and encouraged fellows to address the complex challenges shaping the future of road transport.

Historically, transport systems have developed without accounting for wider systemic environmental and social impacts that ultimately limit economic prosperity and human wellbeing. Achieving a more sustainable transport system requires attention to three interconnected challenges: reducing environmental impacts, adapting infrastructure to a changing climate, and ensuring that transport serves people equitably. The sustainability-themed fellowships have addressed these challenges through research on flood resilience, transport equity, systems-level material use and the development of more robust carbon accounting practices.

Collaboration with industry partners has been integral to the success of this work, helping to ensure that research is informed by practical needs and opportunities. In turn, the programme has contributed knowledge and evidence to support advances in the assessment of road-network resilience and to increase the maturity of carbon-management practices in the sector.

DATA SCIENCE

The decision-making capabilities of road Digital Twins are enabled by advances in data science and AI. However, the use of AI within Digital Twins should go beyond black-box models that provide condition assessments or predictions without explaining the reasons behind them. The future of trustworthy AI for roads lies in developing new mathematical techniques, derived from areas such as probabilistic machine learning and physics-informed neural networks.

These methods need to be developed and evaluated using industrial data provided by our FUTUREROADS partners, ensuring that they address real-world challenges, including the complexity, uncertainty, and imperfections inherent in infrastructure data. Below you will find examples of research towards this aim. They include approaches for combining physics-based modelling and data-driven analysis for structural health assessment, developing probabilistic Digital Twin frameworks for understanding road conditions and supporting predictive maintenance, and enabling transparent and reliable decision-making throughout the lifecycle of road assets.

Prof Lavindra de Silva
Data Science Academic Lead
Research Professor, Technical Director,
Digital Roads Prosperity Partnership,
University of Cambridge

MESSAGES
FROM ACADEMIC LEADS

AUTOMATION & ROBOTICS

Prof Fumiya Iida
Automation & Robotics Academic Lead
Professor of Robotics,
University of Cambridge

Serving as the academic lead of the FUTUREROADS programme has been a truly rewarding experience. I had the pleasure of working with five outstanding FUTUREROADS Fellows whose research spanned human–robot interaction, embodied AI, evolutionary optimization of traffic systems, and novel sensing principles for autonomous vehicles. Despite their diverse topics, they shared a common ambition: advancing robotics and automation through innovative, interdisciplinary research.

What impressed me most was their ability to combine scientific depth with creativity, tackling challenging problems with both technical excellence and broad vision. The FUTUREROADS programme provided an ideal environment for pursuing ambitious ideas and fostering collaboration across disciplines.

I am particularly delighted that all Fellows have been progressing as academic researchers, and most had secured academic faculty positions at leading universities in the UK. Their achievements demonstrate the importance of supporting outstanding early-career researchers with the freedom to pursue bold ideas. I am confident they will continue to make lasting contributions to robotics, automation, and AI, and inspire the next generation of researchers.

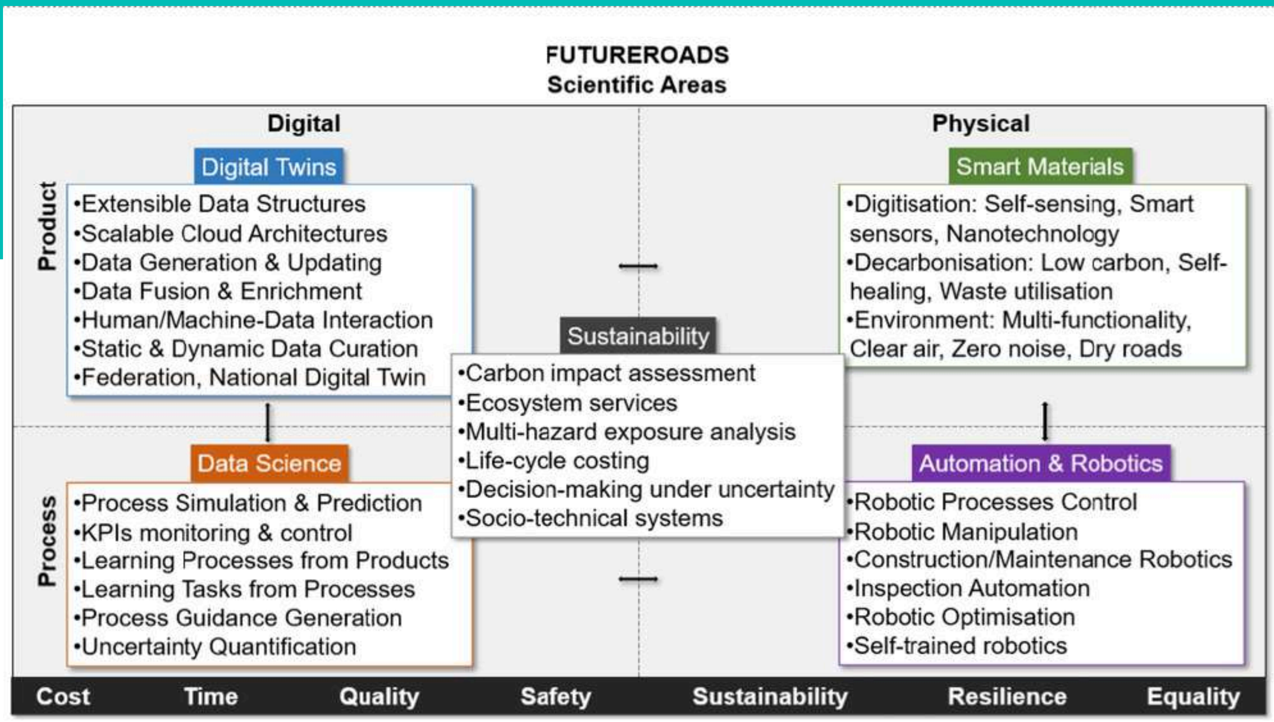
PROGRAM OVERVIEW

FUTUREROADS PROGRAMME

OVERVIEW

The FUTUREROADS Programme is an interdisciplinary fellowship initiative designed to reimagine the future of road infrastructure through innovation, collaboration, and global talent. EU H2020 MSCA COFUND Postdoctoral Programme hosted at the University of Cambridge and co-funded by the European Commission alongside a strong consortium of 24 industry partners, the programme brings together academic excellence and real-world challenges to shape the next generation of infrastructure systems.

Over a five-year period, the programme has attracted outstanding postdoctoral researchers from around the world, offering them the opportunity to develop independent research while working closely with leading academics and industry practitioners. This international mobility and individual-driven research are fundamental principles of the programme, ensuring that fellows not only contribute to cutting-edge science but also grow into future leaders of the sector.



The programme addresses some of the most pressing challenges facing the road infrastructure sector today, including sustainability, resilience, safety, and performance. Through five interconnected research themes: Digital Twins, Data Science, Automation & Robotics, Smart Materials, and Sustainability, fellows are encouraged to adopt an integrated perspective on physical and digital infrastructure systems. This interdisciplinary approach enables innovations that move beyond traditional engineering practices towards smarter, data-driven, and future-ready transport networks.

A distinctive strength of FUTUREROADS is its deep integration with industry. From the earliest stages of defining research challenges to the delivery of secondments and joint outputs, industry partners play a central role in shaping and applying the research. This ensures that the programme's outcomes are not only scientifically solid but also practical, scalable, and aligned with real-world needs. Fellows benefit from this environment through exposure to live projects, access to data and facilities, and opportunities to translate research into impact.

Dr Nevena Vajdic
DRF Senior Project Manager,
University of Cambridge

Equally important is the programme's commitment to training and career development. Fellows undertake a structured programme that combines technical expertise with transferable skills, enabling them to navigate careers across academia, industry, and entrepreneurship. The emphasis on interdisciplinary thinking, intersectoral collaboration, and international networking creates a unique ecosystem.

From my perspective as a programme manager, what stands out most is the community that has emerged. At its peak, FUTUREROADS brought together over a hundred participants: researchers, academics, and industry professionals, creating unique and collaborative environment that extends well beyond the formal boundaries of the programme. The relationships built here, and the knowledge generated, will continue to influence the road sector for years to come.

This programme has been made possible through the dedication and support of many people working behind the scenes. We sincerely thank the independent peer reviewers, the Selection Committee members and Chair, and colleagues across the Department and the wider University for their expertise, commitment, and collaboration. Your contributions have been instrumental in delivering the programme and supporting its success.

OUR JOURNEY

FIVE YEARS OF TRANSFORMING ROAD INFRASTRUCTURE RESEARCH

2021 – Programme Launch

BUILDING THE FOUNDATION

- FUTUREROADS programme begins
- Management and governance structures established
- Calls for Applications (CfA) developed
- First fellowship opportunity advertised globally
- Industry partners and academic network assembled

2022 – Cohort 1 Starts

- Application screening and interviews completed
- Fellows matched with industry partners
- Induction programme delivered
- Technical and transferable skills training launched
- Personal Career Development Plans (PCDPs) established

2023 – Programme Expansion

Two new cohorts join

Cohort 2: *11 Fellows recruited*

- Second international recruitment campaign
- Evaluation and selection process completed
- New research themes launched

Cohort 3: *9 Fellows recruited*

- Third and final fellowship call
- Total fellowship community reaches 26 researchers

2024 – Research at Full Scale

The programme reaches full momentum

- All three cohorts active
- Collaborative projects across academia and industry
- Regular progress reviews and mentoring
- Knowledge exchange between fellows and infrastructure partners

Programme-wide achievements

- Training events delivered
- Technical workshops organised
- International collaborations expanded

2025 – Delivering Impact

Research outputs accelerate

- Journal papers
- Conference presentations
- Industry engagements
- Seminars and outreach activities
- Fellows gain recognition across academia and industry

Career Impact

- Fellows move into:
  - Academic positions
  - Research roles
  - Industry positions

2026 – Legacy & Future Impact

Closing the programme

- Final dissemination activities
- FUTUREROADS Conference
- Research outputs consolidated
- Long-term collaboration prospects

Legacy

- 26 Fellows trained
- 3 International Cohorts
- Hundreds of dissemination activities
- Strong academia-industry partnerships
- New generation of infrastructure researchers and leaders

FUTUREROADS PROGRAMME
IN NUMBERS

64 months

26 fellowships

3 cohorts

£6.33M budget

500 hours of training

24 Industry partners

ACTIVITIES

OUTREACH

PROGRAMME ACTIVITIES

The FUTUREROADS programme has implemented a broad range of activities to ensure effective dissemination and stakeholder engagement. These include maintaining a regularly updated programme website, active use of social media channels, and the use of a dedicated YouTube channel to share research outputs and promotional content. In parallel, fellows have contributed to academic dissemination through journal publications, conference participation, and workshops, ensuring both scientific impact and industry relevance.

Strong industry engagement has been a central component of programme activities. Regular meetings with industry partners and participation in collaborative forums have enabled alignment of research with real-world needs, while workshops, technical networking events, and Industry Days have facilitated knowledge exchange and collaboration. In addition, short visits and secondments have provided fellows with opportunities to engage directly with leading academic organisations worldwide and industrial partners, supporting interdisciplinary collaboration, skills development, and the transfer of knowledge across sectors.

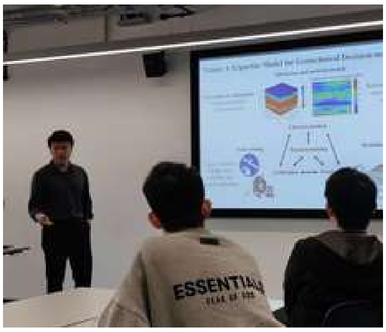
At the European and public engagement levels, FUTUREROADS has actively contributed to outreach initiatives, including participation in the MSCA event in Katowice, Poland, and the Science is Wonderful! science fair in Brussels, Belgium. The programme has also engaged wider audiences through events such as the Cambridge Festival, where fellows delivered interactive demonstrations and educational activities, and the University of Cambridge Open Days. Together, these activities have enhanced the visibility of the programme, promoted STEM careers, and highlighted the societal impact of research on sustainable and digital road infrastructure.

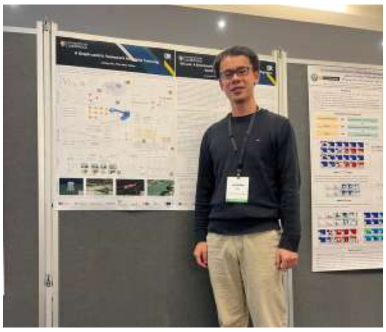
41 Industry engagements

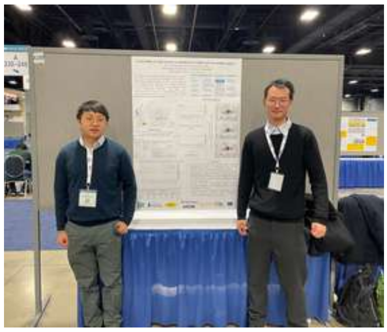
57 academic conferences

30 intersectoral and international placements

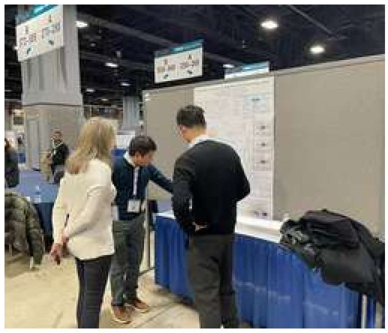
FUTUREROADS Fellows' participation in conferences and workshops

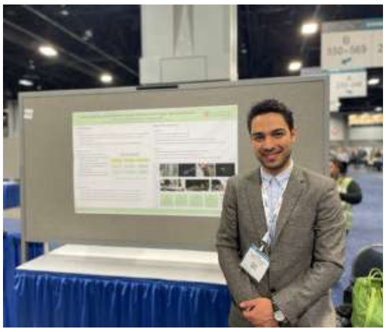


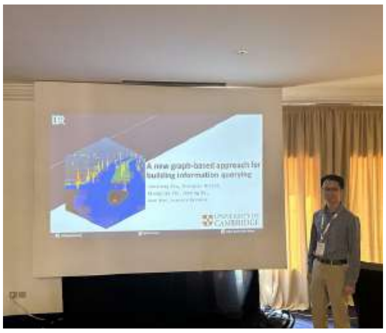


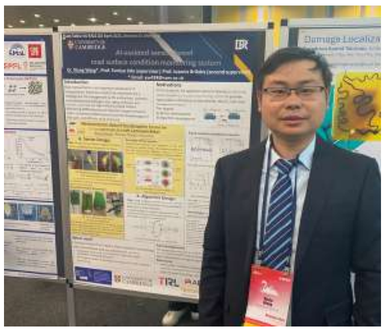


FUTUREROADS Fellows' participation in conferences and workshops

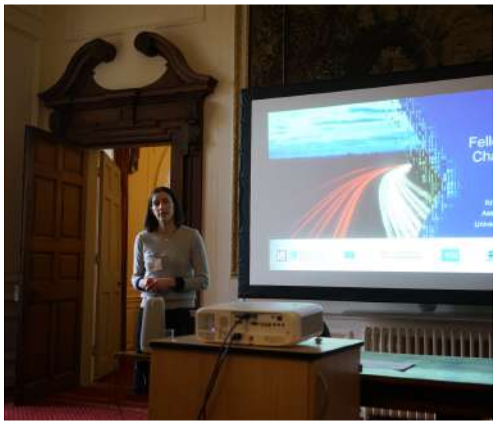








Industry Day
December 2022



Industry Day
September 2023

Industry Day
November 2024

Industry Day

February 2026

Industry visits

M25 Visit
organized by
AtkinsRéalis
April 2023

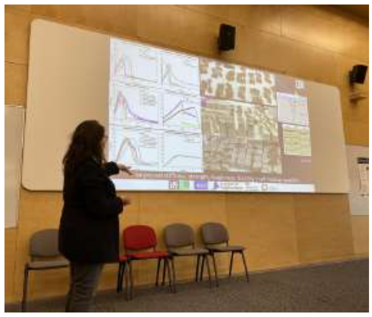
Cohort 1 visit to TRL Smart Mobility Living Lab
in London September 2022

Cohort 2 visit to Korec
July 2023

Cohort 3 visit
to Amey
March 2024

Trimble visit to
Cambridge
June 2024

Department of
Transport Visit
to Cambridge
September
2024



Ringway/Eurovia
visit to Cambridge
February 2025

Industry visits

Roads Research
Alliance Showcase
National Highways
Development Center
April 2025








A47 Tuddenham Site
Visit organized by
Galliford Try
November 2025

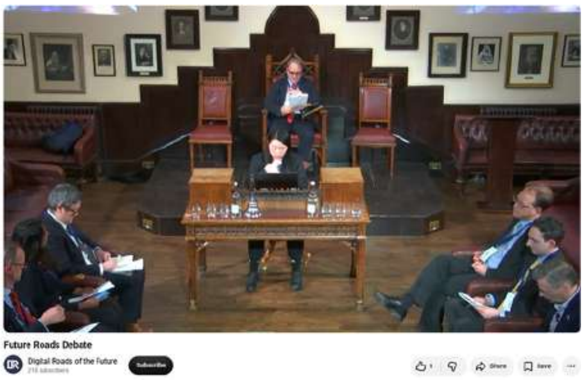

Public Engagement

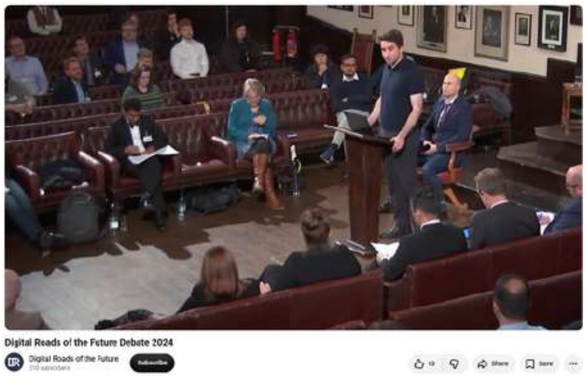
Science is Wonderful,
Brussels, Belgium
April 2024


Department of
Engineering Open
Days, University of
Cambridge
July 2024

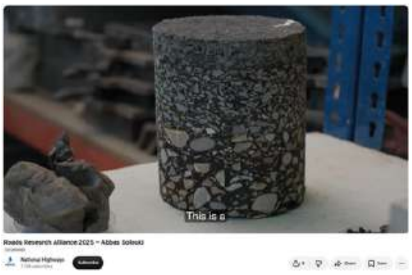
Cambridge Festival
March 2025


This video collection highlights the communication and outreach activities of the FUTUREROADS Programme, showcasing research achievements, fellow experiences, industry collaborations, and key events. Together, these videos demonstrate how FUTUREROADS is advancing innovation in digital and sustainable road infrastructure while engaging researchers, industry partners, and the wider community.

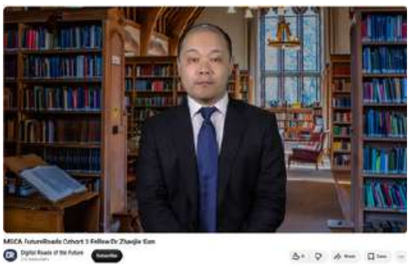


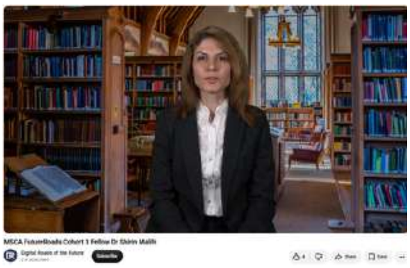


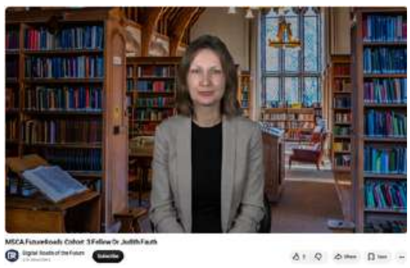
Livestream recap of Debate Event in November 2024 and February 2025



A collection of videos produced by National Highways highlighting research developed in collaboration with FUTUREROADS Fellows and its impact on the future of road infrastructure.







Introduction videos from FUTUREROADS Fellows, highlighting their research, expertise, and contributions to the future of road infrastructure.

Scan the QR code to visit the FUTUREROADS video library and explore our research, fellowship stories, events, and communication activities.

OUR
PEOPLE

STEERING COMMITTEE

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OUR
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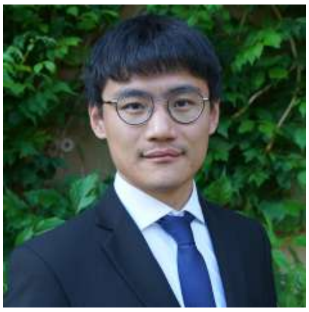

Dr Linjun Lu
Assistant Professor, East
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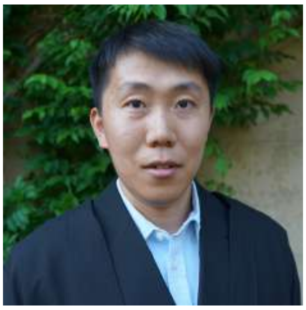

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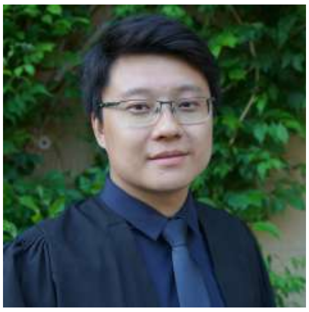

Dr Ze-Zhou Wang
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Loughborough University, UK

Dr Mengtian Yin
Assistant Professor
University of Nottingham
Ningbo China

MARIE SKŁODOWSKA CURIE FUTUREROADS FELLOWS - COHORT 3

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Dr Xiang Wang

Dr Zizhen Xu

Dr Jie Liu

Dr Khashayar Kazemzadeh
Assistant Professor,
The University of Manchester, UK

Dr Junxiang Zhu

Dr Fengqiao Zhang
Assistant Professor,
TU Delft, Netherlands

Dr Shirin Malihi

Dr Zhaojie Sun

OUR ALUMNI

POST-PROGRAMME PATHWAYS: ACROSS THE GLOBE

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RESEARCH

DEVELOPING A FRAMEWORK FOR ROAD DIGITAL TWIN PLANNING

Dr Munkhbaatar Buuveibaatar
Marie Skłodowska Curie FUTUREROADS Fellow
Researcher at the Korea Institute of Transport

Digital twin (DT) is an emerging technology gaining traction across various industries. However, its development and application in the architecture, engineering, and construction (AEC) industry remain in their early stage, lagging considerably behind other sectors. This is primarily attributed to the challenges facing the AEC industry, including digital transformation and the lack of formal standards for DT implementation. This research aims to contribute to the conceptualization of DT planning—the early stage of the DT lifecycle—focusing on the road transportation sector, particularly road physical twin planning within the AEC industry.

Scientific concept and goals

4DT applications in the road sector have mainly focused on the maintenance and operation phase. In contrast, other lifecycle stages, such as planning and design, particularly road planning, are less considered. Generally, the planning stage is often overlooked and not recognized as a distinct lifecycle stage, as it is typically integrated into the design stage.

In contrast, urban DTs or smart city applications do not significantly consider road planning aspects. Rather, they are focused on comprehensive aspects of cities, representing their facilities and city elements in a multidimensional virtual space, and underlining existing infrastructures to create future scenarios.

In this work, we approached from the DT lifecycle concept, particularly emphasizing the beginning of the lifecycle—DT planning. Thus, as DT planning is referred to as the early stage of the DT lifecycle, we have focused on the early-stage development of DTs. However, some underlying concerns exist regarding the concept and application of DT planning. First, the definition of DT planning is unclear, making its practical implementation challenging. Second, there is a lack of guidelines or roadmaps necessary for creating DT planning. This study aims to contribute to the conceptualization of DT planning, which is the early stage of the DT lifecycle, focusing on the road transportation sector, particularly the planning of road PT within the AEC industry.

Summary of the work carried out

provide stakeholders with an initial idea about the project, offering insights without the need for immediate economic investment. However, the specific steps and processes involved in DT planning, particularly in the road infrastructure, are yet to be clarified, as this phase has received less attention than other lifecycle stages. The project is approached from the road planning perspective, which serves as a use case for developing DT planning. Specifically, the present work took examples from road planning activities and processes mainly in the United Kingdom (UK).

To achieve the research goal, we reviewed the relevant literature defining DT planning. We also examined stakeholders' relevant guidelines and documents from national bodies that roadmap the road DT planning process to understand the scope and identify knowledge gaps.

Based on the literature review, we conceptualized the structure and elements of DT planning by comparing and contrasting various related frameworks and models. In addition, five core layers of DTs are defined as a data acquisition layer, a data processing layer, a data models and algorithms layer, a data analysis layer, and a user interface or a service layer, which can be used for structuring the backbone of the road DT planning process.

On the other hand, the study aimed to examine the road PT planning process to draw parallels from the relevant literature and stakeholder perspectives. In the UK, the Transport Analysis Guidance or WebTAG, by the DfT, offers specific step-by-step guidance for implementing the project control framework (PCF) stages.

To determine what road planning steps would apply to DT planning, mapping existing processes to the corresponding DT functions or layers is paramount. Therefore, mapping of the existing road planning process to the constituents of road DT planning was performed for the applicable planning steps.

Basically, existing road planning processes can be broadly divided into two main phases: before and after option generation, as options are the most important results/part of solving the transportation problem. Before generating options, there are four basic steps: understanding the current situation, understanding the future situation, demonstrating the need for intervention, and clarifying objectives. From this perspective, this step is related to the input, modeling, and analysis (parts) of DT planning.

On the other hand, the option generation process comprises three constructive steps: generating options, undertaking an initial sift, and developing and assessing potential options. These steps are based on the earlier stages (four steps) and are all commonly mapped to the analysis part of DT planning.

Finally, we proposed a five-layered road DT planning framework that will roadmap future implementations comprising data acquisition, data processing, data modeling and algorithms, data analysis and control, and a service layer plus users. In addition, a case study is incorporated to validate the feasibility of the framework for applying it further in practice.

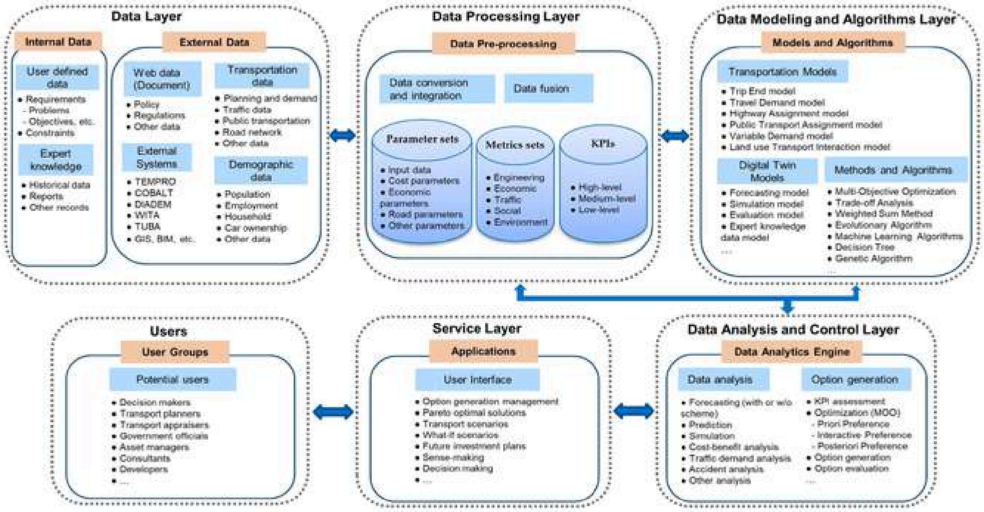


Fig 1. Research Flow/ Methodology

Major outcomes and significance

by conceptualizing a novel framework for road DT planning and proposing a system architecture that can serve as a roadmap for future development in this area. Therefore, we aimed to contribute to the research gap by clarifying certain concerns in the research and application of DT planning. Specifically, we formulated the DT planning concept and its constituents, providing implementation guidelines, including a case study as part of a DT planning framework that will support not only the adoption of DT planning but also digital transformation in the AEC industry, particularly the road transportation sector, toward realizing digital roads in the future.

We proposed a DT planning framework consisting of five layers: data acquisition, data processing, data modeling and algorithms, data analysis and control, and service layer plus users. The core of our proposed framework/architecture model is that it generates viable options for road transportation planning problems for better decision-making. It includes three modules—a priori, interactive, and posteriori approaches—and the one to use for better decision-making depends on the stakeholders or users.

The data acquisition layer obtains data that is similar to the road planning steps. Most input data are part of the pre-option generation phase, which is divided into internal and external data. The data processing layer processes the data collected through the data acquisition layer from various sources. These data must be converted into a standardized format to produce useful information for further data manipulation. Multiple data sources can be integrated into the DT data structure.

The data modeling and algorithms layer comprises several models integral to the road PT planning process. These models can be divided into transportation-related models and DT-related models, and they support DTs in efficiently and effectively generating viable solutions for road transportation planning problems.

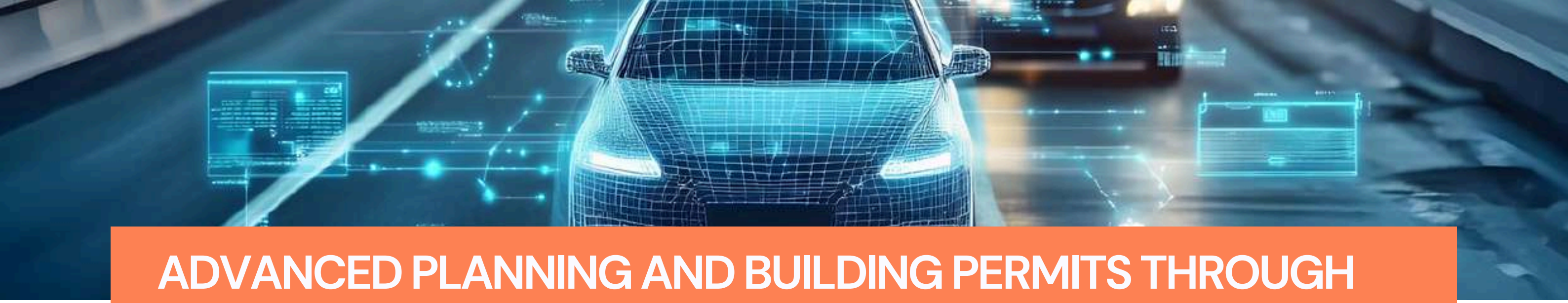
The analysis layer serves as the core of the DT model, whose main purpose is to provide an analytical environment based on the DT input and models. The service/application layer is the topmost layer that interacts with users through a user interface. Users can manage and control the whole process of planning with the aid of a user interface.

Moreover, from a broader perspective, the proposed framework is expected to significantly contribute to national decarbonization and net-zero efforts. Decarbonization and transportation improvements are intended to be essential components of local transport planning. Our proposed framework aims to support sustainable road transport planning activities by streamlining the necessary steps for planning major road infrastructure once it is adopted and implemented. Specifically, it is anticipated that corporate emissions—such as those from lighting, power, work travel, and energy consumption—will be reduced by facilitating a preliminary phase in the planning process, allowing stakeholders to begin planning independently.

Future directions

Future research should focus on compiling a comprehensive list of data or information requirements for a study about road DT planning. Additionally, a proof of concept is essential for implementing the framework presented in this paper. The proposed lightweight implementation framework could be one potential solution, but it may not encompass all the capabilities and functions suggested. Web-based applications can be designed with user interfaces, incorporating embedded models and algorithms that process input data and requirements. This enables analysis and generates optimal options. DT planning can also be created for other new infrastructure assets, such as railroads, and other relevant facilities, as this study only used a road planning approach from practice as an example to conceptualize DT planning. Furthermore, considerations regarding costs and the overall feasibility of DTs should extend beyond the road planning aspect.

This project aimed to contribute to the conceptualization and application of DT planning, focusing on the road transportation sector within the AEC industry, taking the UK as a case study. The study expanded the one potential use case of DTs in the road transportation sector, which would support the decision-making process of road planning. Unlike the conventional road planning process, stakeholders can plan DTs early in the lifecycle for further adoption while having pre-planning stage thoughts before starting the actual planning process, including feasibility by using the road DT planning. Specifically, it will be valuable to deal with the decision-making related to the major infrastructure project development, where large amounts of budget and effort are required. In addition, in general, the proposed framework contributes to the advancement of the smart city and/or urban DT concept and framework by introducing elemental technology such as road DT planning. Particularly, if the smart city framework is implemented and extended at the national level, the proposed framework will be an essential part of it.



ADVANCED PLANNING AND BUILDING PERMITS THROUGH ROAD DIGITAL TWINS

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Planning and building permitting processes play a critical role in shaping the built environment but remain fragmented from infrastructure planning, particularly road networks. This project explores how Road Digital Twins (RDTs) can support more efficient, transparent, and informed planning and building permitting by enabling structured data exchange between buildings and roads as interconnected built assets. The research develops information packages, semantic models, and decision-support approaches to link regulatory requirements, infrastructure constraints, and approval processes. By integrating RDTs into permitting workflows, the project aims to reduce uncertainty, improve coordination between stakeholders, and support more sustainable and resilient development decisions.

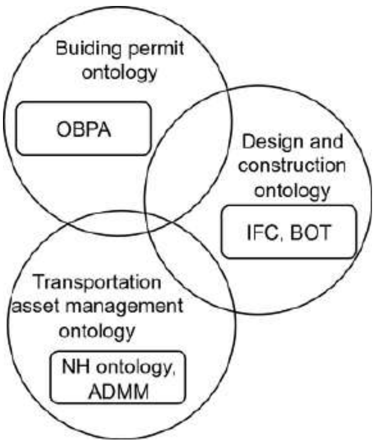
Scientific concept and goals

Planning and building permitting processes form a critical interface between public governance, infrastructure planning, and the built environment. While road authorities increasingly develop Road Digital Twins (RDTs) to support asset management, resilience, and lifecycle optimisation, planning and building permits remain largely disconnected from these digital representations. As a result, decisions on access roads, construction logistics, safety, capacity, and long-term infrastructure impacts are often assessed using fragmented data and manual coordination.

The scientific concept of this project is to treat buildings and roads as interdependent built assets and to investigate how RDTs can systematically support planning and building permitting processes. The project develops a structured, information-centric approach that connects regulatory requirements, permitting workflows, and road infrastructure data through semantic models and decision-support mechanisms.

The main goals are threefold. First, the project aims to identify and formalise information packages that are exchanged or required at the interface of building permits and road infrastructure, such as access requirements, traffic impacts, construction phases, and safety constraints. Second, these information packages are organised using knowledge-management techniques, including ontologies and rule-based reasoning, to enable traceable, machine-interpretable links between regulations, road data, and permitting decisions. Third, the project addresses uncertainty and discretion in permitting by developing decision-support concepts that help authorities and applicants interpret regulatory requirements more consistently.

Overall, the project seeks to establish a transferable scientific foundation for integrating RDTs into planning and building permitting, enabling better coordination between stakeholders, reducing uncertainty, and supporting more sustainable and resilient development decisions.

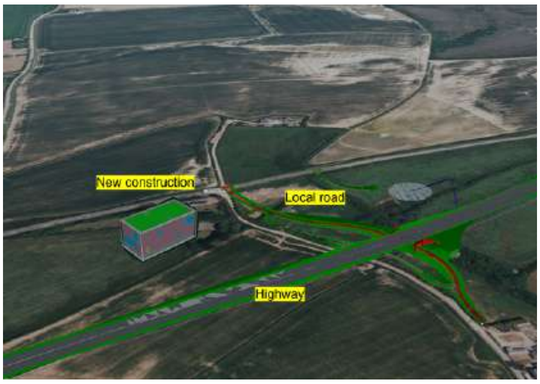


Summary of the work carried out

During the programme, work focused on Work Package 1 (WP1) and Work Package 2 (WP2). Due to leaving the programme before its completion, WP3 and WP4 were not carried out. Nevertheless, substantial foundational results were achieved that directly support the project's overall objectives.

WP1 addressed the identification and structuring of shared information between planning and building permitting processes and road-related systems. This work focused on understanding what information is required, when it is needed in permitting workflows, and which stakeholders are involved. Two journal articles were developed as part of this work. One article, co-authored with a programme fellow, is currently under peer review, while a second journal manuscript is finalized and prepared for submission. These publications establish a systematic mapping of shared influencing factors and information needs between building permitting and road infrastructure planning, providing an empirical and conceptual foundation for linking Road Digital Twins with regulatory processes.

The WP1 research employed literature analysis, regulatory document analysis, and qualitative expert input to identify recurring interaction points between building permits and road systems, such as access requirements, traffic impacts, utilities, safety, and construction logistics. The results demonstrate that these interactions are neither incidental nor marginal, but structurally embedded in permitting workflows across jurisdictions.

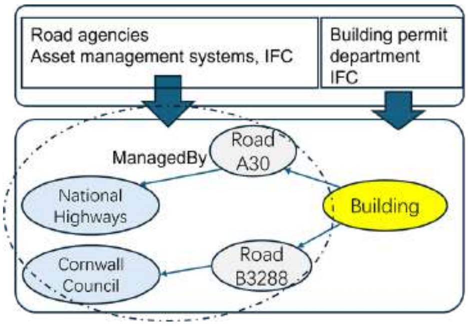


WP2 focused on organising this knowledge using semantic and process-oriented approaches. A conference paper presenting this work was accepted, presented at the Digital Building Permit Conference 2025 (DBP25), and is currently in production. This contribution demonstrates how structured information packages and semantic models can support cross-domain coordination between building authorities and road agencies. The work highlights the potential of ontologies and rule-based reasoning to formalise agency involvement, clarify responsibilities, and improve traceability in permit review processes where road infrastructure plays a role.

In addition to the work explicitly assigned to WP1 and WP2, several related peer-reviewed publications were developed during the programme that focus on building permitting processes more broadly. These include journal articles on reference process models, digital building permitting, and regulatory workflows. While not exclusively centred on road digital twins, these outputs form an essential contextual and methodological basis for the project by advancing the understanding of permitting as a socio-technical, multi-actor decision-making process.

Major outcomes and significance

The major outcome of this project is a structured framework that connects road digital twins with planning and building permitting processes. By identifying and formalising information packages, the project makes explicit which road-related data is relevant at different permitting stages and how it can be reused across stakeholders and lifecycle phases.
A key scientific contribution lies in the development of semantic models that bridge regulatory requirements, permitting workflows, and infrastructure data. These models support traceability, consistency, and machine-interpretable representations of complex regulatory relationships, which are currently handled manually or through document-centric processes.
From an industry perspective, the project demonstrates how RDTs can deliver value beyond traditional asset management. Integrating RDTs into permitting processes enables earlier identification of conflicts, improved coordination between authorities and applicants, and reduced uncertainty in decision-making. This can lead to shorter approval times, fewer revisions, and more predictable outcomes.
Another significant outcome is the explicit treatment of uncertainty in permitting decisions. By acknowledging and modelling uncertainty rather than ignoring it, the project provides a more realistic basis for decision support. This is particularly relevant for assessments related to traffic impacts, safety, and construction phases, where precise data is often unavailable at early stages.
The business case analysis further highlights the strategic relevance of the approach. It shows how upfront investments in data integration and knowledge management can lead to long-term efficiency gains, reduced risk, and improved sustainability outcomes. Overall, the project contributes to the digital transformation of planning and building permitting while strengthening the role of RDTs as a cross-sectoral digital infrastructure.



Future directions

Future research will focus on validating the developed concepts through pilot implementations with road authorities and permitting bodies. This includes testing the information packages and semantic models in real-world permitting scenarios and refining them based on stakeholder feedback.
Further work will also explore integration with other digital twins, such as building or urban digital twins, to support more holistic decision-making across the built environment.
In addition, there is potential to extend the decision-support models to include sustainability, resilience, and climate-adaptation criteria.
In the long term, the approach could support cross-jurisdictional comparisons of permitting practices and contribute to harmonisation efforts at national and international levels.

This project demonstrates the potential of Road Digital Twins to support planning and building permitting processes by treating buildings and roads as interconnected built assets. By developing structured information packages, semantic models, and decision-support concepts, the project addresses key challenges in current permitting practices, including fragmentation, uncertainty, and limited data reuse.
The results show that integrating RDTs into permitting workflows can improve transparency, coordination, and efficiency while maintaining human oversight and regulatory discretion. Beyond short-term efficiency gains, the approach supports more sustainable and resilient infrastructure and development decisions.
Overall, the project contributes both scientific insights and practical foundations for the future integration of digital twins into regulatory processes, making it highly relevant for industry, public authorities, and research communities engaged in FUTUREROADS initiatives.

AN LLM-DRIVEN MULTI-AGENT FRAMEWORK FOR ENHANCING HUMAN-DIGITAL TWIN INTERACTION IN BUILT INFRASTRUCTURE MANAGEMENT

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Digital twins (DTs) have significant potential for built infrastructure management, but their adoption is limited by GUI-based interaction modes that impose steep learning curves, rigid workflows, and high cognitive load. This research proposes an LLM-driven multi-agent system (MAS) as an alternative human-DT interaction paradigm. A Leader Agent, supported by a Reasoning Agent, coordinates specialized agents to orchestrate DT functions through natural language. A proof-of-concept prototype, HighwayMAS, was evaluated with 18 highway experts. Results show significant reductions in cognitive workload and improvements in task performance, usability, and user experience, enabling effective DT use even by novice users.

Scientific concept and goals

The scientific concept underpinning this research is that the effectiveness and societal value of digital twins (DTs) for built infrastructure management are fundamentally constrained not by sensing, modeling, or analytics capabilities, but by the limitations of human-DT interaction. Existing DT systems predominantly rely on graphical user interfaces (GUIs), which encode rigid workflows, demand extensive system-specific expertise, and impose high cognitive workload, thereby limiting accessibility, adaptability, and real-world adoption. This research advances the hypothesis that large language model (LLM)-driven multi-agent systems (MAS) can serve as a new interaction layer that fundamentally redefines how humans engage with DTs. By enabling natural language interaction, task decomposition, and autonomous orchestration of heterogeneous DT functions, MAS can transform DTs from tool-centric systems into human-centered, adaptive decision-support partners.

The primary goal of this research is to develop a generalizable LLM-driven MAS framework that augments existing DT architectures to support intuitive, flexible, and context-aware human-DT interaction. Specifically, the research aims to (1) design a hierarchical agent architecture in which a coordinating Leader Agent, supported by structured reasoning mechanisms, dynamically decomposes user intents and orchestrates specialized agents to interact with DT APIs; (2) integrate human-in-the-loop safeguards to ensure transparency, accountability, and safe execution of critical operations; and (3) empirically evaluate the framework through a proof-of-concept DT application in highway infrastructure management. Through controlled experimental validation, the research seeks to quantify improvements in task performance, cognitive workload, usability, and accessibility compared to conventional GUI-based interaction modes. Ultimately, this work aims to establish MAS-driven interaction as a foundational paradigm for lowering entry barriers, democratizing access to DT technologies, and enabling more effective and trustworthy human–infrastructure collaboration across complex, data-intensive infrastructure systems.

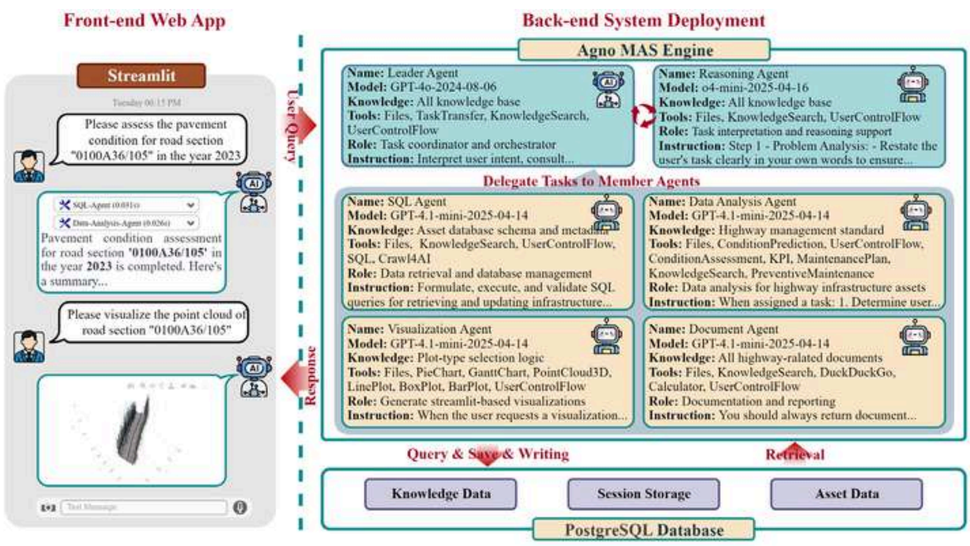

Fig 1. System architecture of the developed HighwayMAS prototype.

Summary of the work carried out

This research investigated how large language model (LLM)-driven multi-agent systems (MAS) can enhance human-digital twin (DT) interaction in built infrastructure management. The work was motivated by the observation that, despite rapid advances in sensing, modeling, and analytics, the practical adoption and effectiveness of DTs remain constrained by conventional graphical user interface (GUI)–based interaction modes. These interfaces impose steep learning curves, rigid workflows, and high cognitive workload, particularly in complex and time-critical infrastructure management tasks. The overarching aim of the research was to develop, implement, and validate a new interaction paradigm that enables more intuitive, adaptive, and human-centered engagement with DT systems.

The first phase of the work focused on conceptual development and system design. A generalizable LLM-driven MAS framework was proposed, positioned as an additional abstraction layer on top of existing DT architectures. Within this framework, a hierarchical agent structure was designed, consisting of a Leader Agent responsible for task orchestration, a dedicated Reasoning Agent to support structured multi-step planning, and multiple specialized Member Agents that interact directly with DT application programming interfaces (APIs). The framework was designed to support natural language interaction, dynamic task decomposition, agent collaboration, and autonomous workflow orchestration, while maintaining compatibility with existing DT databases, analytical functions, and services.

The second phase involved the development of a proof-of-concept prototype, termed HighwayMAS, for highway infrastructure management. A mirrored DT environment was implemented to replicate the functionalities of a real-world highway DT platform, including asset databases, condition assessment tools, predictive models, and visualization modules. The MAS was integrated with this environment using tool-calling mechanisms, agentic retrieval-augmented generation (RAG) for domain knowledge access, and session memory for maintaining conversational continuity. To address safety and trust concerns, human-in-the-loop (HITL) mechanisms were incorporated, requiring explicit user confirmation before executing high-impact actions such as database updates or intervention planning.

The third phase focused on empirical evaluation. A mixed-design laboratory experiment was conducted with 18 highway infrastructure experts, including participants with and without prior DT experience. Participants completed a set of representative highway management tasks using both the traditional GUI-based DT interface and the developed HighwayMAS. Performance was evaluated across multiple dimensions, including task completion time, correctness, cognitive workload (NASA-TLX), usability (System Usability Scale), and subjective preference. The results demonstrated that the MAS-driven interaction significantly reduced cognitive workload, improved task efficiency and accuracy, and enhanced overall usability and user experience. Notably, participants without prior DT experience were able to complete complex tasks successfully using HighwayMAS, highlighting its potential to lower entry barriers and democratize access to DT technologies.

Finally, qualitative feedback was analyzed to identify limitations and future research directions. While participants strongly favored the MAS-driven interaction for efficiency and ease of use, concerns were raised regarding transparency, trust, and confidence in LLM-generated outputs. These findings informed recommendations for future work, including hybrid interaction modes that combine MAS adaptability with GUI visual transparency, improved explainability of agent reasoning, and expanded multimodal interaction capabilities. Overall, the work establishes LLM-driven MAS as a promising and rigorously validated paradigm for advancing human-centered digital twin systems in built infrastructure management.

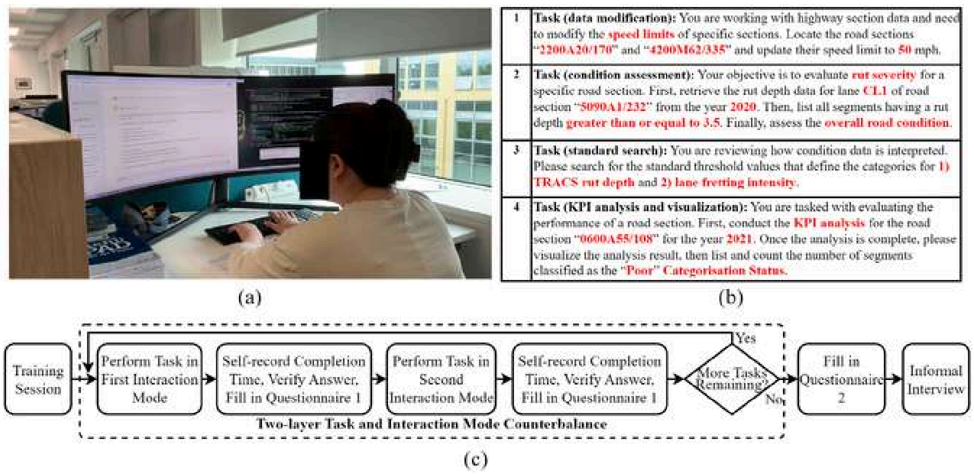

Fig 2. Mixed-design experiment for performance evaluation: (a) experimental setup and environment, (b) experimental tasks, and (c) experimental procedure.

Major outcomes and significance

This research delivers several significant outcomes that collectively advance the state of the art in digital twin (DT)–enabled infrastructure management and human–machine interaction. The most important outcome is the demonstration that large language model (LLM)–driven multi-agent systems (MAS) can fundamentally overcome long-standing limitations of conventional graphical user interface (GUI)–based DT interaction. By shifting the interaction paradigm from rigid, system-centered workflows to adaptive, natural language–driven task orchestration, the research establishes MAS as a viable and effective human-centered interface for complex DT systems.

A primary scientific outcome is the development of a generalizable MAS framework that integrates seamlessly with existing DT architectures without requiring extensive system redesign. The framework introduces a hierarchical agent structure in which a coordinating Leader Agent, supported by structured reasoning mechanisms, dynamically decomposes user intents and orchestrates specialized agents to interact with heterogeneous DT functions through APIs. This architectural contribution provides a principled way to manage complexity, scalability, and reasoning in LLM-enabled DT systems, addressing critical limitations of single-agent approaches such as context window constraints, tool-selection errors, and lack of modularity.

From a practical perspective, the research demonstrates measurable and substantial improvements in DT usability and effectiveness through rigorous experimental validation. The proof-of-concept prototype, HighwayMAS, significantly reduced cognitive workload, task completion time, and user effort while improving task accuracy and overall usability compared to a widely used GUI-based DT platform. Importantly, participants without prior DT experience achieved performance comparable to experienced users when using the MAS-driven interface. This finding highlights a key societal and industrial significance: MAS-based interaction can lower training requirements, reduce dependence on specialist expertise, and broaden access to DT technologies across diverse stakeholder groups.

Another major outcome concerns human factors and trust. While MAS-driven interaction was strongly preferred for efficiency and ease of use, the research identified transparency, explainability, and user confidence as critical challenges. By explicitly integrating human-in-the-loop (HITL) confirmation mechanisms and structured reasoning workflows, the study provides concrete design principles for balancing autonomy and human oversight in AI-driven DT systems. These insights contribute to the emerging discourse on trustworthy AI and human–AI collaboration, particularly in safety-critical infrastructure contexts.

The broader significance of this work extends beyond highway infrastructure management. The proposed MAS framework is domain-agnostic and can be applied to other built infrastructure systems, such as bridges, tunnels, buildings, and utilities, as well as to other complex cyber–physical systems that rely on DTs. By demonstrating how LLMs can be safely and effectively embedded into DT workflows, this research contributes to the digital transformation of infrastructure management, enabling more responsive, inclusive, and resilient decision-support systems.

In summary, this research advances both theory and practice by redefining human–DT interaction through LLM-driven MAS. It provides a validated pathway for making DT systems more accessible, adaptive, and trustworthy, with significant implications for infrastructure operations, workforce development, and the long-term adoption of intelligent infrastructure technologies.

Future directions

Future research will focus on enhancing the transparency, trustworthiness, and interaction richness of LLM-driven multi-agent digital twin systems. A key direction is the development of hybrid interaction modes that tightly integrate MAS-driven natural language reasoning with graphical user interfaces, enabling users to visualize intermediate reasoning steps, data sources, and model outputs in real time. This integration aims to improve explainability, user confidence, and oversight, particularly for safety-critical infrastructure decisions. Further work will also explore multimodal interaction, including voice and gesture-based inputs, to reduce interaction friction and support time-critical scenarios such as emergency response. From a system perspective, research will investigate adaptive agent learning, where agents refine behavior based on user feedback and operational outcomes while maintaining strict human-in-the-loop control. Finally, large-scale field deployment and longitudinal studies across different infrastructure domains will be pursued to evaluate scalability, long-term user trust, and organizational impact of MAS-driven digital twin interaction in real-world settings.

This research has demonstrated that large language model (LLM)–driven multi-agent systems (MAS) offer a powerful and practical new paradigm for human–digital twin (DT) interaction in built infrastructure management. By addressing the fundamental limitations of conventional graphical user interface–based interaction, namely steep learning curves, rigid workflows, and high cognitive workload, the proposed MAS framework enables more intuitive, adaptive, and human-centered engagement with complex DT systems. Through natural language interaction, structured reasoning, and autonomous orchestration of heterogeneous DT functions, the framework allows users to focus on decision-making rather than system operation.

The proof-of-concept prototype, HighwayMAS, and its rigorous experimental evaluation provide strong empirical evidence of the benefits of MAS-driven interaction. Results show significant improvements in task performance, usability, and user experience, alongside substantial reductions in cognitive workload. Notably, the ability of participants without prior DT experience to successfully complete complex tasks highlights the framework's potential to lower entry barriers and democratize access to DT technologies.

At the same time, the study underscores the importance of transparency, explainability, and human oversight in LLM-enabled systems. By integrating human-in-the-loop mechanisms and structured reasoning, this work offers concrete design principles for developing trustworthy and safe MAS-driven DTs. Overall, the research establishes a validated foundation for advancing human-centered digital twin systems and paves the way for broader adoption of intelligent, AI-enabled infrastructure management solutions.

CONSTRUCT AND MAINTAIN A HIGHWAY DIGITAL TWIN FROM MULTI-MODAL DATA

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This project aims to automate digital twin construction and maintenance using Artificial Intelligence (AI) methods applied to multi-modal data, including laser-scanned point clouds, RGB images, thermal images, and ground-penetrating radar (GPR) data. Leveraging the capabilities of deep learning in processing these data, the project introduces an automated approach to developing highway digital twins, mitigating costs and human involvement.

Scientific concept and goals

The goals of this research encompass: a) contributing a registered and annotated multi-modal dataset and trained deep learning models to the research community; b) introducing an automated approach to developing highway digital twins, mitigating costs and human involvement; and c) facilitating industry advancements through the integration of digital twins in real-world applications, enhancing maintenance procedures, optimising planning and construction processes, and monitoring asset conditions.

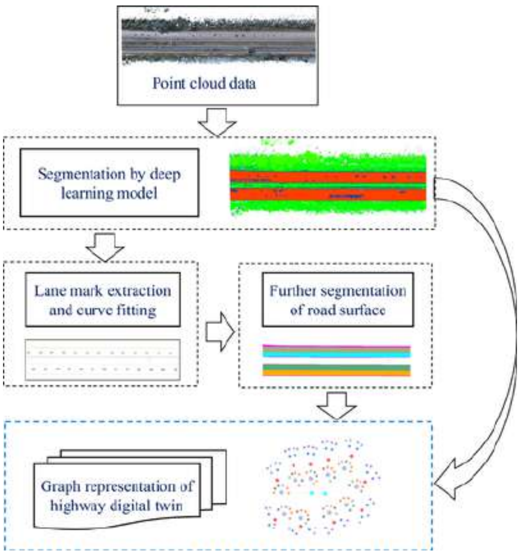

Fig 1. Proposed Scan-to-Graph pipeline for constructing graph representations of digital twins

Summary of the work carried out

Ground-penetrating radar (GPR) is a widely used non-destructive sensing technique for subsurface inspection in civil and transportation engineering. One part of my work contributes a practical dataset creation method and a high-performing deep learning framework, providing an opportunity for more accurate and automated GPR-based road infrastructure assessment.

We proposed an automatic approach extracts geometric and object category information from point clouds and stores the information in a graph, showing the hierarchical relationships among various components and offering the potential for expansion into more comprehensive digital twins encompassing the entire highway network.

Major outcomes and significance

This research delivers two major methodological and conceptual contributions to the intelligent assessment and digital representation of transportation infrastructure. The first major outcome is the development of a practical dataset creation pipeline and a high-performing deep learning framework for ground-penetrating radar (GPR)-based road infrastructure assessment. GPR is widely recognised as a powerful non-destructive sensing technology for subsurface inspection; however, its broader adoption has been constrained by the lack of large-scale, well-annotated datasets and the reliance on expert-driven interpretation. This work addresses both challenges by proposing a systematic and scalable method for constructing GPR datasets that balance practical feasibility with learning effectiveness. The resulting framework enables automated feature extraction and condition assessment from raw GPR signals, significantly reducing manual effort while improving consistency and accuracy. From an engineering perspective, this contributes directly to more reliable detection of subsurface anomalies, supporting proactive maintenance strategies and enhanced road safety.

Beyond the dataset and model performance improvements, the proposed GPR-based framework demonstrates the feasibility of integrating deep learning into operational infrastructure inspection workflows. By emphasising automation, robustness, and generalisability, the work advances GPR analysis from a largely interpretive practice toward a data-driven and repeatable process. This shift has important implications for transportation agencies, as it lowers the technical barrier to large-scale deployment and enables more frequent, objective assessments of road conditions. In the broader context of intelligent infrastructure management, the framework represents a step toward real-time or near-real-time subsurface monitoring supported by artificial intelligence.

Fig 2. Point cloud of one road section

The second major outcome lies in the development of an automatic approach for extracting geometric and semantic object information from point clouds and organising this information into a graph-based representation. Unlike conventional point cloud processing methods that focus primarily on geometry or isolated object detection, this approach captures hierarchical relationships among infrastructure components. By encoding spatial structure, object categories, and topological relationships in a graph, the proposed method provides a structured and machine-interpretable representation of complex road environments. This representation supports not only analysis and querying but also downstream reasoning tasks, such as component-level assessment and network-scale inference.

The significance of this contribution extends beyond standalone modelling. The graph-based representation establishes a foundation for expanding toward comprehensive digital twins of highway networks, where surface assets, subsurface conditions, and contextual information can be integrated within a unified data structure. Such digital twins have the potential to transform infrastructure management by enabling holistic analysis across spatial scales and asset types. By bridging unstructured sensing data (e.g., point clouds and GPR measurements) with structured knowledge representations, this research advances the state of the art in data integration for civil infrastructure systems. Collectively, the outcomes contribute to more intelligent, scalable, and interpretable approaches for monitoring, modelling, and managing transportation infrastructure.

Future directions

Future research can build upon this work in several important directions. For GPR-based assessment, extending the dataset to cover a wider range of pavement structures, environmental conditions, and deterioration mechanisms would further improve model robustness and transferability. The integration of multi-sensor data, such as combining GPR with surface imagery or LiDAR, also presents an opportunity to enhance subsurface interpretation through complementary information.

For the graph-based point cloud framework, future efforts can focus on scaling from local road segments to city- or network-level representations, enabling system-wide digital twins of transportation infrastructure. Incorporating temporal data would allow the graph to capture asset evolution and degradation over time, supporting predictive maintenance and lifecycle analysis. Additionally, coupling the graph representation with reasoning or decision-support modules could further strengthen its role in intelligent infrastructure management systems.

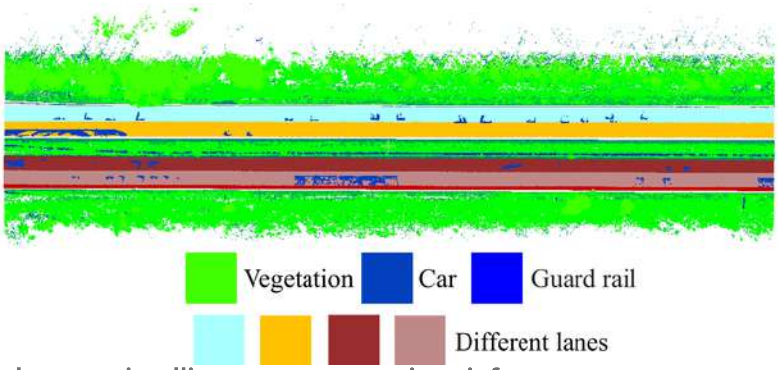

Figure 3. Semantic segmentation of point cloud data

This research advances intelligent transportation infrastructure assessment through the combined use of non-destructive sensing, deep learning, and graph-based modelling. By addressing key limitations in GPR data availability and interpretation, the proposed dataset creation method and learning framework enable more accurate, automated, and scalable subsurface road condition assessment. This contribution supports a shift toward data-driven inspection practices that reduce reliance on manual expertise while improving reliability and consistency.

In parallel, the automatic extraction of geometric and semantic information from point clouds and its organisation into a hierarchical graph representation provides a structured foundation for understanding complex road environments. By explicitly modelling relationships among infrastructure components, this approach moves beyond isolated object detection toward system-level representation and reasoning.

Together, these contributions bridge sensing, data representation, and intelligent analysis, aligning with the broader vision of digital twins for transportation infrastructure. The outcomes demonstrate how advanced data-driven methods can support safer, more resilient, and more sustainable infrastructure systems, while the proposed future directions highlight clear pathways for extending this work toward large-scale, integrated, and operational digital twin platforms.

ESTABLISHING ASSET INFORMATION REQUIREMENTS FOR ROAD DIGITAL TWINS

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Road Digital Twins (RDTs) have emerged as a critical enabler for data-driven asset management across the lifecycle of highway infrastructure. However, their effectiveness is fundamentally constrained by poorly defined and fragmented Asset Information Requirements (AIRs). This work establishes a structured framework for defining, organising, and operationalising AIRs for road digital twins, explicitly aligned with maintenance objectives and decision-making processes. The framework links asset types, maintenance stages, influencing factors, and multi-scale information needs across geometry, condition, and performance domains. By bridging gaps between data collection, analysis, and actionable insights, the proposed approach supports scalable, interoperable, and purpose-driven digital twins for efficient, resilient, and sustainable road infrastructure management.

Scientific concept and goals

The scientific concept underpinning this work is that Road Digital Twins (RDTs) can only deliver operational value when they are driven by explicit, well-structured, and purpose-oriented Asset Information Requirements (AIRs). While digital twins are often framed as high-fidelity virtual replicas, their effectiveness in road asset management depends far less on geometric detail and far more on what information is captured, at what resolution, at which lifecycle stage, and for which decision-making purpose. This research therefore shifts the focus from technology-centric digital twin development to information-centric digital twin design.

The core concept is to treat AIRs as the backbone of road digital twins, systematically linking management objectives—such as safety, serviceability, resilience, sustainability, and cost efficiency—to data requirements across the maintenance lifecycle. Rather than assuming that "more data is better," the work argues for minimum sufficient information: information that is decision-relevant, scalable, interoperable, and economically justifiable. This is achieved by structuring AIRs across multiple spatial and temporal scales (macro, meso, and micro), and aligning them with key maintenance stages including data collection, condition assessment, prioritisation, planning and resource allocation, execution, and quality control.

The primary scientific goal of this work is to establish a transferable framework for defining, evaluating, and fulfilling asset information requirements for road digital twins. This framework aims to bridge the gap between strategic asset management goals and operational digital twin implementations. A secondary goal is to demonstrate how these AIRs can be operationalised using real-world sensing technologies (e.g., LiDAR, imagery), geospatial data models, and analytical workflows, ensuring that digital twins remain actionable rather than static repositories.

Ultimately, the research seeks to contribute a decision-driven paradigm for road digital twins, enabling infrastructure owners and operators to design digital twins that are fit-for-purpose, scalable across networks, and capable of supporting long-term, sustainable road maintenance strategies.

Summary of the work carried out

This body of work focuses on establishing information-centric foundations for Road Digital Twins (RDTs), with a particular emphasis on defining, structuring, and operationalising Asset Information Requirements (AIRs) for effective road asset maintenance and management. The research collectively addresses a critical gap in current digital twin implementations, where technological capabilities often outpace clarity on what information is actually required to support engineering and management decisions.

The first strand of the work concentrates on the systematic identification and structuring of AIRs for road digital twins. Here, road maintenance is decomposed into six core lifecycle stages—data collection, condition assessment, prioritisation, planning and resource allocation, execution of maintenance activities, and quality control and monitoring. For each stage, key influencing factors are identified, and the corresponding information requirements are explicitly mapped. These requirements span multiple information types, including geometric, condition, semantic, temporal, and contextual data. A key contribution is the articulation of AIRs across macro, meso, and micro scales, ensuring that strategic network-level decisions, corridor-level planning, and asset-level interventions are coherently supported within a single digital twin framework.

The second major strand focuses on roadside vegetation management as a demonstrator use case for information-driven digital twins. Vegetation management represents a complex, cyclic, and safety-critical maintenance activity that is poorly served by traditional inspection regimes. This work introduces a LiDAR-based, geospatially enabled digital twin approach to roadside vegetation management, centred around the concept of Vegetation Free Volume (VFV). High-resolution mobile mapping LiDAR data are processed at scale using chunked point cloud storage, wedge-based spatial querying, and geometric transformations aligned to locally straight road segments. These methods enable automated detection of vegetation encroachment relative to regulatory clearance envelopes.

Beyond static assessment, the vegetation work extends into simulation-based digital twins, where vegetation growth and pruning cycles are modelled over time. Stochastic growth models are applied to point cloud representations, allowing long-term experimentation with inspection frequencies, pruning strategies, and resource allocation policies. The simulation outputs generate actionable reports for field crews and provide a testbed for evaluating maintenance strategies before deployment. This work demonstrates how clearly defined information requirements enable automation, scalability, and predictive maintenance—key promises of digital twins that are often unrealised in practice.

The third strand integrates these contributions into a broader digital twin information requirements perspective, linking sensing technologies (e.g., LiDAR, imagery, mobile mapping), data models, and analytical workflows to decision-making needs. Rather than advocating for high-fidelity models by default, the research emphasises minimum sufficient information—data that is fit-for-purpose, interoperable, and economically viable. This principle is shown to reduce computational burden, improve scalability across large road networks, and enhance trust in digital twin outputs.

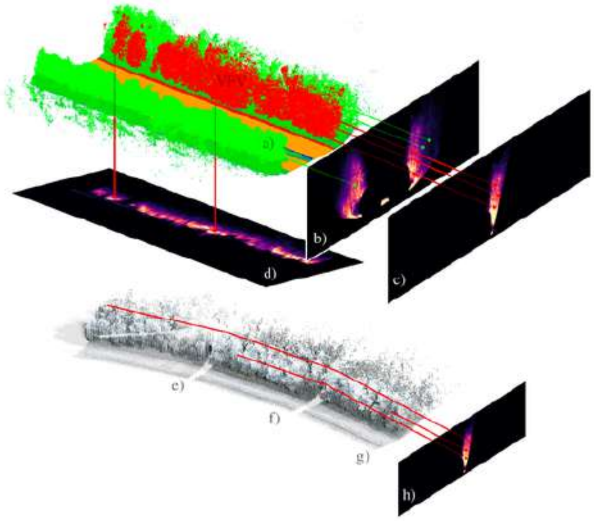

Fig 1. Vegetation Density Integrals for 3D Computer Vision Approach for Roadside Vegetation Management

Major outcomes and significance

This research delivers three interlinked outcomes that collectively advance the theory and practice of Road Digital Twins (RDTs): (i) a rigorous, decision-oriented framework for Asset Information Requirements (AIRs), (ii) a scientifically grounded and computer vision–enabled approach to roadside vegetation management, and (iii) a structured articulation of pavement-specific information requirements. Together, these outcomes reposition digital twins as information-led decision support systems rather than technology-driven visualisations.

- The primary outcome is a transferable AIRs framework that systematically connects asset management objectives to data needs through explicit decision nodes. Road maintenance is decomposed into six lifecycle stages—data collection, condition assessment, prioritisation, planning and resource allocation, execution, and quality control and monitoring. For each stage, the framework identifies influencing factors (e.g., safety risk, regulatory thresholds, traffic exposure, deterioration mechanisms, resource constraints) and translates them into stage-specific information requirements. Crucially, the framework embeds decision nodes—points at which information directly supports an operational or strategic choice (e.g., intervene vs. defer, inspect vs. monitor, prune vs. reschedule). This structure enables the principle of minimum sufficient information, ensuring that only decision-relevant data are captured at the appropriate spatial (macro–meso–micro) and temporal resolutions. The significance lies in providing infrastructure owners with a defensible basis for designing scalable, interoperable, and economically justifiable digital twins.

- Scientific and computer vision–based roadside vegetation management: The second major outcome is a novel, operationally validated digital twin approach for roadside vegetation management, a domain that is cyclic, safety-critical, and under-served by traditional inspection practices. The work introduces the concept of Vegetation Free Volume (VFV) and demonstrates how high-resolution mobile LiDAR and computer vision techniques can be combined with geospatial processing to automate encroachment detection. Methodological contributions include chunked point cloud storage, wedge-based spatial querying aligned to road geometry, and geometric transformations that enable scalable analysis across long corridors. Beyond detection, the research advances simulation-enabled digital twins by modelling vegetation growth and pruning cycles stochastically over time, allowing scenario testing of inspection frequencies, intervention strategies, and crew allocation. This outcome is significant because it translates AIRs into an end-to-end, data-driven maintenance workflow that improves safety, reduces manual inspection burden, and supports predictive, rather than reactive, management. a clear pathway for integrating pavement management into broader RDT architectures. The significance here is the alignment of pavement engineering knowledge with digital twin design, ensuring consistency between physical behaviour, data collection strategies, and decision-making needs.
- Pavement information requirements: The third outcome is the explicit articulation of pavement AIRs, structured around deterioration mechanisms, performance indicators, and intervention thresholds. The work identifies how geometric, condition, material, traffic, and environmental information should be combined across scales to support decisions such as maintenance prioritisation, treatment selection, and performance monitoring. By linking pavement AIRs to sensing modalities (e.g., imagery, LiDAR-derived surface metrics) and lifecycle stages, the research provides a clear pathway for integrating pavement management into broader RDT architectures. The significance here is the alignment of pavement engineering knowledge with digital twin design, ensuring consistency between physical behaviour, data collection strategies, and decision-making needs.

Future directions

Future research will extend this work toward automated and adaptive digital twin design, where Asset Information Requirements (AIRs) are dynamically updated in response to changing asset conditions, operational priorities, and policy objectives. A key direction is the integration of AI-driven decision support, enabling digital twins to learn from historical interventions and continuously refine inspection frequencies, intervention thresholds, and resource allocation strategies.

Further work will focus on multi-asset integration, combining pavements, roadside vegetation, structures, and drainage within a unified road digital twin, supported by interoperable information models and common decision nodes. Scaling the framework to network-level and national digital twins will require advances in data governance, uncertainty quantification, and information security.

This work demonstrates that the true value of Road Digital Twins lies not in increasing model fidelity, but in defining and fulfilling the right information at the right time for the right decisions. By placing Asset Information Requirements (AIRs) at the centre of digital twin design, the research provides a coherent, decision-driven framework that systematically links asset management objectives to data collection, analysis, and intervention across the maintenance lifecycle.

The proposed AIRs framework, structured around lifecycle stages, influencing factors, and explicit decision nodes, offers a transferable and scalable approach for designing fit-for-purpose digital twins. Its practical relevance is demonstrated through the development of a scientifically grounded, computer vision–enabled digital twin for roadside vegetation management, where clearly defined information requirements enable automated detection, simulation of growth and pruning cycles, and predictive maintenance planning. The articulation of pavement-specific information requirements further illustrates how traditional engineering knowledge can be operationalised within modern digital twin architectures.

Overall, this research advances road digital twins from technology-led visualisation tools to trustworthy, information-led decision support systems. By emphasising minimum sufficient information, interoperability, and lifecycle alignment, the work lays a robust foundation for scalable, sustainable, and actionable digital twins capable of supporting long-term road asset management and infrastructure resilience.

AN UNCERTAINTY-AWARE ROAD GEOMETRIC DIGITAL TWIN USING MULTI-MODAL DATA

Dr Shirin Malihi
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FUTUREROADS Fellow

This project develops an uncertainty-aware road digital twin that fuses multimodal sensing—image-derived and laser-scanned point clouds—to represent road geometry and assets with measurable confidence. Beyond building a detailed 3D road model, the work quantifies uncertainty in the twin's underlying point cloud and studies how that uncertainty affects downstream road-asset detection. The central aim is to use confidence estimates to improve detection performance and reliability, particularly for safety-critical assets that are rare or appear in complex, co-occurring configurations, including challenging aerial mapping scenarios.

Scientific concept and goals

The project focuses on developing uncertainty-aware road digital twins—digital representations of road infrastructure that not only capture what assets exist and where they are, but also how confident the system is about them. By treating the twin as a probabilistic model, the research integrates multimodal sensing data (vision-derived and laser-derived point clouds) to build and maintain accurate, dynamic road twins. The central idea is to explicitly model and quantify confidence across both geometry and asset layers, using these uncertainty estimates to enhance the detection and interpretation of safety-critical road assets, particularly in challenging scenarios such as rare objects, co-occurring assets, and
complex or degraded sensing conditions. The overarching goal is to make road digital twins more reliable for safety-relevant decisions, enabling them to attach trust scores to detected assets, flag uncertain regions for verification, and support downstream applications—such as maintenance planning, inspection, and risk monitoring—with transparent and quantifiable reliability rather than blind confidence.

Summary of the work carried out

The work began with a focused literature review to establish a solid theoretical and methodological baseline for building road digital twins from multimodal data. This step mapped out how 3D sensing and vision data are commonly fused in practice, what "good" fusion looks like for road environments, and which assumptions typically underpin digital-twin pipelines. The outcome was a clearer framework for comparing image-based and laser-based 3D reconstruction, and for defining where uncertainty enters the chain.

Next, 3D geometry was synthesized through point cloud generation from images, using image-based reconstruction approaches such as photogrammetry and SfM–MVS-style pipelines, along with visual SLAM (V-SLAM). This established a passive-sensing route to produce point clouds from imagery, enabling scalable 3D capture without dedicated active sensors.

In parallel, point cloud generation from laser scanning was studied, focusing on laser-scanning fusion and multiple variants of SLAM-based workflows. This provided an active-sensing counterpart to the image-derived pipeline, supporting comparison in terms of geometric fidelity, robustness to lighting/texture issues, and performance in complex road scenes.

A major component of the work then shifted to uncertainty analysis for synthesized (image-derived) point clouds. The goal was to quantify confidence levels of the detected road assets. This step linked reconstruction uncertainty to the practical question: "How trustworthy is a detection result using different types of point clouds?"

Similarly, uncertainty analysis for laser-based point clouds examined how uncertainty propagates downstream to road asset detection, with particular attention to difficult scenarios such as rare asset classes and co-occurring assets (e.g., clusters of signs, markings, barriers, and poles in close proximity), especially in aerial point clouds where viewpoint and density patterns can be challenging. This analysis aimed to determine not only where detection fails, but whether high-confidence predictions are genuinely reliable.

Overall, the work is centered on leveraging confidence estimates to improve detection performance, especially for safety-relevant road assets that are rare or appear in complex co-occurrence patterns. The key idea is that explicitly modeling confidence can support better decision-making: prioritizing dependable detections, flagging uncertain outputs for review, and ultimately improving robustness where mistakes carry higher safety cost.

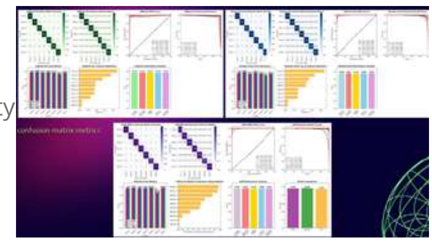


Fig 1. Confusion matrixbased quality metrics for 3 ML methods of SVM, XGBoost, Random Fores

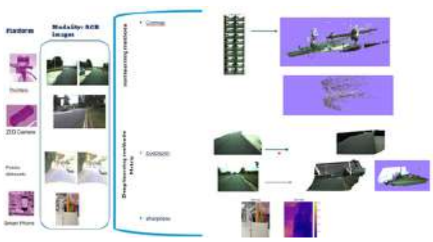


Fig 2. . A summary of synthesized image drived point cloud

Major outcomes and significance

This project establishes a rigorous methodological baseline for road digital twins (RDTs), transforming them from simple geometric replicas into high-integrity, reliability-aware infrastructure models. By integrating multimodal data—specifically through image-based (photogrammetry/V-SLAM) and laser-based (LiDAR/SLAM) pipelines—the work defines a standardized framework for geometric fidelity, completeness, and asset-level usability.

Key Outcomes

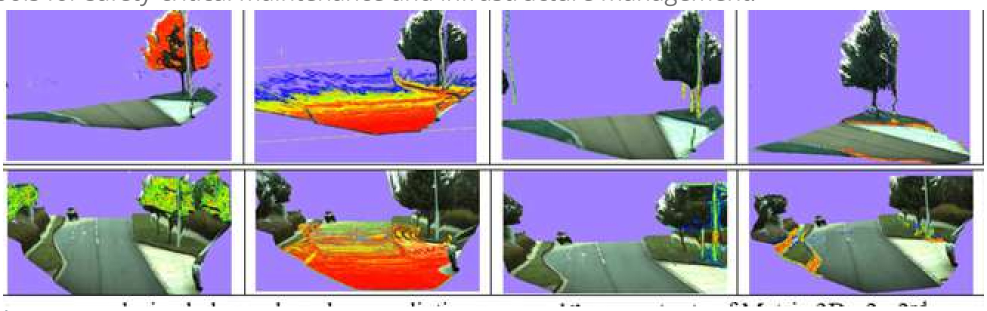
- Operational Multimodal Pipelines: The project developed two distinct paths for populating the RDT. The image-based route leverages passive sensing for scalable 3D capture, while the laser-based route provides active-sensing robustness. Together, they allow for a comparative evaluation of sensing regimes across diverse environmental conditions.
- Integrated Uncertainty Quantification: A core achievement is the creation of a "trust layer" for 3D point clouds. By quantifying how noise, occlusion, and point density propagate into asset detection, the framework identifies reliable regions versus those likely to cause errors.
- Confidence-Centered Detection: The focus shifts from simple detection to reliability-aware perception. By using confidence estimates, the system significantly improves the detection of rare or safety-critical assets that often drive errors in traditional models.

The significance of this work lies in its ability to bridge the gap between research-grade perception and deployable road monitoring. By adding a dimension of "trust" to the digital twin, the project enables:

- Smarter Decision-Making: Road authorities can flag uncertain detections for human review and prioritize re-surveying in low-confidence zones.
- Increased Robustness: The system reduces false positives/negatives in crowded or ambiguous scenes where conventional detectors typically fail.
- Defensible Sensing Strategies: It provides a common lens to evaluate passive vs. active sensing, helping agencies make risk-informed investments in data collection.

Ultimately, this research ensures that road digital twins are not just visual models, but traceable, dependable tools for safety-critical maintenance and infrastructure management.

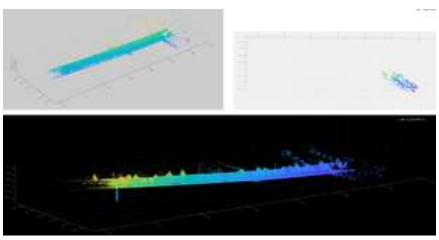
Fig 3. A summary of synthesized image-drived point clouds



Future direction

Future work will focus on turning confidence into a direct control signal for detection and validation inside the road digital twin. The next step is to improve detection methods that explicitly use per-point/per-region confidence. A dedicated emphasis will be placed on rare and co-occurring road assets by combining confidence-driven sampling, class-imbalance mitigation, and scenario-specific evaluation protocols. The twin will also be extended to monitor confidence over time, enabling automated alerts when asset changes are detected

Fig 4. Registration of different types of image-drived point clouds



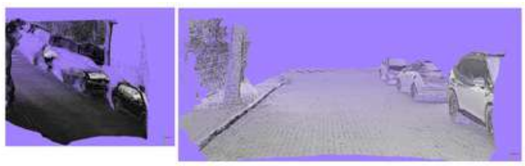


Fig 5. . Monocular point clouds of new image-drived modalities

This project demonstrates that a road digital twin should be treated not only as a geometric and semantic representation of road infrastructure, but as a confidence-bearing model whose reliability varies across space, sensing modality, and scene complexity. By establishing multimodal pipelines for populating the twin with image-derived and laser-derived point clouds, and by quantifying uncertainty in each source, the work links the quality of the underlying 3D evidence to downstream road-asset detection performance. The analyses show that uncertainty is a primary driver of failure in challenging conditions—especially for rare assets and co-occurring configurations —and that "high-confidence" detections are not inherently trustworthy unless confidence is properly grounded in the data's geometric reliability. Centering detection on uncertainty therefore provides a principled path to improve robustness, calibration, and decision readiness in digital-twin applications. Overall, the study establishes confidence-aware digital twinning as a scientifically sound approach for safer, more dependable road-asset understanding and monitoring.

EXPLORING THE MINIMUM VIABLE PRODUCT (MVP) OF A DIGITAL TWIN FOR ROAD INSPECTION AND MAINTENANCE

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Highway agencies face challenges managing scattered asset data across maintenance processes and information systems, obstructing efficient retrieval of dynamic cross-system road information for timely interventions. This research project investigate a Digital Twin (DT)-based data federation framework to effectively manage fragmented systems and dispersed data for highway infrastructure operation and maintenance. The DT-based framework provides a federation middleware that can decompose users' queries and request data from different subsystems based on a metadata model and a distributed system architecture. The connected data ecosystem enables dynamic communication between different asset systems, ensuring the data synchronisation, discovery, retrieval, and process coordination for different users and teams. The objectives of this research include (a) develop foundation data models (FDM) and reference data libraries (RDL) to represent a common ontology and metadata models in the federation middleware; (b) design an integration architecture (IA) that supports data sharing and retrieval between different subsystems; (c) implement a prototype of digital twin systems and evaluate the performance based on real-world use cases. The presented framework will be demonstrated based on datasets and synthesised systems conforming to asset management practices adopted by United Kingdom (UK) National Highways.

Scientific concept and goals

1. Design a conceptual framework of road digital twins for highway maintenance.
2. Architecture design and data modeling for digital twins using knowledge representation languages.
3. Implementation of road digital twins integrating key use cases for highway maintenance.
4. Deployment of graph databases, clouds, and APIs to enable future-proofing digital twin systems for highway operation and maintenance.

Summary of the work carried out

This project develops a practical digital twin for road inspection and maintenance that brings together asset information held across different systems without moving or duplicating data. It creates a shared structure that helps organisations understand what each asset is, where the most reliable information is stored, and how assets link to inspections, defects and maintenance works. The digital twin allows users to ask straightforward but important questions, such as which assets need inspection, where problems have been reported, and whether planned works may clash with other activities, and receive clear, joined-up answers. A working prototype has been tested using real road data from industry partners, showing how the approach can reduce manual data checking, improve coordination between teams, and speed up access to information needed for maintenance decisions.

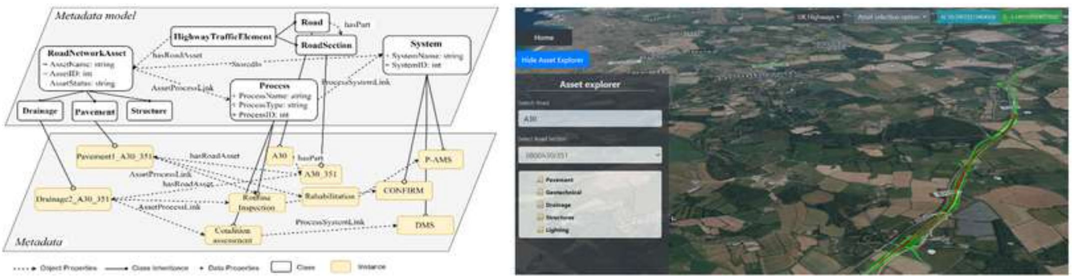


Fig 1. Road Digital Twin Prototype and ontology-based metadata models

Major outcomes and significance

This project delivers important conceptual and practical contributions to the development of digital twins for highway asset management and information interoperability. A key outcome is the design of a DT-based data federation framework that demonstrates how fragmented asset data across multiple legacy systems can be connected dynamically without centralising or duplicating data. By structuring the framework around foundation data models, reference data libraries, and integration architecture, the research provides a reusable conceptual foundation for future infrastructure digital twin systems.

A second major outcome is the development of an ontology-based metadata model that enables semantic consistency and cross-system interoperability. This model provides a shared conceptual layer that allows different asset management systems to be queried and coordinated in a consistent manner, while preserving the autonomy of existing databases. The project demonstrates that knowledge representation techniques can be operationalised to support real maintenance workflows such as asset identification, inspection coordination, defect tracking, and work planning, helping bridge the gap between academic semantic modelling and deployable infrastructure systems.

A further significant outcome is the exploration of LLM agent–based automatic ontology engineering over complex asset databases. The project demonstrates how large language models, orchestrated as task-specific agents, can analyse heterogeneous database schemas, infer domain concepts and relationships, and support the semi-automated construction and refinement of infrastructure ontologies. This significantly reduces the manual effort and specialist expertise traditionally required for ontology development, and provides a scalable pathway for maintaining and evolving semantic models as asset systems change over time.

Overall, the research contributes to advancing digital twins from data visualisation tools towards interoperable, intelligent, and information-centric systems that support complex infrastructure operations. Its outcomes provide a practical pathway for organisations seeking to modernise asset information management while protecting existing investments in legacy systems, and offer transferable insights for other infrastructure sectors facing similar data fragmentation challenges.

Future directions

Future work will extend this research in three directions to enhance the automation and decision-making capability of road digital twins. First, geometric deep learning–based asset model classification will be explored to support digital twin initialisation. Mesh- and graph-based learning methods can enable automated recognition and decomposition of BIM and 3D asset models, improving semantic alignment with asset data standards and reducing manual effort in model preparation.

Second, the project will investigate digital twin updating using UAV and airborne LiDAR data. By integrating multi-source remote sensing data into the digital twin framework, future work will support change detection, condition monitoring, and automated updating of asset states, strengthening the connection between physical assets and their digital representations.

Third, future research will focus on multi-asset maintenance coordination and optimisation using federated road digital twins. By modelling interdependencies between different asset types and incorporating AI-based decision support, the framework can support coordinated maintenance planning that balances cost, risk, disruption, and long-term network performance.

This work proposes a digital twin–driven framework for addressing fragmentation in road asset information systems. By introducing a data federation architecture supported by ontology-based metadata, the research demonstrates how heterogeneous asset databases can be semantically connected without disrupting legacy systems. The study further shows the potential of LLM agent–based ontology engineering to reduce manual effort in building and maintaining semantic models over complex asset schemas. Together, these contributions advance road digital twins from isolated visualisation tools towards interoperable, intelligent information infrastructures. The proposed directions for geometric learning, remote sensing–based updating, and federated optimisation provide a clear pathway for future research and practical deployment.

A GRAPH-BASED APPROACH FOR ROAD DIGITAL TWINNING

Dr Junxiang Zhu
Marie Skłodowska Curie
FUTUREROADS Fellow

This project develops a graph-based digital twin for road infrastructure, modelling roads, assets, traffic, and events as a unified, evolving graph. By integrating BIM, GIS, sensor, and mobility data, the approach captures topology, semantics, and temporal change in a single representation. The resulting digital twin enables advanced querying, real-time analytics, and AI-driven prediction, supporting safer, more efficient road operations and seamless integration with intelligent transport and connected mobility systems.

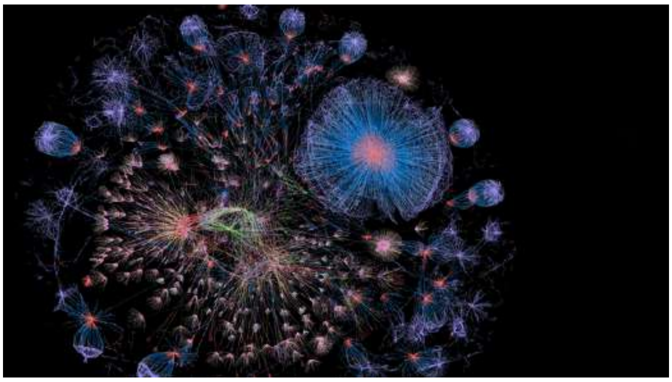
Scientific concept and goals

This project is grounded in the concept of a graph-based digital twin, where road infrastructure, traffic dynamics, sensing systems, and contextual factors are represented as a labelled property graph. Nodes denote physical and logical entities such as road segments, lanes, junctions, assets, sensors, vehicles, and events, while edges encode topological, functional, and causal relationships, including connectivity, directionality, dependency, and interaction. This representation goes beyond traditional BIM- or GIS-centric models by explicitly capturing semantics and network structure, enabling reasoning across infrastructure, mobility, and environment domains. The scientific goal is to establish a unified, evolving graph model that integrates heterogeneous data sources, i.e., BIM, GIS, traffic observations, and real-time sensor streams, within a time-aware framework. The project investigates methods for graph construction, harmonisation, and update, ensuring consistency between historical, real-time, and predictive states of the road system. A further goal is to enable graph-native analytics and AI, including graph queries, pattern discovery, and risk prediction, directly over the digital twin without costly data reshaping.

Summary of the work carried out

The work completed to date has focused on establishing a robust IFC-Graph pipeline that transforms Building Information Modelling data from Industry Foundation Classes (IFC) into a graph-native representation suitable for digital twin applications. A systematic graph generation process was developed to parse IFC entities, relationships, and properties and map them into a labelled property graph. In this process, physical elements (e.g. slabs, spaces, and assets), spatial hierarchies (site-building-storey-space), and semantic constructs (types, materials, and properties) are represented as nodes, while explicit and implicit IFC relationships are encoded as typed edges. This preserves both geometry-linked semantics and relational context while avoiding the rigidity of file-based IFC structures.

A key contribution is the design of the internal graph structure, which separates geometry, semantics, and topology while keeping them coherently linked. Geometry is referenced through lightweight identifiers rather than duplicated meshes, enabling scalable querying and downstream integration with GIS or simulation engines. Semantic enrichment is achieved by normalising property sets and types into reusable nodes, reducing redundancy and improving query efficiency. Temporal and provenance attributes are embedded at node and edge level, laying the foundation for time-aware analysis and versioning.



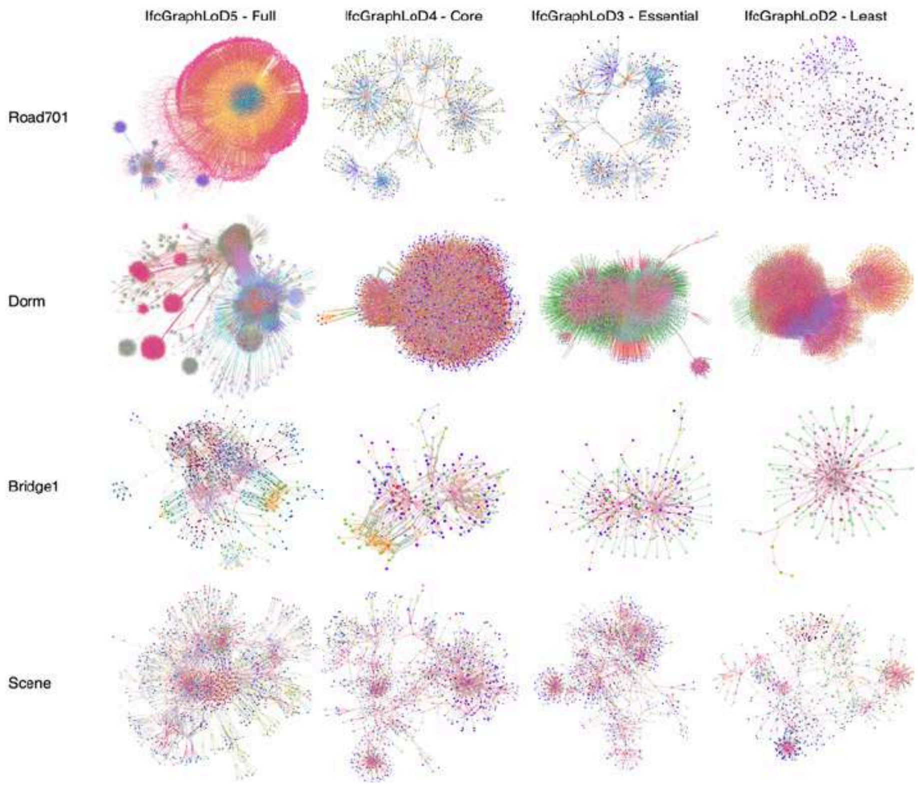
On top of this structure, a suite of graph queries has been developed to validate correctness and demonstrate analytical value. These include hierarchical traversal (e.g. locating all assets within a space or storey), relational reasoning (e.g. identifying elements affected by a modification), and pattern-based queries that combine topology and semantics. Performance experiments indicate that graph-native querying significantly improves flexibility compared with traditional IFC parsing workflows.

Major outcomes and significance

The project delivers a validated IFC-Graph methodology that enables scalable generation, structuring, and querying of BIM data as a graph. Key outcomes include a reusable graph schema, efficient query mechanisms, and a modular internal structure supporting semantic, topological, and temporal analysis. These results demonstrate how graph-based representations overcome limitations of file-centric IFC workflows, enabling flexible reasoning and integration with digital twin platforms. The significance lies in establishing a solid scientific and technical foundation for extending graph-based digital twins beyond buildings to complex infrastructure systems, supporting AI-driven analytics and operational decision-making.

Future directions

Future work will extend the graph-based framework to enable deep integration of BIM, GIS, and AI within a unified digital twin environment. Building- and road-scale IFC-Graphs will be connected with geospatial networks to support seamless multi-scale reasoning from assets to cities. The graph will serve as a common semantic and topological backbone for incorporating machine learning, including graph analytics, predictive modelling, and explainable AI. Additional directions include time-aware graph evolution, uncertainty representation, and interoperability with real-time data streams, enabling adaptive, AI-enabled digital twins for infrastructure planning, operation, and resilience management.



This work advances a graph-based digital twin paradigm for infrastructure by establishing a rigorous IFC-Graph foundation and demonstrating its potential beyond traditional BIM workflows. The project has developed methods for generating semantically rich, queryable graphs from IFC data, with a clear internal structure that separates geometry, semantics, and topology while supporting efficient traversal and reasoning. These results show how graph representations overcome the limitations of file-centric BIM and enable flexible, scalable analytics. Building on this foundation, future work will integrate BIM and GIS within a unified graph and embed AI for prediction, risk analysis, and decision support. Collectively, the research positions graph technology as a core enabler for intelligent, evolving digital twins capable of supporting complex infrastructure systems, from buildings to road networks, within operational and planning contexts.

DIGITAL TWIN-DRIVEN PROBABILISTIC MACHINE LEARNING FOR PREDICTIVE MAINTENANCE OF PAVEMENTS

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Highway agencies face increasing challenges from ageing pavements, deteriorating networks, and constrained maintenance budgets, highlighting the need for effective predictive maintenance strategies. Digital twin (DT) technology offers a promising framework for lifecycle monitoring and decision support; however, current DT-based approaches are limited by data anomalies, computationally expensive black-box models, and inefficient maintenance optimisation. This project proposes a digital twin–driven probabilistic machine learning framework for pavement predictive maintenance by integrating Bayesian dynamic linear models and reinforcement learning. The research will develop automated data anomaly detection and correction, interpretable and uncertainty-aware performance prediction, and an efficient reinforcement learning architecture for maintenance decision-making. The outcomes will support autonomous, reliable, and cost-effective pavement management.

Scientific concept and goals

The scientific concept of this project is to develop an impact-oriented digital twin–driven probabilistic learning framework that enables autonomous, risk-informed predictive maintenance for highway pavements. Ageing pavement infrastructure, increasing traffic demand, and limited maintenance budgets pose significant challenges to highway agencies worldwide, making timely and efficient maintenance decisions critical for ensuring safety, serviceability, and sustainability. While digital twins offer a powerful paradigm for integrating sensing, modelling, and decision-making across the pavement lifecycle, their real-world effectiveness is currently limited by unreliable data, opaque prediction models, and inefficient maintenance optimisation strategies.

This project addresses these challenges by embedding probabilistic machine learning and reinforcement learning within a pavement digital twin, thereby directly supporting actionable maintenance decisions. First, the project will enhance data reliability by developing automated anomaly detection and correction methods that mitigate the impact of noisy, missing, and abnormal monitoring data, ensuring robust digital twin updates. Second, the project will replace computationally intensive black-box models with Bayesian dynamic linear models that provide fast, interpretable, and uncertainty-aware predictions of pavement deterioration and remaining service life. By explicitly quantifying uncertainty, the framework will support risk-informed decision-making and improve confidence in maintenance planning. Third, the project will design an efficient reinforcement learning architecture that integrates probabilistic predictions to optimise maintenance timing and intervention strategies, balancing performance, risk, and lifecycle cost under uncertainty.

The overarching goal is to deliver an autonomous decision-making tool that continuously updates pavement condition assessments and maintenance strategies as new data becomes available. Scientifically, the project advances the integration of digital twins, probabilistic modelling, and learning-based optimisation for infrastructure systems. Practically, it aims to reduce lifecycle costs, improve network-level performance, and enhance the resilience and sustainability of highway infrastructure. The outcomes will provide tangible benefits for transport agencies and foster long-term collaboration between academia and infrastructure stakeholders.

Summary of the work carried out

I conducted independent research on probabilistic modelling for pavement performance prediction, aiming to improve the reliability, efficiency, and decision relevance of pavement management systems. The work addressed a critical challenge faced by highway agencies worldwide: how to predict pavement deterioration accurately under uncertainty while maintaining computational efficiency suitable for large-scale road networks. During the fellowship, I developed a Bayesian dynamic modelling framework for probabilistic prediction of pavement condition, with a focus on the International Roughness Index (IRI). Building on Gaussian process regression (GPR), I proposed a dynamic formulation that explicitly accounts for the time-varying and non-stationary nature of pavement deterioration. To overcome the high computational cost associated with conventional GPR, I introduced a moving window strategy that restricts model training to the most informative recent data, enabling efficient model updating as new observations become available. A genetic algorithm was further developed to optimise the window size by balancing prediction accuracy and computational efficiency, ensuring scalability for long-term monitoring applications. Comparative studies against static GPR and both static and dynamic Bayesian linear regression models demonstrated that the dynamic GPR achieved superior predictive accuracy and uncertainty quantification, highlighting its suitability for risk-informed pavement management.

Major outcomes and significance

The main outcomes of this work were disseminated through a peer-reviewed journal paper in Engineering Applications of Artificial Intelligence and an international conference paper presented at the Transport Research Arena. The work laid a clear foundation for my subsequent research on digital twin–enabled predictive maintenance and reinforcement learning–based maintenance optimisation, demonstrating a coherent progression toward autonomous decision-making frameworks for sustainable transport infrastructure.

Future directions

Future research will build directly on the probabilistic modelling framework developed to advance digital twin–enabled predictive maintenance for pavement and broader transport infrastructure systems. The Bayesian dynamic models will be extended to integrate multi-source monitoring data, including traffic, environmental, and structural information, enabling more comprehensive and resilient digital twins. A key direction is the coupling of uncertainty-aware state prediction with reinforcement learning to optimise maintenance timing and intervention strategies under budgetary and performance constraints. This will allow the transition from condition prediction to autonomous, closed-loop decision-making. Future work will also focus on scaling the framework from individual pavement sections to network-level asset management, supporting system-wide optimisation. Methodologically, efforts will be made to enhance model transferability across regions and pavement types, reducing data dependency. These developments aim to deliver deployable decision-support tools that improve lifecycle performance, reduce maintenance costs, and support sustainable, data-driven management of transport infrastructure

By addressing key limitations of existing deterioration models, including non-stationarity, computational inefficiency, and limited uncertainty representation, the work has produced a robust Bayesian dynamic modelling framework suitable for large-scale pavement management applications. The proposed methods demonstrate improved predictive accuracy, efficiency, and interpretability, enabling more reliable and risk-informed assessment of pavement condition. The research outcomes provide a critical foundation for digital twin–enabled predictive maintenance, where uncertainty-aware state estimation supports continuous updating and adaptive planning.

DIGITAL TWIN-DRIVEN STRUCTURAL HEALTH MONITORING OF ROADS BY USING PHYSICS-BASED MODEL AND MACHINE LEARNING

Dr Zhaojie Sun
Marie Skłodowska Curie FUTUREROADS Fellow

Road infrastructure is vital for mobility, economic activity, and social development. Hence, it is necessary to maintain the high service performance of roads, which requires timely and effective maintenance and rehabilitation (M&R) activities. In the process of formulating M&R strategies, an important factor to consider is the structural health information, which is related to the service life of existing roads. However, a technique which can accurately and efficiently provide the structural health information of roads is still missing. This project aims to fill in this gap by combining physics-based modelling and data-driven analysis.

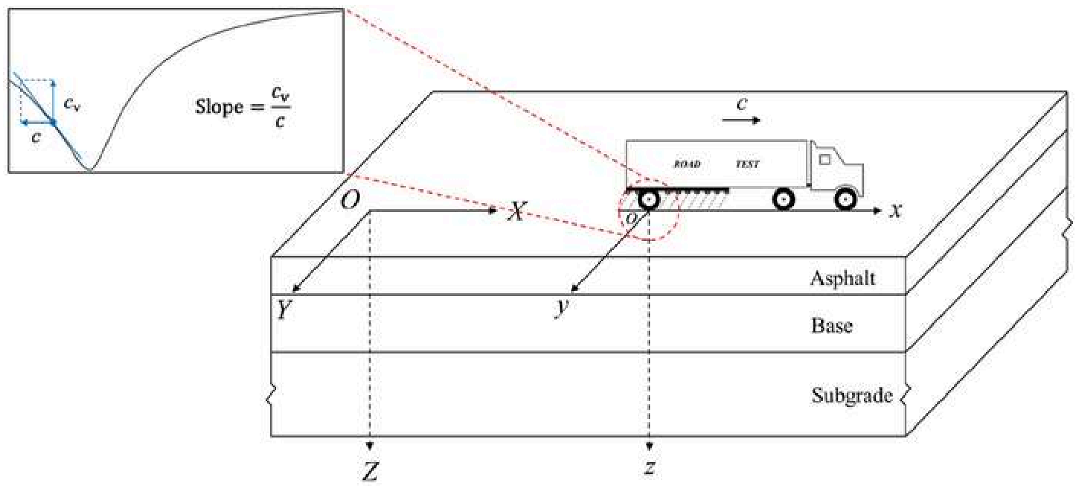
Scientific concept and goals

In this project, a tool which can provide the structural health information of roads in service will be developed, it can be integrated into a digital twin platform of roads to help formulate more informed maintenance and rehabilitation strategies. The key goals are to advance the understanding of pavement response and deterioration mechanism, to enable the reliable evaluation of structural health and the accurate prediction of remaining life, and to provide a scientific basis for predictive, performance-based maintenance and rehabilitation decision-making for road infrastructure.

Fig 1. Traffic Speed Deflectometer (TSD)

Summary of the work carried out

A document which summarises the state-of-the-art information in this field has been prepared. In addition, a theoretical model (named as PaveMove) which can predict the response of pavements caused by moving loads has been developed, and its performance has been validated. This model was further used to investigate the influence of different factors on pavement responses to have a better understanding of pavement behaviours in different scenarios.



Note: The coordinate system $OXYZ$ is stationary, while the coordinate system $oxyz$ moves along with the TSD device.

Fig 2. Theoretical modelling of TSD tests

Major outcomes and significance

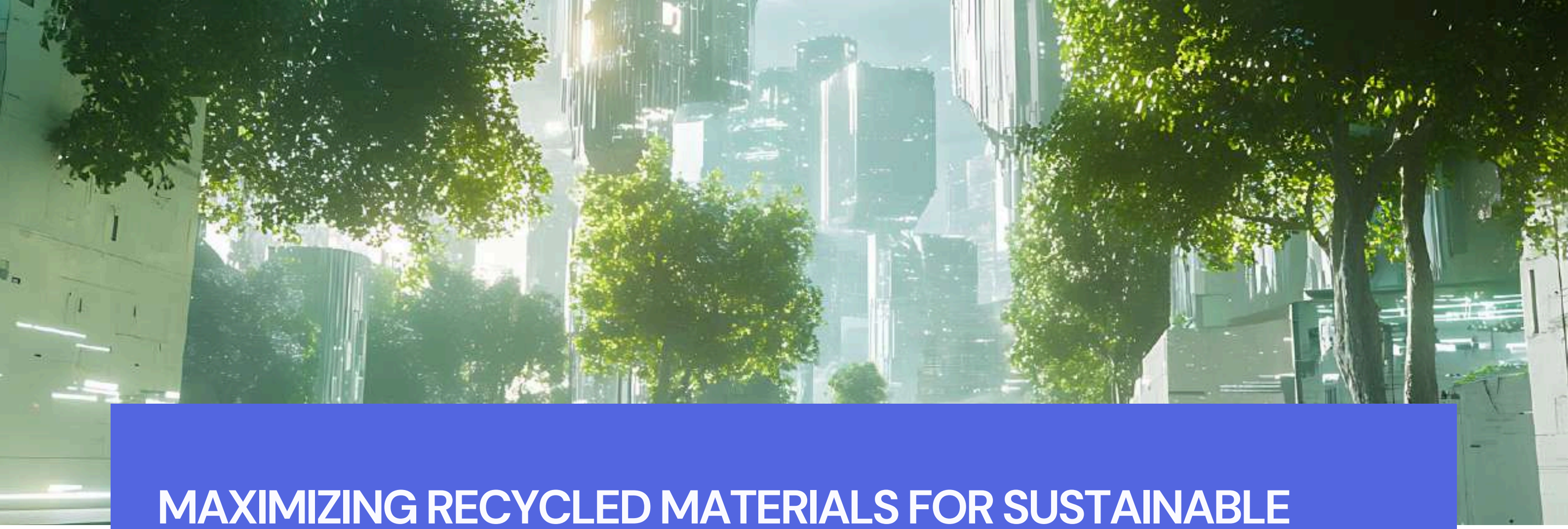
The major outcomes are a state-of-the-art literature review and a theoretical pavement model called PaveMove. The literature review helps us identify what is already known, what methods and theories have been developed, and where knowledge gaps or unresolved problems remain. It establishes the scientific foundation of this study and positions this research within existing knowledge. The developed pavement model helps us have a better understanding of the response characteristics of pavements under moving loads, which is beneficial to the development of a robust parameter back-calculation technique.

Up to now, the main outputs of my research are a state-of-the-art literature review on the structural evaluation of roads and a theoretical model (called PaveMove) of TSD tests of roads. The literature review establishes the scientific foundation of my research and positions it within existing knowledge. The developed PaveMove model helps us have a better understanding of the response characteristics of pavements under moving loads, which is beneficial to the development of a robust parameter back-calculation technique.

Future directions

In future work, the developed theoretical pavement model will be used to generate a database which contains responses of different pavement structures. This database will be analysed by using some data science methods to develop a data-driven technique for parameter back-calculation and structural health evaluation.

The developed theoretical pavement model can accurately and efficiently predict the response of pavements under moving loads. Based on this model, a robust technique which can provide the structural health information to a digital twin of roads can be developed.



MAXIMIZING RECYCLED MATERIALS FOR SUSTAINABLE PAVEMENT CONSTRUCTION

Dr Anand Sreeram
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The construction of pavements utilizes a significant amount of non-renewable natural resources that generate substantial amount of greenhouse gases. One way to mitigate this issue would be using waste materials for new construction which will lower its overall carbon footprint. However, the maximum utilization of the most relevant and compatible national waste streams into the pavement infrastructure with appropriate design methods is still missing. The goal of this research is to maximize the use of the most pertinent recyclable materials for new pavement construction through evaluating its potential to be incorporated into the roadway infrastructure from multi-scale perspectives.

Scientific concept and goals

Based on an extensive review of literature, assessment of local construction practices and discussions with stakeholders, the maximum usage scenario and most compatible waste streams will be firstly identified. Following this, the structural performance of rigid pavements incorporated with these materials will be comprehensively evaluated, and its design optimized using machine learning (ML) approaches. To prepare for field evaluation, the use of low-cost radio frequency identification (RFID) sensors will be explored in order to integrate it into the modified pavement for its structural health monitoring. The outcomes of the study are expected to advance the understanding of this highly relevant and critical infrastructural issue and provide a field ready technology for potential large-scale adoption directly over the digital twin without costly data.

Summary of the work carried out

Literature review and identification of research gaps : Conducted a literature review regarding the application of different waste streams in pavement applications. The review provides a solid fundamental knowledge foundation for achieving the objectives of the project and to develop early strategies to increase the use of specific recycled materials in local and national level construction projects. Several research gaps were also identified for potential work.
Technical communication with stakeholders and engagement with industry: Various meeting and discussions were held with relevant stakeholders in National Highways and Ringway to identify practical challenges and major breakthroughs required to accelerate the adoption of sustainable technologies in pavements. Engagement included conference calls and visits to different production facilities and RAP recycling facilities.
Design of initial experimental plan : Based on 1. and 2., an initial experimental plan was devised for the early part of the experimental work. The work will mainly involve devising fundamental physicochemical models based on solubility science to assess compatibility between mixing materials in an easy to interpret manner.

Further direction

The fellowship had a transformative impact on my career. The training, network and culture of excellence it fostered were instrumental in helping me secure my current position. Several of the scientific research papers I have since completed were first conceived and initiated during my time on the DRF. I am deeply grateful for the support and guidance of my academic supervisor, Prof Abir Al-Tabbaa, and my industrial supervisor throughout the fellowship.

LOW CARBON SELF-HEALING CONCRETE PAVEMENTS

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This research aimed to accelerate the adoption of low-carbon concrete in UK construction. Given that Portland cement (PC) production accounts for 5-8% of global greenhouse gas emissions, the work directly addressed priorities set out in the UK Low Carbon Concrete Routemap towards net zero by 2050. The research focused on underutilised alkali-activated concretes (AACs) based on slag and fly ash, examining their materials performance and barriers arising from lack of standardisation, alongside the development of calcined clay supplementary cementitious materials (SCMs) from locally excavated shale and clays. In parallel, low-carbon self-healing concretes for road infrastructure were investigated, incorporating superabsorbent polymers (SAPs) and fibres to enhance durability and reduce maintenance.

Scientific concept and goals

4% of the UK Strategic Road Network, most of which are ageing jointed concrete pavements experiencing significant deterioration. Repair and maintenance alone cost the UK £26.2 m/year, with a further £4.1 m/year budget shortfall, highlighting the urgent need for more durable, efficient, and sustainable pavements. PC production contributes 5-8% of global CO_2 emissions, reinforcing the importance of developing low-carbon alternatives. This research aimed to revolutionise road infrastructure materials by developing effective self-healing systems for concrete pavements and transitioning traditional roads to more efficient, sustainable, and smart networks.

The primary objectives were to: (i) develop low-carbon concrete pavements using existing and emerging technologies, including AACs and calcined clay-based systems; (ii) explore self-healing additives such as SAPs and fibres to repair cracks autonomously; and (iii) investigate pathways for scaling laboratory-optimised mixes towards pilot production.

To achieve these objectives, an extensive multidisciplinary experimental programme was implemented. Laboratory material characterisation included standard fresh and hardened property tests alongside advanced techniques such as XRD, TGA-DTA, FTIR, SEM/EDX, early-age calorimetry, and resistivity measurements. Durability assessments encompassed carbonation resistance, chloride penetration resistance, and freeze-thaw performance with and without de-icing salts. Low-carbon concrete mixes were optimised by varying SCMs, activator types, and precursor materials to achieve balanced workability, strength, and long-term durability. Roller-compacted concretes (RCC) with significantly lower cement content than conventional pavements were also developed, and their fresh and hardened properties were investigated.

Self-healing concretes were developed to address targeted damage mechanisms, with SAPs mitigating freeze-thaw damage and expansive minerals and fibres preventing early-age thermal shrinkage. This integrated approach combined materials science, experimental validation, and innovative design to provide a foundation for low-carbon, durable, self-healing concrete pavements suitable for future adoption in the UK.

Fig 1. Dynamic vibration hammer for the compaction and moulding of RCC cylindrical specimens

Fig 2. Freeze-thaw chamber with concrete specimens exposed to the de-icing salts or water

Summary of the work carried out

External pavements are exposed to XF4 and XD3 exposure classes, which relate to freeze-thaw cycles and chloride-induced corrosion, making freeze-thaw resistance a critical performance parameter, particularly for pavements subjected to de-icing salts. The research initially focused on developing low-carbon, durable RCC pavements with enhanced freeze-thaw resistance, addressing key durability challenges for UK road infrastructure. The work explored the use of low-carbon cementitious systems combined with engineered self-healing additives, such as SAPs and fibres, to improve long-term performance and reduce maintenance needs. Four RCC mixes were designed with a water- to-binder ratio of 0.45, in which ordinary PC was partially replaced by 80% ground granulated blast-furnace slag (GGBS), producing a low-carbon concrete with reduced embodied CO_2. To evaluate the effectiveness of smart additives for mitigating freeze-thaw damage, SAPs were incorporated at 0.3% by weight of total binder, while 12-mm polypropylene (PP) fibres were added at 0.3% fibre volume. These additives were intended to enhance internal self-healing mechanisms, mitigate microcracking, and improve resistance to surface scaling, producing a more durable pavement system suitable for the harsh UK environmental conditions.

A comprehensive laboratory experimental programme was conducted to assess both mechanical and durability performance. Standard compressive strength tests were carried out to evaluate the structural performance of each RCC mix. Freeze-thaw resistance was examined by subjecting concrete specimens to 56 freeze-thaw cycles under water and de-icing salt conditions. Mass scaling measurements quantified surface degradation, providing a detailed assessment of material behaviour under extreme exposure.

Fig 3. Proceq ultrasonic device to measure the RDME and concrete internal structural damage due to freeze-thaw

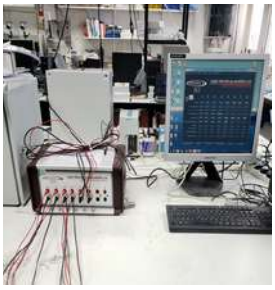

Fig 4. Rapid chloride penetration test (RCPT) set-up

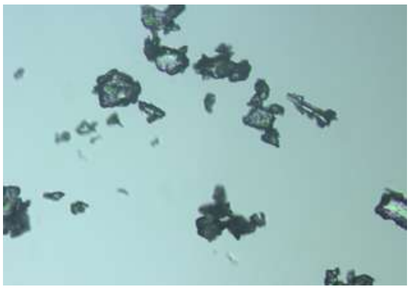

Fig 4. Superabsorbent polymers (SAPs) observed under an optical microscope

Major outcomes and significance

The experimental programme demonstrated that the inclusion of SAPs and PP fibres improved both compressive strength and freeze-thaw resistance relative to reference mixes without additives. PP fibres were particularly effective in mitigating internal structural damage and reducing mass scaling, outperforming SAPs under both water and de-icing salt conditions.

The study confirmed that the combination of low-carbon binder systems with self-healing and fibre-based additives can significantly enhance the durability of RCC pavements, offering a pathway to more sustainable, efficient, and long-lasting road infrastructure. These findings provide evidence for the potential of low-carbon RCC mixes incorporating engineered additives to meet the durability requirements of XF4 and XD3 exposure classes while contributing to reductions in CO_2 emissions. The work established a foundation for further optimisation and pilot-scale trials of low-carbon, self-healing RCC pavements, aligning with the broader goals of transitioning traditional pavements to more sustainable, smart, and resilient road networks.

Future directions

Due to time constraints and a short period of involvement in the FUTUREROADS programme, not all primary objectives were fully explored. Future work should prioritise scaling low-carbon, self-healing concrete mixes from laboratory-optimised formulations to pilot and field trials, validating their performance under realistic pavement loading and environmental conditions. Extended studies are required to assess the long-term durability of AACs and limestone calcined clay (LC3) systems, including carbonation, chloride penetration, and freeze-thaw resistance over multiple seasons. Self-healing systems should be further optimised with a broader range of additives, fibre types, and dosages to address multiple damage mechanisms concurrently. Additional research could investigate integration with RCC to reduce cement content while maintaining workability and strength. Collectively, these efforts would generate robust evidence for adopting low-carbon, durable, and self-healing pavement technologies, supporting the transition of traditional road networks toward sustainable, efficient, and resilient infrastructure.

The FUTUREROADS programme provided an opportunity to explore the development of low-carbon, durable, and self-healing concrete pavements for UK road infrastructure. Due to time constraints and limited involvement in the project, not all primary objectives could be fully addressed. Nonetheless, the work undertaken demonstrated the potential of combining low-carbon binder systems, including high replacement of PC with GGBS, with engineered self-healing additives such as SAPs and PP fibres. Laboratory investigations on RCC mixes showed improvements in compressive strength, freeze-thaw resistance, and surface scaling mitigation, highlighting the feasibility of low-carbon, self-healing concretes for pavements exposed to harsh environmental conditions.

The research established a foundation for future optimisation, including pilot-scale trials, extended durability assessments, and exploration of alternative binders such as AACs and LC3 concrete mixes. Further work is needed to fully integrate self-healing mechanisms, optimise additive combinations, and evaluate long-term performance under realistic pavement loading and environmental exposures. Collectively, these findings provide a strategic basis for transitioning traditional pavements to more sustainable, resilient, and smart road networks, aligning with the UK's net zero 2050 goals and reducing lifecycle maintenance and carbon emissions.

THERMAL PERFORMANCE OPTIMIZATION OF RIBBONS-BASED ELECTRICALLY HEATED PAVEMENTS

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Infrastructures in many countries experience accumulations of snow. On pavements, this causes unsafe conditions for road users. An alternative technology to snow plowing and de-icing consists of embedding near the ride surface ribbon-like elements that melt snow and ice due to the Joule effect as an electrical current is passed through the ribbons. This study dealt with the optimization of electrically heated pavements utilizing such ribbons. For this, a thermal model was mathematically outlined; it considered the 2D heat equation applied to a three-layered domain representing such pavement. The top boundary (i.e., pavement surface) was subjected to a heat flux representing weather effects, which were quantified with measured data obtained in the UK. A large number of cases were considered for the optimization: ribbon spacing and embedment depth, thermal conductivity of the top layer representing AC, and energy consumption of the ribbons. Amongst all cases, for the considered weather data, it was found that the optimal heated pavement consists of a ribbon spacing of 0.2 m, an embedment depth of 0.07 m with a thermal conductivity of 2.5 W·m-1·K-1 for the asphalt concrete. The developed thermal model is seen as a tool that engineers can utilize for the thermal design of heated pavements.

Scientific concept and goals

Electrically heated pavements have been developed as an alternative to snow ploughing and de-icing chemicals. Heat is generated through ribbon-like elements embedded near the pavement surface, melting snow and ice by the Joule effect. The present study was carried out to optimise the geometric and material parameters that control the thermal efficiency of this technology. Specifically, the spacing and embedment depth of heating ribbons and the thermal conductivity of the surrounding asphalt concrete were optimised.

A mathematical model based on the two-dimensional transient heat equation was formulated to simulate the pavement's thermal performance. The model incorporated multiple layers representing asphalt, base, and subbase materials. Heat transfer mechanisms—including conduction, convection, and radiation—were modelled along with the latent heat effects caused by moisture freezing and thawing. The pavement surface was subjected to realistic boundary conditions derived from measured UK winter weather data, ensuring practical applicability.

The model was discretised using a finite-difference scheme implemented in Fortran 90, ensuring high computational efficiency and accuracy. Verification was performed against analytical solutions and commercial software (GeoStudio), with deviations under 0.1 °C.

The research aimed to provide an engineering tool for designing electrically heated pavements with minimal energy consumption while maintaining sufficient surface temperatures to prevent ice formation. Optimisation was based on thermal performance, geometric constraints, and ribbon activation duration. The study's outcomes were expected to support the development of efficient, energy-conscious de-icing systems applicable to both asphalt and concrete pavements under various climatic conditions.

Summary of the work carried out

A mathematical model describing heat transfer within an electrically heated pavement was established. The model employed the two-dimensional heat equation incorporating variable thermal properties, internal heat generation, and boundary conditions representing atmospheric interactions. A three-layer structure—comprising asphalt concrete, aggregate base, and subbase—was considered. Ribbons were modelled as discrete rectangular heat sources embedded within the top layer.

To evaluate the system, the governing equations were solved numerically using a forward finite-difference scheme. The computational domain was discretised at 2.5 mm spatial intervals and 0.1 s time steps, ensuring stability and precision. Model verification was carried out against analytical and numerical benchmarks, confirming a maximum temperature deviation below 0.1 °C.

Meteorological boundary conditions were defined from field measurements collected on the A628 highway near Crowden, UK, during a 20-hour cold-weather event in December 2022. The recorded parameters—air temperature, wind speed, and longwave radiation—were used to simulate realistic heat fluxes at the pavement surface.

The parametric study involved 336 simulation cases combining seven asphalt thermal conductivities (0.5–3.5 $W \cdot m^{-1} \cdot K^{-1}$), six ribbon spacings (0.10–0.20 m), and eight embedment depths (0.03–0.10 m). Each configuration was evaluated based on the minimum surface temperature achieved and the duration of ribbon heating required to maintain the surface above freezing.

The results demonstrated that higher asphalt thermal conductivity enhances heat transfer and surface uniformity. The optimal configuration was identified as a ribbon spacing of 0.2 m, embedment depth of 0.07 m, and thermal conductivity of 2.5 $W \cdot m^{-1} \cdot K^{-1}$. Under these parameters, sufficient de-icing was achieved with reduced heating duration. Larger ribbon spacing or deeper embedment increased energy consumption due to diminished heat propagation to the surface.

The developed model successfully reproduced observed thermal behaviours and was proposed as a predictive tool for pavement thermal design. It was noted that the code could be extended to account for economic and sustainability criteria, enabling multi-objective optimization of heating performance and cost efficiency.

Fig 1. The heating technology investigated in this study

Major outcomes and significance

The study yielded significant insights into the thermal design and optimisation of electrically heated pavements. A validated two-dimensional numerical model was established, capable of accurately predicting surface temperature responses under varying design and climatic conditions.

The main findings can be summarised as follows:

1. Model development and validation: A Fortran-based finite-difference code was created and verified against analytical and commercial references, providing reliable results for multi-layered pavement systems.
2. Thermal performance dependency: The efficiency of snow and ice melting was found to depend strongly on ribbon geometry and asphalt thermal conductivity. Optimal results were achieved with a spacing of 0.2 m and embedment depth of 0.07 m, balancing thermal performance and energy efficiency.
3. Material influence: Enhanced heat transfer was observed in pavements incorporating thermally conductive asphalt concrete. Increasing conductivity from 0.5 to 3.5 W·m^{-1}·K^{-1} significantly elevated surface temperatures and reduced required heating time.
4. Energy optimisation: Energy savings were achieved by modulating ribbon activation in response to monitored surface temperatures. The results suggested that intelligent control algorithms can further minimise power usage.
5. Practical implications: The developed methodology provides engineers with a tool for thermally designing heated pavements under site-specific weather data. This enables predictive analysis before construction, reducing trial-and-error costs and environmental impacts.
6. Contribution to sustainable infrastructure: By reducing the reliance on chemical de-icing and snow-ploughing operations, electrically heated pavements can lower maintenance costs, limit salt-induced damage, and improve safety. The study demonstrates how thermally optimised designs can enhance energy efficiency, contributing to more resilient winter road infrastructure.

Overall, this research represents the first systematic thermal optimisation of ribbon-based heated pavements. Its outcomes establish a foundation for developing full-scale design guidelines that balance performance, durability, and environmental considerations. The modelling framework can be readily adapted to other climates or heating technologies, underscoring its versatility for future road engineering applications.

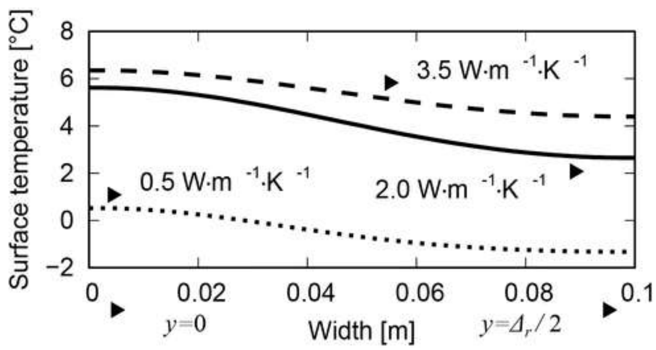

Fig 2. The surface temperature distribution across the pavement width one hour after ribbon activation for three different asphalt concrete thermal conductivities: 0.5, 2.0, and 3.5 W·m^{-1}·K^{-1}

Future directions

Future work should involve the integration of electrical, mechanical, and thermal models to enable comprehensive multi-physics optimisation. Experimental validation under real climatic conditions is recommended to confirm numerical predictions and refine input parameters. The model should be expanded to three dimensions to capture edge effects and non-uniform heat distribution. Additional studies may explore advanced materials—such as conductive fibers, graphene, or metal oxides—to improve asphalt thermal conductivity. Incorporating smart control systems for adaptive heating could reduce energy consumption further. Sustainability assessments should also be performed to evaluate lifecycle costs and carbon emissions. Ultimately, a complete design framework combining performance, cost, and environmental indicators is envisaged for application in both highway and airport pavement systems.

A numerical optimisation study of ribbons-based electrically heated pavements was performed to determine the most efficient configuration for snow and ice control. The thermal behaviour of the system was simulated using a two-dimensional heat-transfer model incorporating real weather conditions. A comprehensive parametric analysis identified the optimal design parameters—ribbon spacing of 0.2 m, embedment depth of 0.07 m, and asphalt concrete thermal conductivity of 2.5 W·m^{-1}·K^{-1}. The model accurately predicted surface temperature evolution, confirming its capability as a practical design tool.

Through the developed approach, the potential of thermally conductive asphalt and intelligent heating management was demonstrated for enhancing pavement safety and sustainability. The study established a foundation for future research combining thermal, electrical, and mechanical aspects of heated pavement systems. It was concluded that the model could be utilised to guide engineers in designing cost-effective and energy-efficient infrastructure capable of withstanding severe winter conditions.

ZERO WASTE GEOPOLYMER PAVEMENT

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Highway construction faces dual sustainability constraints: reclaimed asphalt pavement (RAP) is typically limited to around 20% in conventional practice, and large volumes of excavated clay from infrastructure works lack viable reuse pathways. This project addresses both challenges by developing binder systems that enable 100% RAP recycling and incorporate up to 30% waste clay in pavement materials. By replacing traditional binders with geopolymer cement (and, in parallel, an LC3-based route), the approach targets substantial carbon reduction while converting high-volume waste streams into useful construction resources for both new pavements and repair applications.

Scientific concept and goals

Geopolymers are inorganic aluminosilicate binders formed through alkali-activation of aluminosilicate precursors (e.g., metakaolin or calcined clay), producing three-dimensional Si–O–Al networks via dissolution and polycondensation reactions. This chemistry is presented as a lower-emissions alternative to Portland cement, with the report indicating up to 80% lower carbon emissions than conventional cement. In this project, geopolymer binders are used to (i) overcome limitations in incorporating RAP beyond conventional levels while maintaining structural integrity and (ii) enable excavated clay to function as a reactive binder component and filler.

The project aims to develop three complementary material systems: (i) low-carbon geopolymer mortar as a foundational formulation, (ii) low-carbon geopolymer rigid pavement incorporating high levels of reclaimed asphalt pavement (RAP) and waste clay reuse, and (iii) geopolymer-based repair binder for large crack and pothole applications. Together, these systems target carbon reduction, waste diversion, and practical deployment across new pavement construction and maintenance operations.

Summary of the work carried out

Literature Review and Standards Development: The work began with a critical review of geopolymer concrete literature and analysis of Australia's first geopolymer concrete standard to establish benchmarks for compressive strength, durability requirements, and mix design principles.

Material Characterization and Activation: Excavated clay waste was characterised using XRD (mineralogy), XRF (Si/Al ratios), and TGA (thermal stability). Calcination transformed the clay into reactive amorphous aluminosilicates, enabling it to replace up to 30% of commercial metakaolin while maintaining geopolymer performance.

Geopolymer Mortar Optimization: Parametric studies varying activator concentration, Si/Al ratios, and curing conditions achieved 40 MPa compressive strength at 7 days. A predictive model linking compositional parameters to mechanical performance was developed to accelerate mix design for different applications.

Repair Agent Development: A repair agent incorporating polyvinyl alcohol (PVA) fibres was formulated to improve crack-bridging and ductility for pothole and crack repair, demonstrating superior adhesion, rapid strength gain, and lower carbon footprint compared to conventional repair products.

Full-Depth Pavement Systems: Two parallel approaches were developed: geopolymer concrete with 100% RAP and partial activated clay replacement, and an LC3-based system also achieving 100% RAP incorporation. Both systems target 40–50 MPa compressive strength at 28 days, demonstrating complete waste recycling without performance compromise.

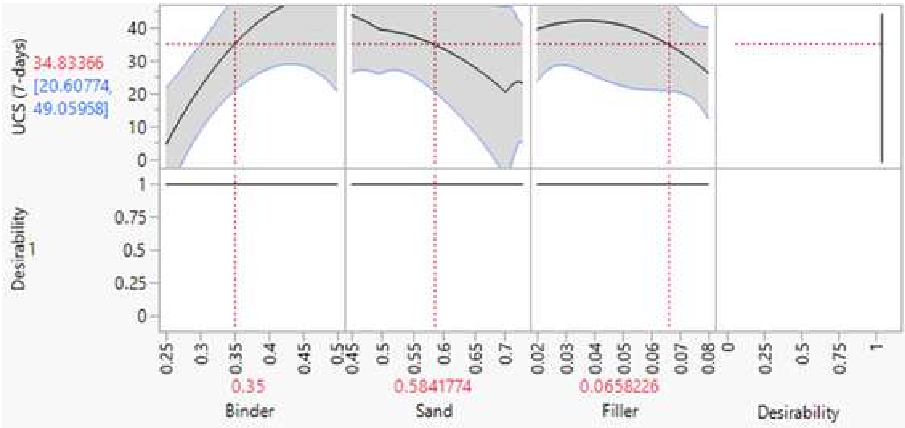

Fig 1. Mixture profiler indicating various strengths obtained for different mixture designs. The red dotted lines for instance indicate that a mortar having 35% binder, .58.4% sand and 6.5% filler will have a strength of approximately 35 MPa after 7-days curing.

Major outcomes

- 100% RAP rigid pavement mixes were produced, showing near closed-loop aggregate reuse is technically achievable.
- Excavated clay was characterised, calcined, and reused as a geopolymer precursor/partial replacement (up to ~30%) instead of disposal.
- Geopolymer mortar mix optimisation achieved ~40 MPa at 7 days, supported by a predictive model linking composition to target strength.
- A PVA fibre-reinforced geopolymer repair binder was developed for potholes and large cracks, with testing indicating strong adhesion, rapid strength gain, and durability versus conventional repair products.
- Two deployment pathways were advanced—geopolymer (with partial clay replacement) and LC3—both enabling 100% RAP incorporation and targeting 40–50 MPa at 28 days.

Significance

Carbon and resource impact: The work targets reduced virgin aggregate demand through high-RAP use and reduced binder emissions through geopolymer/LC3 routes, aligning with low-carbon road infrastructure objectives.

Waste diversion at scale: Because RAP and excavated clay occur in high volumes in infrastructure projects, demonstrating viable reuse routes supports zero-waste ambitions and reduces landfill dependence.

Faster translation to practice: Engagement with standards and performance-targeted mix design helps bridge laboratory development and field specification/acceptance for pavement materials.

Operational resilience: Repair-focused materials extend impact beyond new construction by enabling lower-carbon maintenance strategies for potholes and cracks, which require frequent interventions.

Future directions

Extend durability testing to pavement-relevant mechanisms (freeze–thaw, wet–dry, abrasion, shrinkage/creep, fatigue) and relate results to expected service performance.

Scale-up for constructability, including workability/setting control, curing approaches, and repeatability when RAP and clay properties vary between sources.

Run pilot-scale mixes and targeted field trials for new pavement sections and pothole/crack repairs, with structured monitoring of early-age cracking, stiffness/deflection, and surface wear.

Define practical acceptance envelopes for RAP and clay (gradation, contaminants, mineralogy, binder content) and translate outcomes into guidance or specification-ready recommendations to support industry uptake.

The project advances a circular, low-carbon pavement strategy by turning RAP and excavated clay into engineered resources through geopolymer (and parallel LC3) binder systems, supported by standards review, material characterisation, and mix optimisation with a predictive design approach. It reports technical feasibility of rigid pavements with 100% RAP and partial activated-clay replacement, and develops fibre-reinforced geopolymer repair materials for cracks and potholes. Next steps focus on durability validation, scale-up/constructability, and field trials.

AN INNOVATIVE ZONATION-BASED MACHINE-LEARNING METHODOLOGY FOR STUDYING THE INTERACTIVE IMPACTS OF TRAFFIC, MICROCLIMATE AND NATURAL HAZARDS ON PAVEMENT DETERIORATION

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This data-driven project aims to provide new knowledge on pavement deterioration. A wealth of traffic, climate and environment-related datasets will be processed to provide new engineering information. A zonation strategy will also be established to facilitate the training of a machine-learning model for pavement deterioration predictions. Ultimately, the new knowledge and the machine-learning model will be output as a standalone software for all partner organizations. With the tangible toolbox: (i) the frequency of maintenance work can be reduced, contributing to achieving carbon neutrality in U.K., and (ii) the new knowledge can lead to informed decision-makings on future road planning and design.

Scientific concept and goals

The objective is to develop an in-depth and new understanding of pavement deterioration over time through the processing, interpretation and learning from (i) a wealth of national data, (ii) sensor data generated on-demand, and (iii) pavement images. Specifically, the objective will be measured and verified through the following aims: The proposal of an innovative zonation strategy that can effectively divide the country road network into several macroscopic and mesoscopic zones based on the characteristics of traffic, climate and microclimate information. The development and delivery of a validated machine-learning methodology that can explain and forecast the interactive effects of multiple factors that include but are not limited to traffic, climate, microclimate, extreme natural events and pavement materials on pavement deterioration. The translation and export of the upstream research to downstream implementation and commercialization.

Summary of the work carried out

A literature review has been conducted to understand the state-of-the-art pavement deterioration models and factors affecting pavement deterioration. A conference paper on the literature review has been published at the 5th International Conference on Transportation Geotechnics. Building on this conference paper, an additional study has been conducted to benchmark four categories of strategies to preprocess data for training machine-learning-based deterioration forecasting models. The Long-Term Pavement Performance (LTPP) dataset is employed to

benchmark these categories. Employing random forest as the machine learning algorithm, the comparative study examines the impact of data preprocessing strategies, the volume of historical data, and forecast horizon on the accuracy and reliability of performance forecasts. The strengths and limitations of each implementation strategy are summarized. Multiple pavement performance indicators are also analysed to assess the generalizability of the findings. Based on the results, several findings and recommendations are provided for short-to medium-term infrastructure management and decision-making. The quantitative guidelines ultimately support more effective and reliable application of data-driven techniques in infrastructure performance forecasting. Beyond data-driven analysis, I explored the use of the traffic speed deflectometer (TSD) as a sensing technology to measure pavement condition. It is a technology that provides continuous, non-destructive monitoring of pavement structural health. Through parameter inference using TSD measurements, engineers can obtain physics-based evidence regarding pavement material parameters, which is crucial for informed decision-making on road operations and maintenance. I then conducted a study to overcome some gaps in the interpretation of TSD data. Specifically, I proposed a methodological framework for probabilistic parameter inference using TSD measurements. The innovation lies in the synergistic combination of: (i) a physics-based simulator, PaveMove, that directly simulates pavement responses under TSD dynamic loading, (ii) machine learning surrogates to accelerate PaveMove calculations, and (iii) Bayesian updating to transform traditional deterministic parameter inference into a probabilistic framework that explicitly incorporates multiple material and measurement uncertainties. The results indicate that the proposed framework effectively addresses the limitations inherent in traditional techniques and provides more accurate, consistent, and reliable results of parameter inference. The proposed framework paves the way for the broader adoption of TSD technology in practice, ultimately permitting real-time, uncertainty-aware pavement management at the network scale. A journal paper has been published based on this study. I have further conducted a more in-depth investigation of the data requirement for TSD data interpretation and proposed a recommendation to improve the use of TSD for pavement structural capacity evaluation. A conference paper has been published, which has been given positive comments from the inventor of TSD. Another journal manuscript is currently under review.

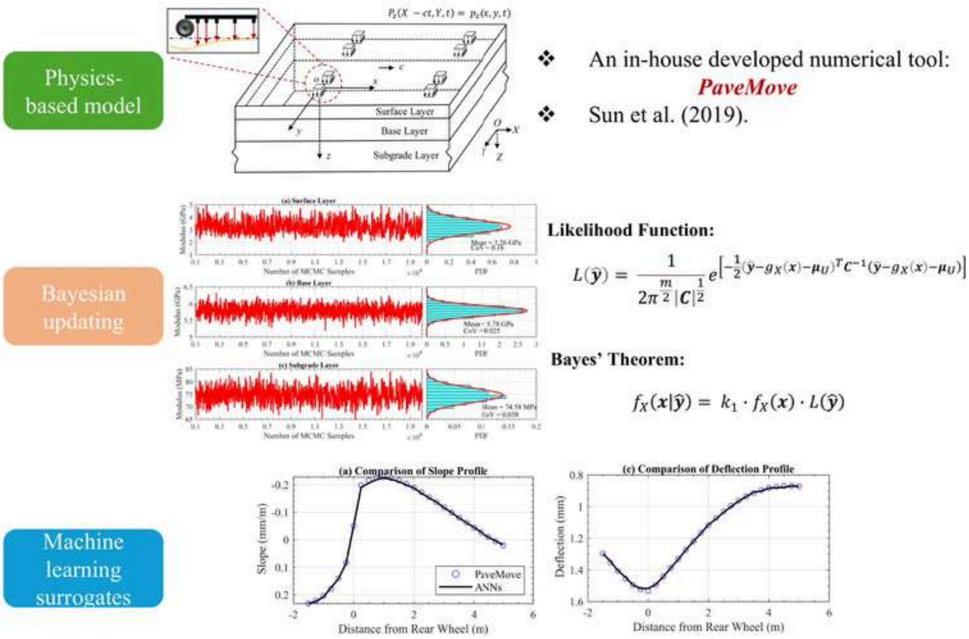

Fig 1. Methodology Framework of Pavement Sensing for Structural Capacity Evaluation

Major outcomes and significance

he project targets at policy makers and pavement engineers in both industry and academia and delivers them a new and advanced software system that houses the developed machine-learning methodology, the processed national data and the interpreted new knowledge of pavement deterioration to address real-world engineering challenges. The methodology will be customizable and adaptable to future new sustainable and smart pavement materials. Through the new knowledge and methodology as well as dissemination activities, the research project aims at creating the following long-lasting and socially desirable outcomes:

Pavement engineers can provide customized and targeted maintenance plan to reduce the frequency of the required maintenance work. Not only can traffic disruption be minimized, but the methodology can also contribute to reducing carbon emissions.

The maximum service life of future pavements can be further extended, and the possibility that pavements are damaged within the design life can also be significantly reduced.

While FUTUREROADS can be designed to be more adaptable and resilient against climate change and natural hazards, policy makers can better plan and manage FUTUREROADS through informed decision-makings.

The establishment of long-term collaborations with partner organizations to collect real-time data to update the reliability and relevance of the methodology.

Future directions

I am currently working on an in-depth investigation on the correlation of TSD measurement data with pavement strain behaviour. This investigation is being conducted using high-fidelity numerical simulations. This will provide engineering knowledge to directly evaluate the use of TSD data for understanding pavement strain under loading and therefore potentially the predictions of the rutting defects.

The project has targeted at policy makers and pavement engineers in both industry and academia and will deliver them a new and advanced software system that houses the developed machine-learning methodology, the processed national data and the interpreted new knowledge of pavement deterioration. This tangible asset will eventually be exported and deployed by both public and private sectors to address real-world pavement engineering challenges. In addition, the methodology will be intelligently programmed to be customizable and adaptable to future new sustainable and smart pavement materials. The research project has created and is creating the following outcomes: (i) several findings and recommendations have been provided to pavement engineers for short-to medium-term infrastructure management and decision-making. These quantitative guidelines ultimately support more effective and reliable application of data-driven techniques in infrastructure performance forecasting, and (ii) the proposed framework for interpreting TSD data effectively addresses the limitations inherent in traditional techniques and provides more accurate, consistent, and reliable results of parameter inference. Therefore, the proposed framework paves the way for the broader adoption of TSD technology in practice, ultimately permitting real-time, uncertainty-aware pavement management at the network scale.

AN INTEGRATED ROAD ASSET MONITORING SYSTEM SUPPORTED BY PROBABILISTIC MODELS AND ARTIFICIAL INTELLIGENCE

Dr Fengqiao Zhang
Marie Skłodowska Curie FUTUREROADS Fellow
Assistant Professor in Concrete Structures at TU Delft, Netherlands

Effective utilization of information is critical for road asset management, emphasizing data-driven proactive strategies. Despite advances in embedded sensors, smart vehicles, and Artificial Intelligence (AI), these technologies remain underutilized due to limited integration across heterogeneous data sources. This research aims to integrate emerging technologies to enhance understanding of road asset performance through a shift from deterministic to probabilistic analysis. Uncertainties will be explicitly quantified using probabilistic models such as Bayesian updating and AI methods including ensemble learning. A future-proof, adaptable framework will be developed and validated through laboratory and field experiments.

Scientific concept and goals

The scientific concept of this research is to develop an integrated road asset monitoring system that combines emerging sensing technologies with probabilistic modelling and artificial intelligence to improve understanding and prediction of road infrastructure performance. While modern technologies such as embedded sensors, smart vehicles, UAVs, and advanced imaging systems can generate large volumes of data, current road asset management practices often rely on limited subsets of this information, leading to underutilisation of available evidence. This research addresses this gap by focusing on systematic data integration and uncertainty-aware decision support.

A core scientific principle is the shift from deterministic to probabilistic analysis. All monitoring technologies are subject to uncertainties arising from environmental conditions, sensor limitations, and data processing algorithms. Rather than ignoring these uncertainties, the research explicitly quantifies them and incorporates them into the assessment process using probabilistic models such as Bayesian updating and AI techniques such as ensemble learning. This allows multiple heterogeneous data sources to be fused in a mathematically rigorous way, producing probabilistic estimates of road condition and damage likelihood.

The primary goals of the research are threefold. First, it aims to conduct a comprehensive and critical review of emerging road monitoring technologies, assessing their feasibility, cost-benefit, and field readiness. Second, it seeks to identify and quantify uncertainties associated with each technology and data processing method. Third, it aims to develop and validate a future-proof integration framework that can dynamically incorporate new technologies as they emerge.

Summary of the work carried out

My project investigates the identification of correlations in road health monitoring data using a Bayesian Network (BN) framework, with the aim of improving understanding of pavement deterioration mechanisms and supporting data-driven maintenance decisions. The work focuses on integrating heterogeneous road monitoring variables and modelling their probabilistic dependencies using copula-based Bayesian networks.

I began by conducting a comprehensive review of current road health monitoring technologies, including laser-based sensors (profilometers, LiDAR, LCMS), Ground Penetrating Radar (GPR), smart vehicles, and embedded sensors. These technologies provide measurements of surface condition, structural integrity, and environmental exposure, but also generate complex and high-dimensional datasets that are difficult to interpret using conventional statistical methods.

For empirical analysis, I used data from the FHWA Long-Term Pavement Performance (LTPP) database. I filtered the dataset to include only Jointed Plain Concrete Pavement (JPCP) sections without maintenance interventions, resulting in 132 sections and 1,145 measurements collected between 1991 and 2021. The selected variables include construction parameters (age, slab thickness, base type), material properties (compressive strength, elastic modulus, thermal expansion), environmental conditions (precipitation, temperature range, freezing index), traffic loading (AADTT), and performance indicators (cracking, spalling, faulting, and roughness).

I performed exploratory statistical analysis to examine the distributions of each variable and to compare pavement behaviour for bound and unbound base types. This revealed systematic differences in cracking behaviour, with bound bases showing higher cracking due to stress concentration, while unbound bases exhibited greater sensitivity to environmental effects.

To model dependencies between variables, I applied Gaussian copulas and Spearman rank correlations, overcoming limitations of traditional covariance-based measures when dealing with non-linear and non-Gaussian data. I identified significant correlations ($|\rho| > 0.2$) and interpreted them in terms of physical mechanisms, such as the influence of age, freezing index, and precipitation on crack development, and the impact of traffic loading on faulting.
I then encoded these statistically significant relationships into a Bayesian Network, representing causal and conditional dependencies among key variables. The BN structure enables probabilistic inference and updating, allowing predictions of pavement condition based on partial observations. Goodness-of-fit tests confirmed that Gaussian copulas provide a generally suitable representation of the joint distributions.
Overall, my project demonstrates that environmental, mechanical, and material factors jointly govern pavement deterioration, and that Bayesian Networks provide a robust and interpretable framework for modelling such complex interactions. The results highlight both the potential of probabilistic modelling for road health monitoring and the need for larger datasets and further validation to strengthen predictive capability.

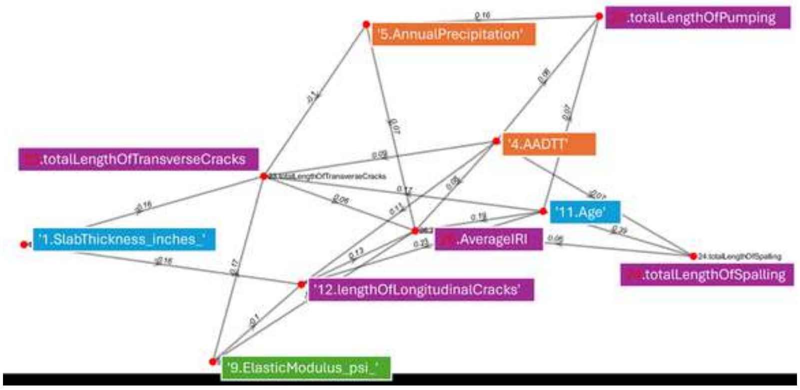

Fig 1. Structure of Bayesian Network

Major outcomes and significance

The major outcome of my project is the development and demonstration of a probabilistic framework for road health monitoring based on Bayesian Networks (BNs), which enables systematic integration and interpretation of heterogeneous monitoring data. Through this work, I showed that complex relationships between pavement performance, material properties, traffic loading, and environmental conditions can be effectively captured using copula-based probabilistic models, rather than relying on traditional deterministic or pairwise statistical approaches.
A key technical outcome is the successful application of Gaussian copulas within a BN structure to model non-linear and non-Gaussian dependencies in large-scale pavement datasets. Using the FHWA Long-Term Pavement Performance (LTPP) database, I demonstrated that conventional covariance or Pearson correlation often fails to reveal meaningful patterns, whereas rank-based and copula-based methods uncover interpretable and physically meaningful dependencies. This represents a significant methodological advance for infrastructure monitoring, where data distributions are rarely ideal and uncertainties are pervasive.
Another major outcome is the identification of systematic deterioration mechanisms across different pavement configurations. My results confirmed that pavement age, freezing index, precipitation, and traffic loading are among the most influential drivers of deterioration, but also revealed more subtle interactions. For example, bound base pavements exhibited higher cracking despite greater stiffness, highlighting stress concentration effects that are not easily captured by simple models. These findings provide empirical evidence that pavement deterioration is governed by interacting mechanical, environmental, and material processes, reinforcing the need for multivariate probabilistic analysis.
From a practical perspective, the Bayesian Network developed in my project provides a decision-support structure that can perform probabilistic inference. This means that missing or uncertain data from one monitoring source can be compensated by information from others, enabling more robust estimation of pavement condition. This is particularly significant for real-world road asset management, where data are often incomplete, noisy, and collected at different temporal and spatial scales. The BN framework therefore offers a foundation for moving from reactive inspection-based maintenance toward proactive and risk-informed asset management.
In terms of scientific significance, my work contributes to bridging a critical gap between advanced statistical learning methods and civil infrastructure engineering. While Bayesian Networks are widely used in fields such as medicine and finance, their application to pavement monitoring remains limited. My project demonstrates not only feasibility but also clear advantages over conventional regression-based approaches, especially in handling uncertainty, causal reasoning, and data fusion.
More broadly, the project establishes a scalable and future-proof modelling paradigm. As new monitoring technologies such as smart vehicles, embedded sensors, and AI-based image analysis continue to emerge, the proposed probabilistic framework can incorporate these data streams without redesigning the entire system. This adaptability is essential for long-term infrastructure systems, where technologies evolve faster than physical assets.
Overall, the significance of my work lies in shifting road health monitoring from isolated measurements toward an integrated, uncertainty-aware, and inference-driven system. It provides both methodological foundations and practical insights that support more resilient, transparent, and data-driven management of critical road infrastructure.

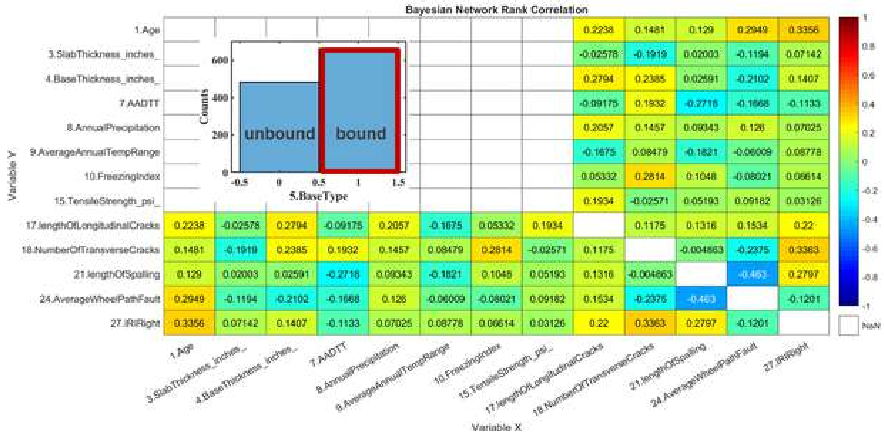

Fig 2. Correlation coefficients using bivariate Gaussian Copulas for pavement sections with bound base type

Future directions

Future work will focus on extending the proposed Bayesian Network framework to incorporate larger, more diverse, and real-time datasets, including data from smart vehicles, embedded sensors, and remote sensing platforms. This will improve model generalization and enable continuous updating of road condition estimates. Further research will also investigate dynamic Bayesian Networks to explicitly capture temporal deterioration processes and long-term performance trends.

Another key direction is the integration of advanced AI techniques, such as deep learning for automated feature extraction and hybrid AI–probabilistic models for improved data fusion. This will allow complex raw data (e.g. images and signals) to be directly linked with probabilistic inference.

Finally, future work will focus on field-scale validation and operational deployment, developing user-friendly interfaces and decision-support tools to embed the framework into real asset management workflows, supporting proactive, risk-based infrastructure management.

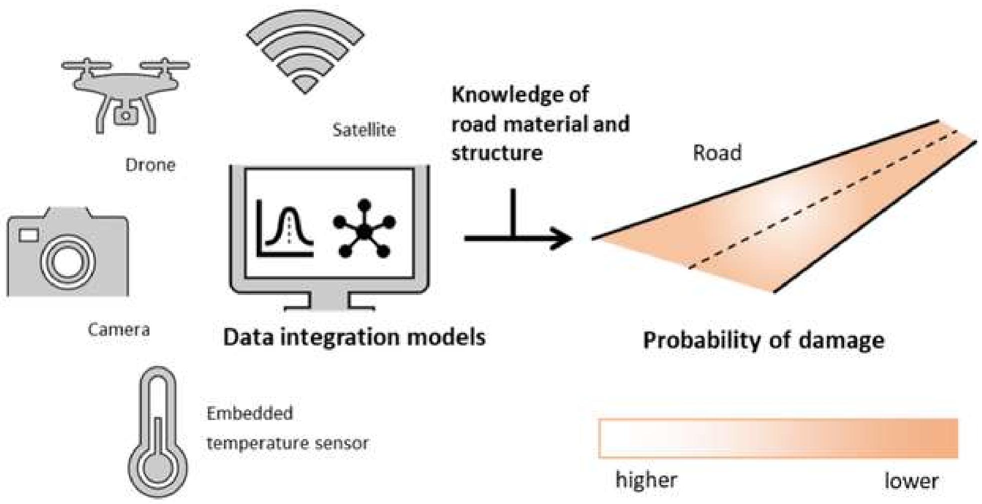

Fig 3. Concept of the probabilistic integration

This research demonstrates the potential of probabilistic and data-driven methods to transform road health monitoring from a fragmented, deterministic process into an integrated and uncertainty-aware system. By applying Bayesian Networks and copula-based modelling to large-scale pavement datasets, my work shows that complex dependencies between structural, environmental, and operational factors can be systematically captured and interpreted. This provides a more realistic representation of pavement deterioration mechanisms compared to traditional regression-based approaches.

A key contribution of this research is the explicit treatment of uncertainty, recognising that all monitoring technologies are inherently imperfect and that meaningful decision-making must account for data quality, variability, and incompleteness. The proposed framework enables heterogeneous data sources to be fused within a unified probabilistic structure, supporting robust inference even when some information is missing or noisy.

Beyond methodological advances, this research offers practical implications for road asset management by supporting proactive, risk-informed maintenance strategies. The developed framework is adaptable and future-proof, capable of incorporating new technologies and data streams as they emerge. Overall, this work provides both a scientific foundation and a practical pathway towards more resilient, transparent, and intelligent infrastructure monitoring systems.

MATERIAL FLOW ANALYSIS OF ROADS: A REVIEW

Dr Daniel Grossegger
Marie Skłodowska Curie
FUTUREROADS Fellow
Alumni

This study reviews 86 publications on the material flow analysis (MFA) of road infrastructure to evaluate current methods, data gaps, and environmental implications. Roads are among the largest material stocks within the built environment, dominated by asphalt, concrete, and granular materials. The review compares top-down and bottom-up quantification approaches and identifies key uncertainties affecting data quality, stock estimation, and greenhouse gas (GHG) accounting. Findings highlight that over half of road-related GHG emissions stem from material production. The paper concludes with recommendations for standardised data collection, improved circularity, and integration of MFA into sustainable infrastructure policies.

Scientific concept and goals

Material Flow Analysis (MFA) provides a systematic framework to quantify the input, stock, and output flows of materials across the life cycle of infrastructure systems. Roads, as one of the most material-intensive assets globally, account for approximately 14–32% of the total built environment material stock. Despite this, MFA applications in road systems remain inconsistent and fragmented due to methodological diversity and data limitations.

The main goal of this study is to synthesise existing MFA research on roads, clarify methodological approaches, and evaluate their application to environmental impact assessment. Specifically, it aims to:

review existing MFA studies related to roads and road materials;

compare bottom-up and top-down methodologies in stock estimation;

analyse the relationship between road material stock, maintenance, and greenhouse gas emissions; and

propose future research directions for achieving circularity and sustainability in the road sector.

By systematically examining 86 peer-reviewed papers and reports, the authors identify recurring issues such as data uncertainty, heterogeneous system boundaries, and inconsistent terminology. They also assess the role of material production, maintenance practices, and climate adaptation in influencing the total material demand. The study ultimately provides an evidence-based foundation to guide policymakers and engineers toward developing low-carbon and resource-efficient road infrastructure systems.

Summary of the work carried out

A comprehensive literature review was conducted using databases including Scopus, Web of Science, and ScienceDirect, through which 267 initial studies were identified. Of these, 86 were found to meet the inclusion criteria, focusing specifically on road material stocks and flows. These studies were categorised based on spatial scale (local, national, global), temporal scope (retrospective or prospective), and methodological approach (top-down, bottom-up, or combined).

Bottom-up MFA approaches dominate, accounting for 56 of the 86 studies. These methods rely on road length and material intensity factors derived from design standards or empirical data. Top-down studies, which use aggregated economic or production statistics, are fewer but useful for macro-level trend analysis. Remote sensing and machine learning are emerging as new tools for quantifying road geometry and material composition.

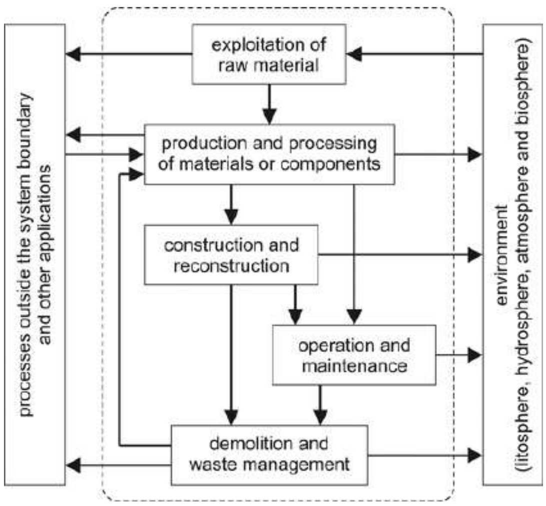

Fig 1. System overview of a material flow model for buildings and infrastructure. Processes are represented as squares, flows are represented through arrows, indicating flow direction, and the system boundary is represented through a dashed line.

The review found that roads primarily consist of granular materials (≈73%), asphalt (≈26%), and minor components such as concrete and cement (<2%). Global road material stocks are estimated between 132 and 294 gigatonnes, ranking second after building materials in total stock contribution.

Material demand continues to increase due to maintenance and reconstruction activities, particularly in developed countries where stock saturation has been reached. Maintenance accounts for over 50% of total material use in mature networks such as the US and Europe. Climate change exacerbates material needs through accelerated degradation caused by temperature and moisture fluctuations.

The authors also examined the link between material stocks and greenhouse gas emissions. Material production represents 54–87% of total road-related GHG emissions, with asphalt identified as the main emitter due to binder and aggregate processing. The study highlights circular economy strategies—such as the use of reclaimed asphalt and secondary aggregates—that can reduce emissions but remain limited by quality constraints and logistical challenges.

Uncertainty quantification is emphasised as a critical area for improvement. Inconsistent road length data, varying material intensities, and underreported recycling rates lead to discrepancies of up to 150% in global stock estimates. The authors recommend adopting standardised data collection, integrating spatially resolved MFA models, and fostering collaboration between road authorities, academia, and industry.

Major outcomes and significance

This review provides the first consolidated overview of road material flow research, revealing critical insights into the structure, magnitude, and environmental impact of global road stocks. The main outcomes are:

1. Comprehensive synthesis of MFA methodologies: Bottom-up approaches offer higher spatial accuracy but depend heavily on data availability and assumptions. Top-down approaches provide macro-level consistency but mask local variability. Combining both enhances reliability.
2. Quantification of global material stock: Roads hold between 132–294 Gt of material, dominated by aggregates and asphalt. This magnitude underscores roads' pivotal role in national material metabolism and environmental policy.
3. Link between material flows and emissions: Over half of total GHG emissions in road life cycles stem from material production. Asphalt accounts for the highest emissions, highlighting the importance of low-carbon binders, recycling, and warm-mix technologies.
4. Identification of key research gaps: The field lacks consistent boundary definitions, uncertainty assessments, and spatially explicit data. Smaller cities and rural areas remain understudied, and road-associated structures (bridges, tunnels, parking) are largely excluded.
5. Significance for sustainability and policy: MFA enables a data-driven understanding of material circularity, supporting strategies for waste reduction and decarbonisation. Integrating MFA into infrastructure management could inform lifecycle-based procurement, recycling standards, and climate adaptation planning.

The study underscores that achieving climate-neutral roads requires a systemic transformation of material production, maintenance, and end-of-life management. Understanding the interdependencies among economic growth, urbanisation, and road stock saturation is essential to managing resource efficiency. Finally, it calls for coordinated action between academia, industry, and policymakers to develop standardised, comparable, and transparent MFA datasets that can serve as decision-support tools for circular economy transitions in infrastructure.

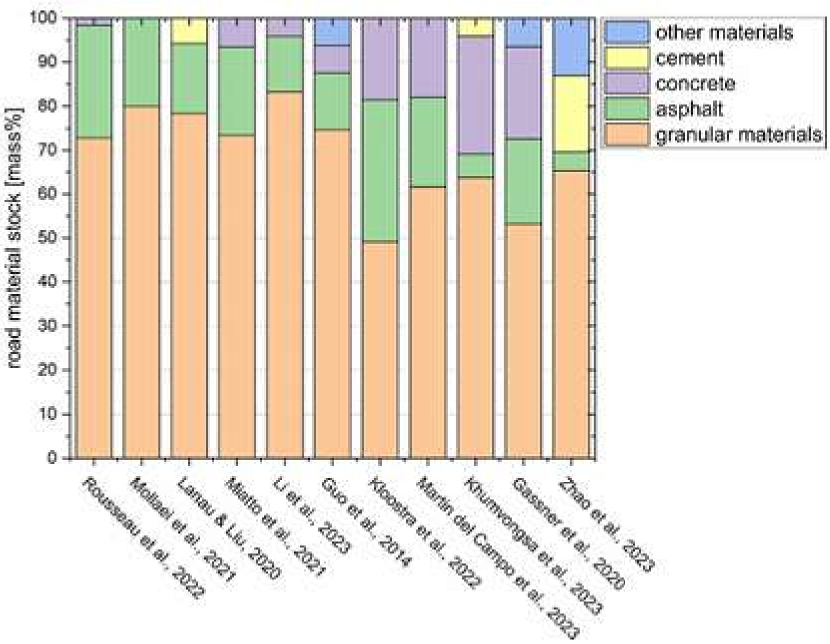

Fig 2. Comparison of road stock composition from different studies

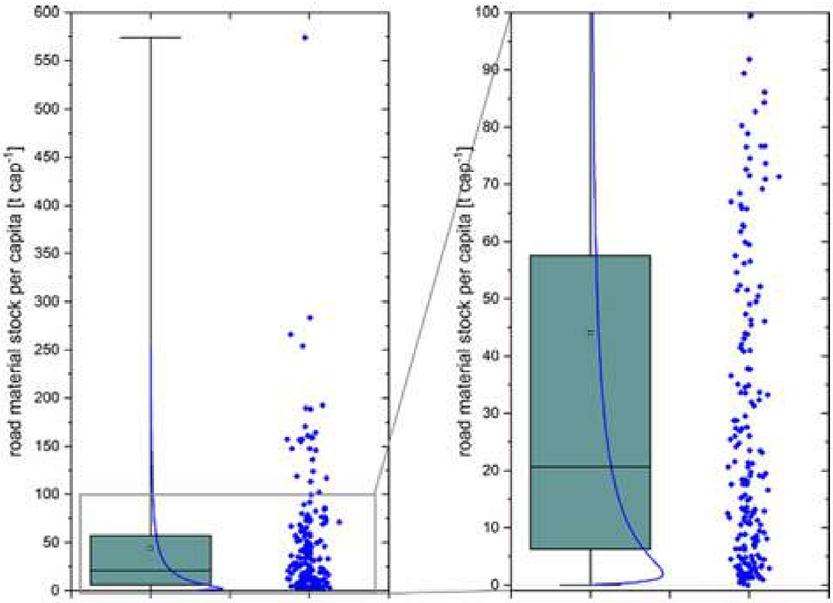

Fig 3. Road stock per capita distribution (Box diagram including lognormal distribution on the left and data points on the right) generated from the supporting information

Future directions

Future research should prioritise developing harmonised frameworks for data collection and uncertainty reporting in road MFA. Expanding analyses to different spatial scales—including smaller cities and rural networks—will provide more representative global estimates. Integrating MFA with dynamic modelling, machine learning, and life cycle assessment can enhance predictive capabilities, particularly under climate change scenarios. Further investigation into material quality, recyclability, and degradation mechanisms will support circular construction practices. The inclusion of supporting structures (bridges, tunnels, parking) and digital tracking of recycled materials will improve system completeness. Ultimately, collaboration among policymakers, researchers, and industry stakeholders is essential to establish MFA as a standardised tool for sustainable road planning and carbon reduction strategies.

The review establishes material flow analysis as a vital framework for understanding the scale, composition, and environmental implications of global road infrastructure. Roads represent one of the most significant anthropogenic material stocks, with continuous material inflows driven by maintenance and upgrading needs. The study highlights that material production—particularly asphalt and cement—dominates greenhouse gas emissions, emphasising the need for low-carbon materials, recycling, and circular economy approaches.
Despite progress, the field faces methodological inconsistencies, data gaps, and limited coverage of smaller regions and infrastructure components. Addressing these gaps through harmonised methodologies, advanced modelling, and cross-sector collaboration will enhance MFA's role in policy and practice. Ultimately, embedding MFA into infrastructure management can help transition the road sector toward climate neutrality, resource efficiency, and sustainability—providing the analytical foundation for responsible material use and reduced environmental footprint across the entire road life cycle.

Reference: *Grossegger, D., MacAskill, K. and Al-Tabbaa, A., 2024. A critical review of road network material stocks and flows: Current progress and what we can learn from it. Resources, Conservation and Recycling, 205, p.107584. https://doi.org/10.1016/j.resconrec.2024.107584*

ENHANCING EQUITY, DIVERSITY, AND INCLUSION IN ACTIVE MOBILITY: A STUDY ON UNDERREPRESENTED GROUPS' PERSPECTIVES IN ROAD INFRASTRUCTURE PLANNING IN CAMBRIDGE

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My research develops new ways to measure how people actually experience transport systems, not just how they move through them. Using digital-twin video experiments and advanced behavioural models, I study how street design, traffic, lighting, and social context shape perceived safety, comfort, and equity for cyclists, pedestrians, and micromobility users. This work, developed through the Marie Skłodowska-Curie FUTUREROADS Fellowship at the University of Cambridge, links high-resolution simulation with real human perception to reveal who benefits from new infrastructure and who is left out. By integrating equity, behaviour, and digital twins, I provide evidence that supports more inclusive transport planning.

Scientific concept and goals

1. This research is built on a simple but largely unmet scientific challenge: transport systems are designed using objective performance indicators, yet they succeed or fail through how they are perceived by real people. Safety, comfort, trust, and fairness shape whether new infrastructure is used, but these dimensions are rarely measured with the same rigour as speed, flow, or emissions.
2. The core scientific concept of my work is to connect high-fidelity digital representations of streets with human perception and behaviour. Using digital twins and video-based stated-preference experiments, I expose participants to controlled but realistic urban scenarios in which features such as traffic volumes, lighting, surface quality, and social interactions vary over time. These visual stimuli are then linked to advanced behavioural models that recover how different people translate what they see into feelings of safety, stress, or willingness to use a mode. This allows us to move beyond average effects and reveal hidden heterogeneity across gender, age, experience, and vulnerability.
3. This framework goes beyond conventional digital-twin applications, which typically optimise infrastructure from an engineering perspective alone. By embedding human perception inside the simulation loop, digital twins become tools for social and behavioural impact assessment, not only technical optimisation. This also addresses a major gap in cycling and micromobility research, where equity is often discussed normatively but rarely measured in ways that can inform design and investment decisions.
4. The scientific goals are threefold. First, to develop robust methods for extracting time-varying perceptual responses from video-based experiments and linking them to street-level design features. Second, to integrate these methods with transport models so that infrastructure and policy scenarios can be evaluated not only in terms of efficiency and emissions, but also perceived safety, comfort, and inclusion. Third, to provide planners, operators, and technology developers with evidence that helps avoid unintended exclusion.

Summary of the work carried out

During my Marie Skłodowska-Curie FUTUREROADS Fellowship at the University of Cambridge, I developed and tested a new methodological framework for analysing how people experience transport systems, with a particular focus on cycling, micromobility, and pedestrian environments. The central idea was to move beyond traditional indicators such as crash rates or traffic volumes and to capture the perceptual and emotional dimensions that shape whether people feel safe, comfortable, and included in everyday mobility.

The core technical platform for this work was a high-resolution digital twin of London, which was used to generate realistic street-level video scenarios under systematically varied conditions. These included changes in lighting (day and night), traffic intensity, surface quality, crowding, and interactions with other road users. Rather than treating the digital twin as a visualisation tool, it was used as a controlled experimental environment in which specific design and traffic features could be manipulated while holding everything else constant.

These videos formed the basis of large-scale stated-preference experiments conducted across multiple English cities, including Cambridge, Oxford, and London. Participants viewed sequences of short video clips and rated their perceived safety, comfort, and overall cycling experience. Each respondent evaluated multiple scenarios, allowing the data to capture both within-person sensitivity to environmental changes and between-person differences in perception. This structure made it possible to identify how the same street could feel welcoming to one group and intimidating to another.

To analyse these data, I developed and applied advanced ordered-response models that account for unobserved heterogeneity and individual-specific thresholds. This modelling framework made it possible to link dynamic visual features in the videos to subjective responses in a statistically rigorous way. The result was not just a ranking of scenarios, but a set of behavioural relationships that reveal how design features such as traffic proximity, surface quality, or social density translate into perceived risk or comfort for different types of users.

Alongside this methodological work, I conducted a comprehensive review of the cycling equity literature. This review showed that most existing studies focus on access and demographics, while systematically under-measuring lived experience, fear, harassment, and social exclusion in public space. By combining this conceptual work with the digital-twin experiments, the research programme bridged a critical gap between normative discussions of justice and empirical measurement.

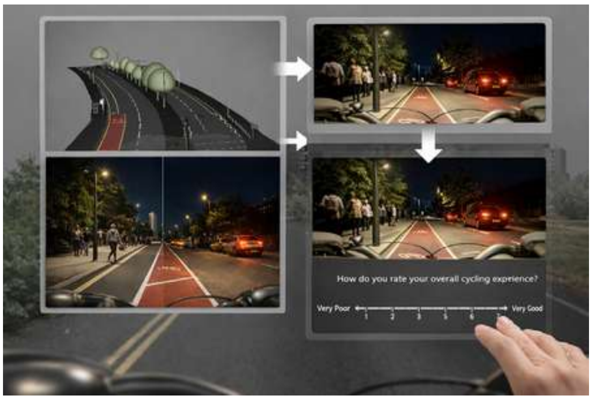


Fig 1. Cyclist-eye-view video generated from the digital twin, showing a night-time on-road cycling environment with pedestrians and motor traffic.

Major outcomes and significance

The FUTUREROADS project produced a set of outcomes that extend well beyond a single case study or modelling technique. Its central achievement was to demonstrate that human experience can be measured, modelled, and embedded into transport system design with the same scientific rigour as physical performance indicators. This represents a shift in how digital tools are used in transport research and practice.

A major methodological outcome was the establishment of digital-twin video experiments as a new form of stated-preference data. Traditional stated-preference surveys rely on abstract text or static images, which struggle to capture the dynamic, multisensory nature of real streets. By contrast, high-fidelity video generated from a digital twin allows people to react to realistic sequences of traffic, lighting, movement, and social interaction. The resulting data are richer, more behaviourally grounded, and better able to reveal how small design changes translate into large differences in perceived safety and comfort. This approach is now directly transferable to industry contexts such as scheme appraisal, user-centred design, and the testing of new mobility services before physical deployment.

A second key outcome was the development of modelling tools that connect these visual stimuli to statistically robust behavioural responses. By using advanced ordered-choice models with heterogeneous thresholds, the project moved beyond average effects and identified distinct perceptual profiles across populations. This allows planners and technology developers to see not only what works on average, but who is being excluded or discouraged by particular design choices. For example, features that appear neutral in aggregate can have strongly negative effects for women, older users, or less confident cyclists. Making these hidden patterns visible is essential for avoiding unintended inequities in future transport systems.

The integration of this modelling framework with a critical equity review represents a third major outcome. The review showed that much of the cycling and micromobility literature talks about justice in abstract terms but lacks tools to measure it empirically. By providing a way to quantify fear, comfort, and perceived legitimacy of space, the project turns equity from a rhetorical goal into an operational design criterion. This has direct implications for how infrastructure investments, micromobility deployments, and digital mobility platforms are evaluated.

The significance of these outcomes lies in their ability to reshape how digital twins are used. Instead of being limited to engineering optimisation or traffic simulation, digital twins become platforms for testing social and behavioural consequences. This opens a pathway for transport authorities, consultants, and technology firms to assess not only whether a scheme will move people efficiently, but whether it will be experienced as safe, fair, and usable by diverse communities.

Future directions

The next phase of this work is to move from experimental insight to real-time decision support. Digital-twin video experiments will be extended to include live or near-real-time data from traffic sensors, micromobility fleets, and environmental monitors, allowing planners and operators to test how proposed changes are likely to be perceived before they are built or deployed. This will make it possible to evaluate not only physical performance, but also social acceptance, safety perception, and equity impacts at the design stage.

Methodologically, future research will integrate physiological and neural measures, such as eye-tracking and electroencephalography, to deepen understanding of how people process complex street environments. Substantively, the framework will be expanded beyond cycling to include pedestrians, e-scooters, automated vehicles, and shared mobility.

The FUTUREROADS research programme has shown that the success of future transport systems will depend as much on human experience as on engineering performance. Streets may be technically safe, low-carbon, and efficient, yet still fail if large parts of the population do not feel able or willing to use them. By combining digital-twin video experiments with advanced behavioural modelling and an equity-focused research agenda, this work provides a practical way to close that gap.

What makes this approach distinctive is that it does not treat people as noise around a technical system, but as central components of it. Perceived safety, comfort, and social inclusion become measurable outcomes that can be evaluated alongside travel time or emissions. This allows planners, policymakers, and industry partners to anticipate not only how infrastructure and technologies will perform, but how they will be experienced by different users.

MEASURING AND ENHANCING THE RESILIENCE OF ROAD INFRASTRUCTURE NETWORKS TO CLIMATE CHANGE

Dr Jie Liu
Marie Skłodowska Curie FUTUREROADS Fellow

Climate change has created a range of environmental and societal challenges, making transport systems increasingly unreliable and vulnerable. This project develops practical, evidence-based methods to measure and enhance road-network resilience under current and future climate scenarios. It focuses on: (i) quantifying the impacts of climatic events (extreme rainfall and flooding) on road-network operations and asset damage; (ii) measuring performance degradation and resilience under these events; and (iii) predicting flood locations and severity, and optimising maintenance to enhance road-network resilience to climate hazards.

Scientific concept and goals

Road infrastructure resilience is defined as the ability of a network to maintain essential functionality (connectivity, travel speed, and accessibility) under climate hazards and to recover rapidly. The core scientific concept is to connect three elements that are often analysed separately: (1) physical hazard and asset exposure (flood depth/extent, rainfall intensity, and failure mechanisms), (2) road-network dynamics (capacity loss, rerouting, and congestion propagation), and (3) impact consequences (travel delays and accessibility losses—who is affected, by how much, and where).

Methodologically, we combine spatial risk analytics with transport-network modelling. Hazard layers (for current and future climates) are overlaid with road assets to estimate scenario-specific disruptions (e.g., closures, speed reductions, and signal failures). These outputs feed into network performance models to quantify changes in key performance indicators, including connectivity, travel delays, and accessibility losses. Network resilience is assessed across multiple extreme rainfall and flooding scenarios that vary in spatial extent and return period. To support proactive management and effective flood response, machine-learning models are applied to predict flood locations and severity on the strategic road network using historical flooding records and contextual predictors.

Goals:

1. To understand the mechanisms through which climatic events disrupt road networks, including travel behaviour changes and cascading failure processes.
2. To quantify the impacts of climatic events on road-network performance.
3. To measure and compare road-network resilience under current and future climate conditions.
4. To develop and evaluate strategies to enhance road-network resilience to climate change.

Summary of the work carried out

We have delivered four complementary strands of work to quantify road-network resilience to climate extremes.

1. Multi-factor vulnerability assessment under extreme rainfall (Greater London and surrounding regions). We developed an integrated framework to evaluate road-network vulnerability by combining rainfall-induced speed reductions, surface-water flood exposure, and traffic-signal failures at junctions. We quantified impacts on network travel time and connectivity across hundreds of rainfall scenarios.
2. Road-network resilience to extreme rainfall: integrating multiple impact factors and delay propagation. We built a network performance modelling workflow that incorporates multiple disruption channels (reduced speeds, capacity drops, closures, and control degradation) and explicitly models delay propagation through rerouting and congestion spillovers. Outputs include time- and space-resolved performance loss and critical-link importance.
3. Accessibility and equity impacts under flooding across England (current and future climate). We evaluated how flooding affects neighbourhood access to essential services under present-day and climate-adjusted scenarios. Flood extent/depth proxies were overlaid with road networks to represent disruption, and we computed scenario-based changes in travel time and reachability for small-area neighbourhood units.
4. Flood location and severity prediction on the strategic road network using historical flood records. We developed data-driven models to predict flood occurrence and severity on National Highways using historical incident records linked with contextual predictors (e.g., rainfall, topography, road characteristics, and traffic flow). The outputs provide segment-level predictions driven by rainfall inputs.

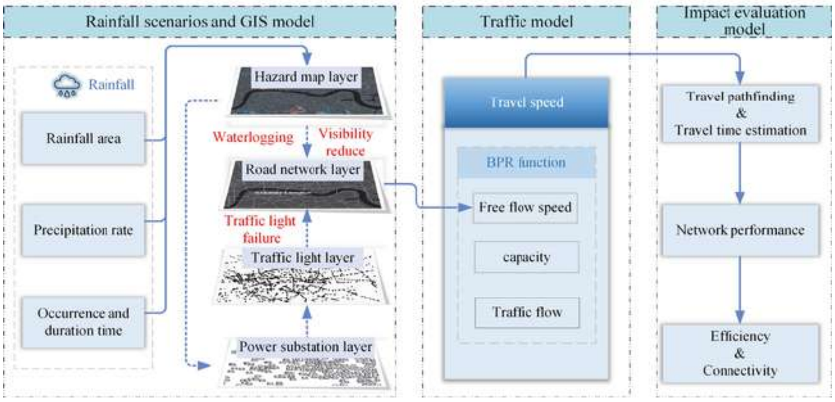


Fig 1. Research framework for extreme rainfall impact evaluation

Major outcomes and significance

This project has generated a coherent set of methods and decision-support outputs to quantify and enhance the resilience of road infrastructure networks under climate change, with contributions at operational, societal, and predictive levels.

Outcome 1: Multi-factor vulnerability framework for extreme rainfall (Greater London). We developed an integrated approach that combines multiple disruption mechanisms (rainfall-driven speed reductions, surface-water flood exposure, and traffic-signal failure) to identify network "pressure points". This provides a more realistic representation of rainfall impacts than single-factor exposure mapping, enabling practitioners to move from hazard maps to network-relevant vulnerability prioritisation.

Outcome 2: Resilience modelling with delay propagation. We advanced the assessment of road-network resilience during rainfall events by explicitly capturing how local disruptions propagate through rerouting, congestion spillovers, and network interactions. The resulting resilience indicators quantify not only direct link impacts, but also system-wide travel delays. This supports operational planning (e.g., targeted traffic management), longer-term adaptation, and incident response by highlighting critical areas where disruption triggers disproportionate delays.

Outcome 3: National-scale accessibility and equity impacts under flooding (England). We built a reproducible workflow to evaluate how flooding affects neighbourhood access to critical services under current and future climate scenarios. By translating flood scenarios into travel-time and reachability losses, we produced spatially explicit evidence on where essential access is most at risk, and how climate change can amplify inequities. The results provide a strong basis for equitable resilience planning, linking infrastructure performance to social outcomes.

Outcome 4: Predictive flood risk intelligence for the strategic road network. Using historical flooding incident records combined with contextual predictors (e.g., rainfall, topography, drainage/land characteristics, and network attributes), we developed models to predict likely flood locations and severity. These outputs enable proactive maintenance, faster incident response, and climate-resilient investment planning.

Future directions

Next, we will strengthen the framework in four ways. First, we will expand beyond extreme rainfall and flooding to other climate hazards (e.g., heavy snow and heatwaves). Second, we will incorporate uncertainty and sensitivity analysis across hazard, demand, and disruption parameters to provide confidence bounds for decision-making.

Second, we will move from assessment to action by developing multi-objective optimisation for maintenance and adaptation portfolios, explicitly balancing performance, cost, and equity. The overall aim is to translate the research into partner-ready tools and pilot demonstrations with transport agencies.

This project advances the understanding and practical assessment of road-network resilience to climate change by integrating hazard processes, network dynamics, and societal consequences. At the urban scale, it provides a multi-factor vulnerability framework and a resilience modelling approach that captures delay propagation and system-wide impacts under extreme rainfall. At the national scale, it quantifies how flooding affects neighbourhood accessibility to critical services under present and future scenarios, revealing where climate change may intensify disruption and inequity. In parallel, it develops predictive models based on historical incident data to identify likely flood locations and severity on the strategic road network, supporting proactive maintenance and targeted mitigation.

Together, these outcomes form an end-to-end workflow—from risk and disruption mechanisms, to network performance and equity impacts, to prediction and prioritisation—that is reproducible and transferable. The project's significance lies in turning climate hazard information into decision-ready evidence for operations, asset management, and adaptation planning, helping road authorities and communities maintain essential connectivity and service access in a changing climate.

DATA SCIENCE AND DIGITAL TECHNOLOGIES FOR INTELLIGENT CARBON MANAGEMENT IN THE WHOLE LIFE OF HIGHWAY ASSETS

Dr Jiyning Xu
Marie Skłodowska Curie
FUTUREROADS Fellow
Assistant Professor at National University of Singapore

For FUTUREROADS, carbon reduction is an inevitable theme to be addressed. This project will investigate data-informed sustainability decision-making in FUTUREROADS, focusing on carbon management. It aims to develop a standardised carbon data model for the precise carbon management of highway projects and study what advanced technologies/techniques could be utilised to improve data availability, operability, consistency, and reliability. To fulfil this aim, the project will develop a standardised data model that can be employed for consistent carbon calculation, assessment, and optimisation by future road developers. A mixed research method with interviews, organisational archival analysis, and ontology modelling is used.

Scientific concept and goals

Four research objectives are outlined: (1) to review existing carbon management theories and practices, attainable advanced technologies for carbon sensing and monitoring, data analysing, sharing, and visualisation; (2) to develop a standardised data model for carbon management; (3) to develop a set of interoperable protocols for data collection, storage, analysis, sharing, and visualisation; and (4) to prepare the data model in a way that is adaptable to the foreseeable adoption of new technologies in the next five years. A carbon data trustworthy framework and an intelligent carbon data management system architecture based on a comprehensive carbon data ontology are developed.

Fig 1. Tentative view of the Carbon digital twin system pilot

Summary of the work carried out

1. Reviewed the current carbon reporting practices in National Highway and its value chain, the National Highways Carbon tool and its use;
2. Reviewed existing carbon tools in other industries and other regions;
3. Reviewed existing carbon management standards and guidance;
4. Industry workshop to understand why carbon data is valuable to them, the status quo, gap and future directions of carbon management
5. Developed carbon data ontology by integrating different sources for granular and comprehensive carbon data collection
6. Extend IFC to include carbon data in BIM models
7. Developed an overarching intelligent carbon management system framework and validated it with industry partners

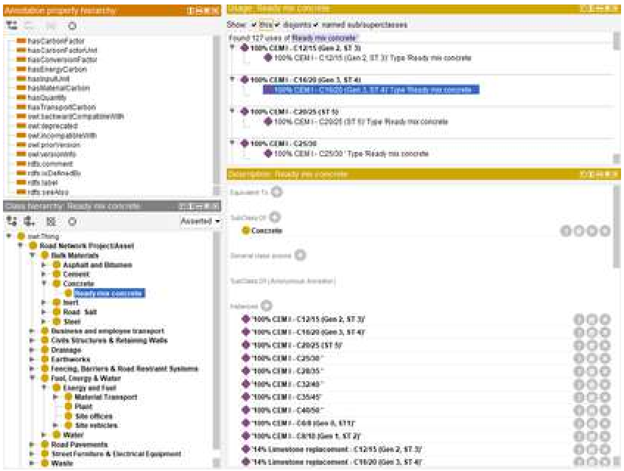


Fig 2. Snapshot of Protégé

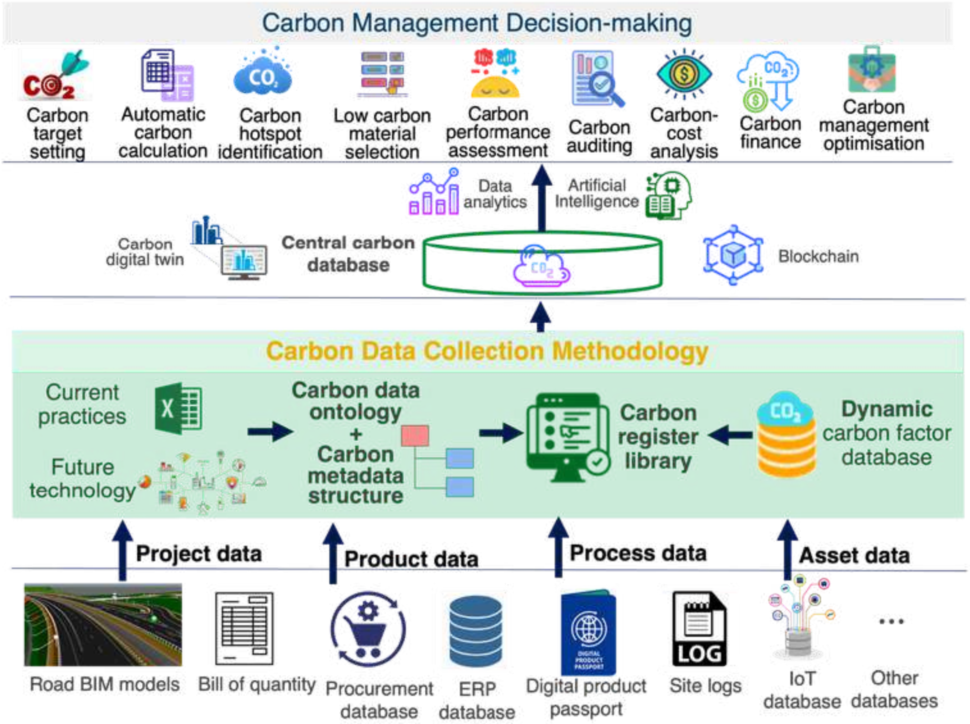


Fig 3. Intelligent carbon management system framework

Major outcomes and significance

1. Major outcomes and significance
2. A whitepaper on Carbon Data Trustworthiness, highlighting the significance of trustworthiness in carbon data;
3. A journal paper on the carbon data gap in existing standards, identifying the lack of an implementable data model and data collection methods;
4. A conference paper on how to address Carbon Data Trustworthiness issues, raising awareness in academia about the issue;
5. A conference paper on Carbon data requirements, summarising what data is needed for carbon reporting;
6. A conference paper on Extending Carbon into Digital Twin, integrating carbon into BIM;
7. A comprehensive carbon data ontology, the data foundation for automatic carbon data tracking.

Future directions: Carbon digital twin of the whole lifecycle of highway assets; Carbon-cost co-optimisation

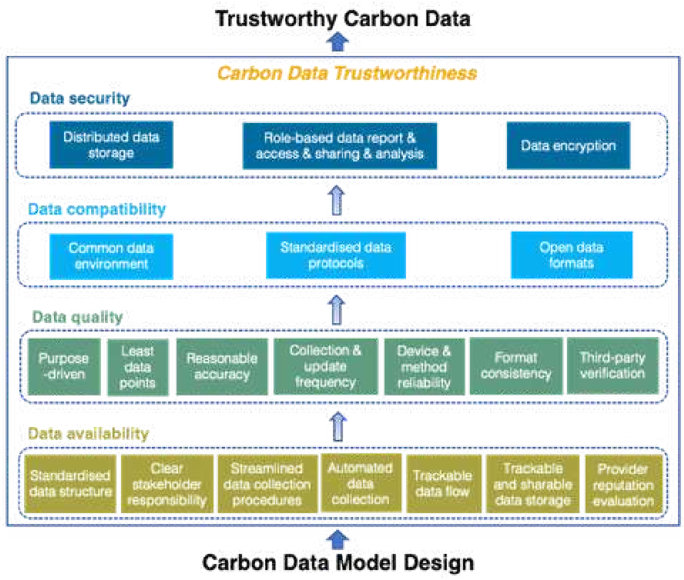


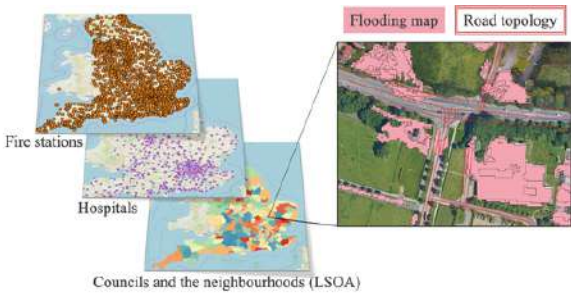
Fig 4. Carbon data trust worthy framework

This research has drilled deep into the challenges of more accurate, dynamic carbon management, especially the lack of data and data trustworthiness. It proposed that a standard data model is essential for automatic actual carbon data tracking. Such data model contains what data to collect, how to collect, what format, etc. The accurate and dynamic carbon data can facilitate better decision-making to reduce carbon emissions more effectively and more cost-efficiently.

ASSESSING ROAD INFRASTRUCTURE RESILIENCE AGAINST EXTREME WEATHER EVENTS AND FOSTERING CLIMATE CHANGE ADAPTATION

Dr Zizhen Xu
Marie Skłodowska Curie
FUTUREROADS Fellow

This research develops a systems approach to assess road network resilience under extreme weather events, integrating geospatial analysis, risk assessment, and network analysis. A regional case study of Greater London demonstrated that extreme rainfall impacts road networks through three impact channels: waterlogging, reduced visibility, and traffic-signal power outages. Via the lens of spatial inequality and neighbourhood-level accessibility, we evaluate climate change impacts on service access (healthcare, fire-rescue) during flooding across England, revealing geographical patterns of vulnerability and emerging service disruption hotspots in the future climate scenario. Secondary work applies reinforcement learning optimisation to winter road maintenance routing, exploring the feasibility of AI-driven decision support for highway operators against adverse weather conditions.



Scientific concept and goals

This research adopts a systems approach to understanding road network resilience under extreme weather through three related tasks. First, we assess the vulnerability of road networks against extreme rainfall in the UK, recognising that impacts operate through multiple interconnected channels—waterlogging, visibility degradation, and cascading infrastructure failures (power outages affecting traffic signals)—with risks propagating across sectors.

Second, we evaluate climate change impacts on neighbourhood-level accessibility to critical services, revealing how future flood risks create new vulnerabilities and exacerbate spatial inequality across communities. Third, we explore operational response strategies to winter weather events through AI-driven optimisation of maintenance routing, bridging the gap between hazard assessment and adaptive management.

Primary Goals:

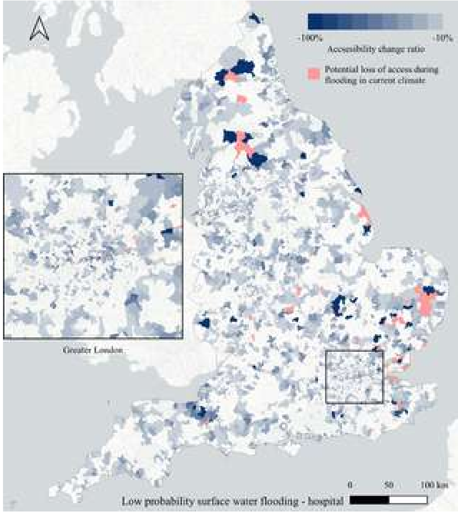
1. Quantify the relative contributions of waterlogging, visibility, and signal failures to road network disruption during extreme rainfall, demonstrating that single-factor models may misestimate impacts.
2. Assess climate change impacts on neighbourhood-level accessibility to critical services (healthcare, fire-rescue) during flooding across England. This accessibility-centred lens reveals how future flood risks disproportionately affect specific communities, creating new service disruption hotspots and exacerbating spatial inequality.
3. Develop and validate a reinforcement learning-based optimization framework for winter road maintenance routing, demonstrating operational feasibility of AI-driven decision support on real UK highway networks.

Summary of the work carried out

Task 1: Multi-factor Impact Analysis of Extreme Rainfall (collaborate with Fellow Dr. Jie Liu)
We conducted a regional case study across 26 Local Government Areas in and around Greater London to quantify how extreme rainfall impacts road networks through multiple channels. Using geospatial analysis, we intersected detailed highway network models with Environment Agency flood risk maps to identify segments affected by 1-in-30, 1-in-100, and 1-in-1000-year flood events. We then integrated three impact mechanisms into segment-level traffic speed estimation and network efficiency assessment: direct waterlogging effects, visibility degradation from intensive precipitation, and cascading power infrastructure failures affecting traffic signals.

Task 2: Climate Change Impacts on Service Accessibility (collaborate with Fellow Dr. Jie Liu)
We expanded the geographical scope to England-wide assessment. Rather than detailed traffic modelling, we adopted macroscopic network analysis to measure community-level accessibility and mobility during flooding events. We evaluated neighbourhood-level accessibility to critical services—healthcare (hospitals) and fire-rescue stations—under current and future climate scenarios (RCP8.5). The analysis further explored different sources of flooding (surface water vs. rivers & sea), returns periods of flooding, critical services, the spatial inequality across neighbourhoods.

Task 3: Reinforcement Learning Optimization for Road Maintenance (collaborate with Fellow Dr. Yue Xie and industrial partner William Beazley)
In collaboration with industry partners, we developed a bi-level optimisation framework for winter road maintenance routing on strategic road network (Area 7) and surrounding local roads. A reinforcement learning agent strategically partitions road networks into manageable clusters and optimally allocates resources from multiple depots. Within each cluster, a multi-objective vehicle routing problem minimises maximum travel time and carbon emissions while respecting vehicle-specific constraints and depot capacities. Validation on operational data demonstrated balanced workloads, reduced maximum travel times below the two-hour threshold, lower emissions, and substantial cost savings, establishing the feasibility of AI-driven decision support for highway operators.



Major outcomes and significance

Task 1: Multi-factor Impact Analysis of Extreme Rainfall (collaborate with Fellow Dr. Jie Liu)

Our analysis of extreme rainfall impacts across Greater London revealed critical findings that focusing solely on waterlogging while disregarding reduced visibility and traffic signal power failures overestimates road capacities by 15-30% and underestimates network efficiency impacts by 1–23% under different rainfall scenarios. Particularly, the largest impact underestimation is observed for 1-in-30-year rainfall risk, where waterlogging is less dominant, while poor visibility considerably contributes to the impacts. The analysis also suggests that signal power failures during rainfall have limited, localised effects at the network level. These results demonstrate that effective resilience assessment requires integrated multi-channel analysis rather than siloed hazard evaluation.

Task 2: Climate Change Impacts on Service Accessibility (collaborate with Fellow Dr. Jie Liu)

Our nationwide assessment reveals that climate change would worsen service accessibility and further exacerbate the inequality across neighbourhoods. These changes drive the shifts of dominant flood source at the neighbourhoods as well as the emergence of new hotspots with complete service disruption, highlighting the potential needs of reassessment of the local flood defence strategy. The analysis also reveals the geographical patterns of climate-change induced accessibility loss and inequality. Overall, inland neighbourhoods experience more climate change-induced losses than coastal areas, though the specific neighbourhood group of coastal rural areas with long rivers bear the greatest impacts. The study suggests it is crucial to adopt a local-context climate adaptation to flood and improve the equality of service accessibility.

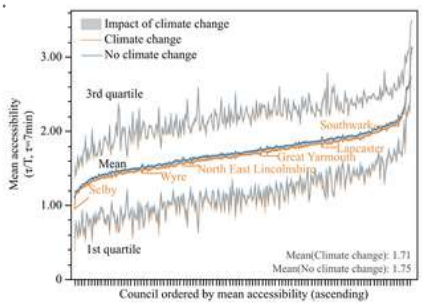
Task 3: Reinforcement Learning Optimization for Road Maintenance (collaborate with Fellow Dr. Yue Xie and industrial partner William Beazley)

The bi-level reinforcement learning optimisation framework demonstrated significant operational improvements on real UK strategic networks. Unlike existing approaches, our method handles large-scale, real-world networks efficiently, explicitly incorporating vehicle-specific constraints, depot capacities, and road segment requirements. Results demonstrate significant improvements, including balanced workloads, reduced maximum travel times below the targeted two-hour threshold, lower emissions, and substantial cost savings. This study illustrates how advanced AI driven bi-level optimisation can directly enhance operational decision-making in real-world transportation and logistics.

Future direction

This research establishes foundations for several promising extensions.

1) Multi-hazard resilience assessment. Hazards can be inherently interrelated and compound each other—flooding, wind, icing, and landslides—yet current frameworks typically assess them in isolation. Integrating multi-hazard interactions into our systems approach will reveal how concurrent or sequential events amplify network vulnerability and create unexpected failure modes.



2) Cascading infrastructure failures. While we investigated cascading impacts from power infrastructure to traffic signals, the complexity of interconnected systems embeds risks of more severe, cross-sectoral failures. Future work must map and quantify the dependencies between infrastructure networks (power, water, communications, transportation) to understand critical vulnerability points and develop targeted resilience interventions.

3) Operational challenges in real-world AI implementation. Many AI techniques are validated in controlled environments; real-world application reveals substantial complexity including incomplete data, network heterogeneity, and operational constraints. Deeper case studies of winter maintenance operations will identify practical barriers to AI adoption, develop robust validation methods, and provide implementable guidance for highway operators deploying optimization frameworks at scale.

This project establishes a systems-based framework for assessing road network resilience under extreme weather. The regional case study demonstrated that integrated analysis of waterlogging, visibility, and signal failures is essential for accurate vulnerability assessment—single-factor models overestimate network capacity by 15–30%. In the England-wide assessment, we revealed how climate change disproportionately impacts neighbourhood-level accessibility to critical services, with distinct geographical vulnerability patterns. Neighbourhoods may experience shifts in dominant flood sources, and new service disruption hotspots emerged under the future climate scenario, highlighting the need for place-based adaptation strategies that explicitly address spatial inequality. These findings challenge conventional retrospective risk management and demonstrate that effective adaptation requires integrated multi-factor assessment coupled with equity-focused, context-specific interventions. The secondary optimisation work explores operational feasibility of AI-driven decision support for highway management, revealing implementation challenges including data complexity and network scalability. Collectively, this research bridges vulnerability assessment and climate adaptation, providing evidence-based insights for policymakers and infrastructure operators to develop more resilient and equitable transportation systems.

HUMAN–ROBOT COOPERATION FOR MAINTENANCE AND CONSTRUCTION OF FUTUREROADS PAVEMENT CONSTRUCTION

Dr Arsen Abdulali

Marie Skłodowska Curie FUTUREROADS Fellow
Assistant Professor at Queen Mary University of London, UK

We developed a human-centric framework for robotic cooperation in road construction and maintenance. Addressing the high-risk and labor-intensive nature of roadside operations, the project introduced a paradigm of robotic orchestration, where human operators supervise and guide semi-autonomous robots through abstract motion primitives rather than direct low-level control. Combining haptic-enabled digital twins, bio-inspired control architectures, tactile sensing, and reservoir-based adaptive learning, the research advanced both theoretical foundations and experimental demonstrations of embodied human–robot communication. The work contributes toward Industry 5.0 by redefining collaboration between humans and machines in safety-critical infrastructure environments.

Scientific concept and goals

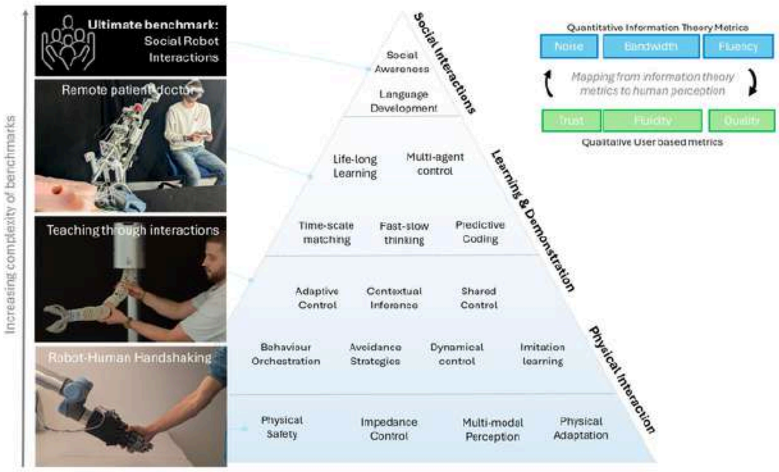
Road construction and maintenance remain physically demanding, high-risk activities that rely heavily on manual labor. The scientific premise of this fellowship was that the next generation of infrastructure robotics should not replace human workers, but rather reposition them into supervisory and decision-making roles through human–robot cooperation. The core hypothesis was that effective collaboration requires moving beyond conventional teleoperation toward embodied, information-rich communication channels that combine autonomy with human guidance.

The project was structured around three conceptual pillars. First, the development of a haptic-enabled digital twin environment enabled safe simulation of roadside manipulation tasks. This virtual environment allowed the study of teleoperation, sensorimotor control, and operator training under controlled conditions while preserving physical realism.

Second, the project advanced physical interaction capabilities through bio-inspired control and tactile sensing. Drawing from embodied intelligence principles, reflex-based controllers and adaptive reservoir computing architectures were investigated to handle nonlinear dynamics and uncertain contact conditions. These approaches emphasized model-free adaptation, scalability, and robustness in manipulation tasks.

Third, the project introduced the concept of robotic orchestration via motion primitives. Rather than directly mapping human hand movements to robot motion, operators express intent through abstract gestures corresponding to canonical actions (e.g., grasp, transport, rotate). Contextual cues such as gaze tracking provide disambiguation, enabling asynchronous and cognitively efficient collaboration.

Across these pillars, the unifying scientific objective was to formalize human–robot interaction as an embodied information channel. By integrating control theory, information theory, learning systems, and haptics, the project aimed to quantify and enhance bandwidth, fluency, and resilience in human–robot communication. This framework contributes to a human-centric Industry 5.0 vision, where robotic systems augment human capability while preserving agency, safety, and inclusivity.



Automation & Robotics

Summary of the work carried out

The fellowship progressed through an integrated programme of theoretical development, simulation-based experimentation, and physical demonstrations, aligned with the original three-stage research vision.

The first stage focused on establishing a digital and theoretical foundation for embodied human–robot communication. A haptic-enabled virtual environment was developed to simulate manipulation tasks relevant to road construction and maintenance scenarios. This environment enabled the study of teleoperation efficiency, operator workload, and control abstraction strategies without the constraints and risks of physical deployment. Within this framework, the concept of Control with Motion Primitives (CMP) was implemented and experimentally evaluated. A mixed-reality interface combining gesture input and gaze tracking allowed operators to express high-level intent while delegating low-level trajectory generation to the robot. Controlled user studies demonstrated significant reductions in trajectory length, grasping attempts, and perceived workload compared to direct teleoperation, validating the orchestration hypothesis.

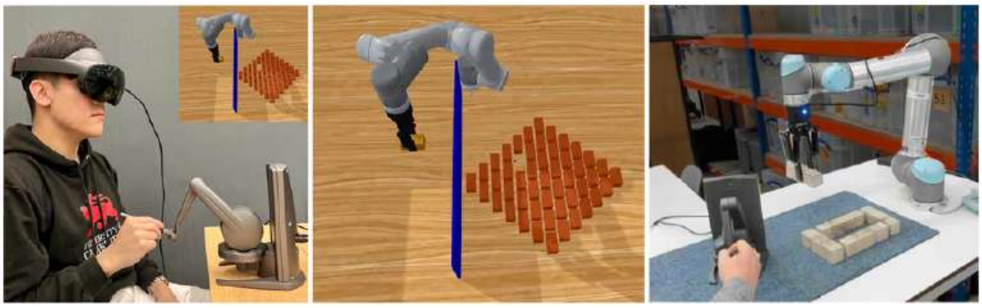
Parallel to interface development, the fellowship advanced theoretical foundations for embodied communication. An information-theoretic framework was introduced to extend Shannon's communication model toward embodied intelligence, incorporating sensor morphology, multi-modality, time-scale matching, and behavioral orchestration as key principles. This theoretical work positioned human–robot cooperation as a measurable communication channel, enabling systematic analysis of bandwidth, noise resilience, and fluency.

The second stage addressed adaptive control and physical interaction. Inspired by biological motor systems, reflex-based kinematic controllers were developed for artificial musculoskeletal systems. These controllers self-organized through learning rules driven by spontaneous motor activity and were capable of robust task-space control without explicit analytical modeling. The approach demonstrated scalability, disturbance rejection, and compensation for actuator failure, highlighting its suitability for complex manipulation scenarios.

In parallel, reservoir computing methods were investigated to encode robot dynamics and improve adaptability across varying body configurations. By aligning the temporal dynamics of reservoir systems with those of robotic platforms, a systematic design methodology was introduced that significantly improved control reliability while reducing manual tuning. These model-free controllers demonstrated strong performance in nonlinear and underactuated systems, reinforcing the feasibility of learning-based control for infrastructure robotics.

To enable safe and precise physical manipulation, a tactile-sensorized gripper was designed and validated for closed-loop control during cutting tasks. Using embedded soft sensors and recurrent neural models, the system estimated contact forces and torque in real time, enabling adaptive force regulation. This work demonstrated the importance of tactile feedback in tool-based manipulation and provided a foundation for sensorized end-effectors applicable to roadside maintenance operations.

Together, these efforts integrated digital twins, motion abstraction, adaptive control, tactile sensing, and learning-based architectures into a coherent framework for human–robot cooperation. The work bridged conceptual theory and experimental validation, advancing both scientific understanding and practical implementation strategies.



Major outcomes and significance

The fellowship produced significant scientific, technological, and conceptual contributions to the field of human-centric robotics.

Scientifically, the project advanced a unifying perspective on human–robot interaction grounded in embodied intelligence. By formalizing communication as an embodied information channel, the work moved beyond traditional command-based paradigms toward measurable, multimodal interaction frameworks. The integration of information theory with robotic embodiment provides a novel analytical lens for evaluating interaction efficiency, fluency, and robustness. This conceptual shift contributes to the broader evolution of human–robot interaction toward more adaptive and cognitively aligned systems.

Methodologically, the introduction and validation of motion-primitive-based orchestration demonstrated a practical pathway for reducing cognitive load in teleoperation. The empirical evidence showing improvements in efficiency and workload highlights the importance of abstraction in collaborative robotics. Rather than increasing autonomy at the expense of human agency, the orchestration paradigm enables shared control, preserving human decision-making while leveraging robotic precision and repeatability.

In adaptive control, the fellowship demonstrated that bio-inspired reflex architectures and reservoir computing frameworks can provide scalable, model-free solutions for nonlinear and underactuated systems. These approaches reduce reliance on precise analytical models and extensive domain randomization, offering improved robustness under structural variation and disturbance. The timescale alignment strategy for reservoir design further introduced a principled method for controller selection, minimizing risk during deployment and increasing reliability.

Technologically, the development of a tactile-sensorized gripper capable of real-time force estimation showcased the feasibility of incorporating soft sensing into tool-based robotic tasks. The integration of recurrent neural networks for mapping nonlinear tactile signals to contact forces enabled closed-loop manipulation under dynamic conditions. This advancement is particularly relevant for infrastructure applications where contact uncertainty and material variability are common.

Beyond individual components, the primary outcome of the fellowship is the integration of these elements into a coherent demonstration of human–robot orchestration. The project illustrates how digital twins, adaptive control, embodied communication, and multimodal interfaces can be combined to reposition human workers from hazardous physical environments into supervisory roles. This aligns directly with the principles of Industry 5.0, emphasizing human-centricity, inclusivity, and social sustainability.

The work also fostered interdisciplinary collaboration across robotics, control theory, cognitive science, and infrastructure engineering, strengthening international research networks. The results have broader applicability beyond road construction, extending to collaborative manufacturing, hazardous environment operation, rehabilitation robotics, and soft robotic manipulation.

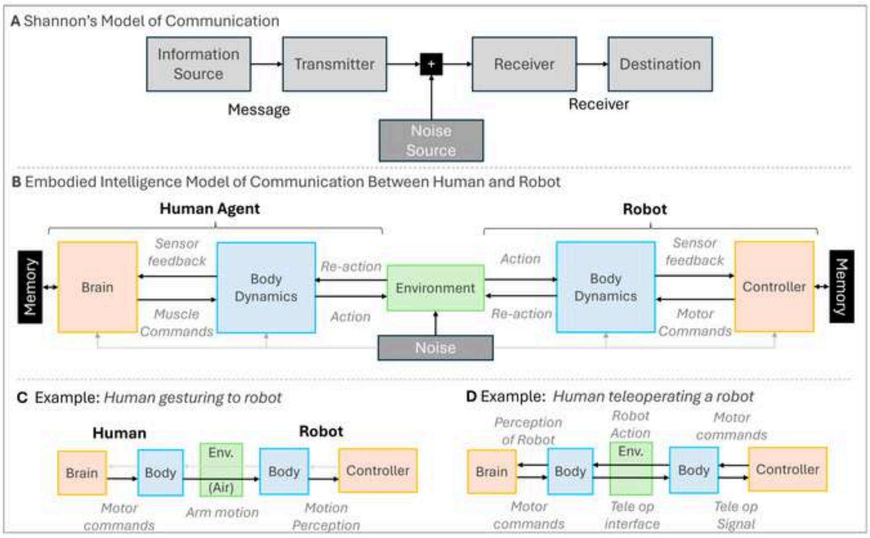
Collectively, the fellowship established both theoretical foundations and practical demonstrations knowledging a shift from teleoperation toward embodied orchestration, contributing to a safer, more intelligent integration of robotics into infrastructure systems.

Future direction

The next phase of this research will focus on scaling robotic orchestration from laboratory demonstrations to infrastructure-relevant deployments. A key direction is the integration of the orchestration framework with high-fidelity digital twins of construction environments, enabling predictive planning and decision support in dynamic roadside scenarios. Further development of sensorized end-effectors will expand tactile perception capabilities, allowing robots to manipulate heterogeneous materials under uncertain contact conditions.

On the control side, continued exploration of reservoir computing and reflex-based architectures will aim to unify adaptive dynamics learning with high-level task reasoning. The combination of embodied communication models and adaptive control opens opportunities for collaborative multi-robot systems coordinated through abstract motion primitives.

Ultimately, the goal is to establish a generalizable human–robot orchestration paradigm applicable across infrastructure maintenance, collaborative manufacturing, and safety-critical domains, advancing human-centric robotics beyond teleoperation toward scalable cooperative intelligence.



The fellowship set out to rethink how humans and robots collaborate in infrastructure maintenance and construction. Rather than pursuing full automation, the project proposed a human-centric paradigm in which robotic systems augment human capability through embodied communication and adaptive cooperation.

Through the development of haptic-enabled digital twins, motion-primitive-based orchestration, bio-inspired control architectures, reservoir computing methodologies, and tactile sensing systems, the fellowship demonstrated a coherent pathway from theory to implementation. The work contributed both conceptual frameworks and experimental validation, establishing orchestration as a viable alternative to direct teleoperation and purely autonomous control.

By framing human–robot interaction as an embodied information channel, the research provided measurable principles for designing interaction systems that are efficient, resilient, and cognitively aligned with human operators. This approach aligns with the broader vision of Industry 5.0, where technology supports safer, more inclusive, and socially responsible innovation.

Collectively, the fellowship advances the foundations of human–robot cooperation and offers a scalable blueprint for integrating robotics into complex, safety-critical environments.

CONTROL AND IMPLICATIONS OF MIXED AUTONOMOUS VEHICLE–INFRASTRUCTURE IN A HETEROGENEOUS MULTI-AGENT SYSTEM FRAMEWORK

Dr Kai Fung Chu

Marie Skłodowska Curie FUTUREROADS Fellow
Assistant Professor/Lecturer in AI at University of Bristol, UK

Connected and autonomous vehicles (CAVs) will soon become integral to road transport, driven by technological maturity and policy support. However, FUTUREROADS will remain heterogeneous, combining CAVs, human-driven vehicles, and intelligent infrastructure with only partial controllability. This fellowship will develop a unified framework to model, control, and assess such heterogeneous multi-agent transportation systems, explicitly accounting for real-time interactions among vehicles, dynamic reversible lanes, and intelligent traffic signals. By integrating data fusion, safety-aware control, and socio-technical analysis, the project will deliver actionable insights for deploying CAVs at intelligent intersections and dynamic road networks, enabling safer, more efficient, and governable future mobility systems.

Scientific concept and goals

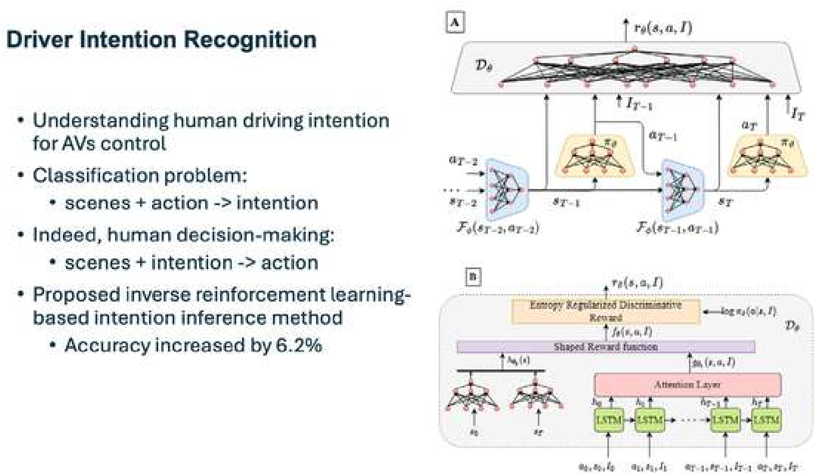
Future road transport systems will evolve into heterogeneous, partially controllable multi-agent systems composed of connected autonomous vehicles (CAVs), human-driven vehicles (HVs), and intelligent road infrastructure. While significant progress has been made in autonomous vehicle control and traffic management, existing studies largely isolate vehicles from infrastructure or assume homogeneous autonomy, limiting their applicability during the long transition toward mixed-autonomy roads. This fellowship is founded on the scientific premise that mobility intelligence must emerge from the coordinated interaction between vehicles, infrastructure, and human behaviour, rather than from vehicle autonomy alone.

The core scientific concept of this project is to establish a unified modelling and control framework for heterogeneous road systems, where vehicles and infrastructure are treated as interacting agents operating across multiple spatial and temporal scales. Building on the candidate's prior work on dynamic lane reversal, traffic signal control, autonomous fleet coordination, and learning-based traffic optimisation, the project will integrate heterogeneous data fusion, graph-based multi-agent modelling, and safety-aware learning control into a coherent framework capable of capturing emergent system-level behaviour. This perspective advances beyond traditional optimisation by explicitly addressing partial controllability, uncertainty from human drivers, and infrastructure-induced coupling effects.

The scientific goals are threefold. First, the project aims to develop high-resolution heterogeneous data fusion and multi-agent models that accurately represent interactions among CAVs, HVs, and intelligent infrastructure. Second, it seeks to design safe and interpretable control policies that coordinate controllable agents—vehicles, reversible lanes, and traffic signals—while guaranteeing safety under mixed autonomy. Third, the project will translate these technical advances into system-level insights by analysing implementation barriers and societal implications, informing governance, deployment strategies, and infrastructure investment.

Collectively, this research will contribute foundational methods for control, safety, and governance of future heterogeneous road systems, enabling a principled transition toward safer, more efficient, and human-centred mobility.

Fig 1. The proposed inverse reinforcement learning-based intention inference method for understanding human driving intention for AVs control. Different from the traditional method that takes scenses and actions for inferencing the intention, the proposed method uses inverse reinforcement learning to mimic human decision-making that takes scenes and intention for deciding the corresponding actions.



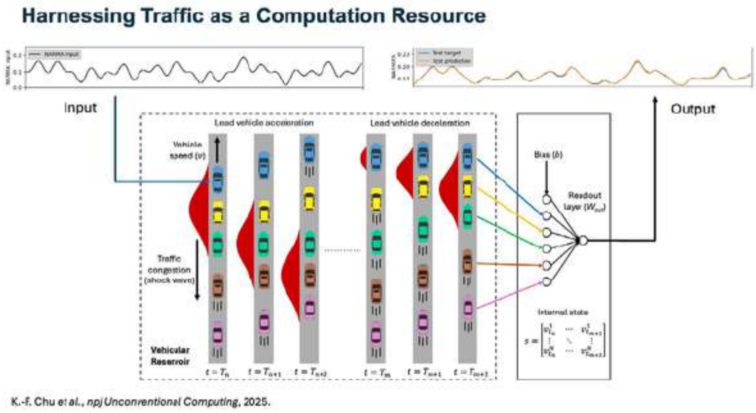


Fig 2. The process of the framework that harnesses traffic as a computation resource. In this unconventional computing framework, input is fed to the lead vehicle for projecting the input signal to a high-dimensional space with the physical dynamics of the following vehicles. With the trained linear readout layer, this framework can regress the target output accurately, similar to supervised learning.

Summary of the work carried out

The fellowship research was organised around the development, analysis, and validation of learning-based methods for heterogeneous transportation systems that combine connected autonomous vehicles (CAVs), human-driven vehicles (HVs), and intelligent infrastructure. The work carried out focused on modelling system interactions, designing control algorithms, and analysing system behaviour under mixed autonomy.

A first body of work addressed data-driven modelling and representation of transportation systems. Learning architectures were developed to process heterogeneous, high-resolution traffic data and capture spatial–temporal dependencies across road networks. Graph-based representations were adopted to model interactions among vehicles, infrastructure, and energy systems, enabling agents to dynamically enter, leave, or reconfigure within the network. These models were applied to travel demand prediction, origin–destination estimation, and state representation for downstream control tasks, forming a common modelling foundation across multiple studies.

A second core area of work focused on learning-based control of transportation systems. Reinforcement learning (RL) and multi-agent RL frameworks were developed and applied to traffic signal control, vehicle routing, fleet management, and infrastructure coordination. This included end-to-end RL for signalised intersections, multi-objective optimisation for routing and charging of electric autonomous vehicles, and cooperative control strategies across coupled traffic–energy networks. Particular emphasis was placed on scalability and decentralisation, allowing controllers to operate in large-scale networks without centralised coordination.

A third stream of work investigated heterogeneity and partial controllability in mixed-autonomy systems. Several studies explicitly modelled interactions between autonomous and human-driven vehicles, examining how learning agents adapt to uncertain and non-cooperative human behaviour. Control policies were designed to operate effectively when only a subset of agents is controllable, and simulation studies explored how infrastructure-level interventions can compensate for limited vehicle autonomy. These investigations provided practical insights into system behaviour during transitional phases of deployment.

Safety and robustness formed an integral component of the work carried out. Learning frameworks were augmented with physical constraints, disturbance awareness, and state-transition modelling to improve reliability under uncertainty. Rather than treating safety as a post-processing step, safety considerations were embedded directly into learning and control architectures. This work extended beyond traffic control to broader mobility systems, including cyber-security risks and adversarial behaviour in mobility-as-a-service platforms.

Finally, the fellowship explored emergent dynamics and collective intelligence in mobility systems. Recent work investigated how traffic dynamics and mobile agent interactions can be exploited for computation and learning, drawing on concepts from reservoir computing and embodied intelligence. These studies reframed transportation systems as active computational substrates rather than passive environments.

Together, the work carried out constitutes a systematic investigation of modelling, learning, and control for heterogeneous road systems, grounded in algorithmic development, simulation-based evaluation, and cross-domain integration.

Major outcomes and significance

The fellowship has produced a substantial and coherent set of scientific outcomes that advance the state of the art in intelligent transportation systems, autonomous mobility, and multi-agent learning. These outcomes are evidenced through high-impact journal publications, interdisciplinary contributions, and emerging conceptual frameworks.

A major scientific achievement is the advancement of learning-based control for real-world transportation systems. The fellowship delivered several journal papers demonstrating that reinforcement learning can outperform traditional optimisation methods in traffic signal control, fleet management, and routing—while remaining scalable to realistic network sizes. These works provide some of the earliest end-to-end demonstrations of off-policy and multi-agent learning applied to large-scale urban traffic, establishing new performance benchmarks in the field.

Another key outcome is the development of infrastructure-enabled autonomy as a scientific paradigm. Publications on dynamic lane reversal, intelligent intersections, and coupled power–traffic networks show that infrastructure can act as an active control agent rather than a passive constraint. This body of work provides rigorous evidence that intelligent infrastructure can unlock system-level benefits even when autonomous vehicle penetration is low, offering a practical and economically viable pathway toward future mobility.

The fellowship has also made significant contributions to safety, robustness, and trustworthiness of learning-based systems. Through physics-informed learning, disturbance-aware control, and constraint-compliant policy design, the work addresses fundamental concerns that have limited the adoption of reinforcement learning in safety-critical domains. These contributions extend beyond transportation and are relevant to robotics, cyber-physical systems, and autonomous decision-making more broadly.

A further important outcome lies in the integration of fairness, security, and societal considerations into mobility optimisation. Publications on proportional fairness, privacy-preserving learning, and adversarial behaviour highlight that intelligent mobility systems must balance efficiency with equity, resilience, and public trust. This work broadens the scope of transportation research and aligns technical innovation with societal needs and regulatory expectations.

Finally, the fellowship has opened a new research direction by linking collective intelligence and unconventional computing with transportation systems. By demonstrating how traffic dynamics and mobile agent swarms can enhance learning and computation, the research introduces a novel conceptual lens that positions road networks as embodied, self-organising systems.

Overall, the fellowship's outcomes significantly advance scientific knowledge, establish new interdisciplinary connections, and position heterogeneous, infrastructure-aware autonomy as a cornerstone of future road systems.

Future directions

Building on the outcomes of this fellowship, future research will extend heterogeneous multi-agent transportation systems toward greater scalability, autonomy, and societal integration. A key direction is the deployment of safe learning-based control in real-world pilot studies, integrating digital twins with live traffic and infrastructure data to enable continuous adaptation and validation. Methodologically, future work will further unify embodied intelligence, reservoir computing, and multi-agent learning to exploit emergent dynamics in large-scale road networks. Expanding beyond vehicles and infrastructure, human factors—such as risk perception, compliance, and ethical preferences—will be incorporated directly into system dynamics rather than treated as external disturbances. Finally, future research will address governance and standardisation challenges by co-designing control frameworks with regulators and industry partners, enabling certifiable, privacy-preserving, and equitable mobility systems. Together, these directions aim to accelerate the transition from mixed-autonomy research to deployable, trustworthy, and socially aligned future road infrastructures.

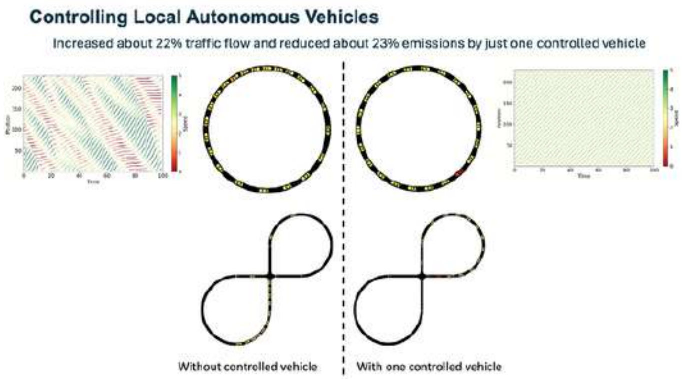


Fig 3. How the controllable autonomous vehicles can mitigate the traffic shockwave in various road structures. The proposed learning-based control approach turns a controllable autonomous vehicle into a traffic regulator that can mitigate the traffic shockwave. The simulation results show that having 5% controlled vehicles can improve 22% traffic flow and 23% emissions. Moreover, the learning-based control approach can learn and adapt to other road conditions.

This fellowship has advanced the scientific and practical foundations required to manage future road systems during the transition to mixed autonomy. By treating connected autonomous vehicles, human-driven vehicles, and intelligent infrastructure as interacting agents within a heterogeneous multi-agent system, the work moves beyond isolated control paradigms and offers a unified framework for understanding and shaping emergent mobility behaviour. The research has delivered rigorous learning-based and optimisation-based methods that improve efficiency while explicitly addressing safety, uncertainty, and partial controllability.

A central contribution of the fellowship is the demonstration that intelligent infrastructure—when co-designed with vehicle autonomy—can significantly amplify system-level performance even under low levels of vehicle automation. Equally important, the work has shown that trustworthy deployment of learning-based control requires embedding physical constraints, safety guarantees, and social considerations directly into algorithmic design. Through a substantial portfolio of high-impact publications, the fellowship has strengthened interdisciplinary links between transportation engineering, robotics, control, and artificial intelligence.

Overall, the outcomes of this fellowship contribute actionable insights for researchers, infrastructure operators, and policy-makers seeking to deploy connected and autonomous mobility responsibly. The research establishes a strong foundation for scalable, safe, and socially aligned road systems, and positions heterogeneous, infrastructure-enabled autonomy as a central pillar of future mobility innovation.

ROBOTICS FOR SAFE HUMAN–MACHINE INTERACTION

Dr Chapa Hewa Pelendage
Marie Skłodowska Curie FUTUREROADS Fellow
Assistant Professor/Lecturer in Assistive Robotics, University of Bristol, UK

This research explores robotic control and simulation to assess the feasibility of semi-automating machinery to improve worker safety. It is conducted in three stages: (1) evaluating multi-agent system algorithms that model close human–machine interactions in construction environments, (2) simulating representative scenarios and implementing safe human–machine interaction strategies, and (3) incorporating human input and preferences during system implementation.

Scientific concept and goals

We propose an agent-agnostic approach to ensure human safety while minimizing unnecessary separation between humans and machines. The primary objective is to allow human workers to operate as close to machines as required for efficiency, without compromising safety. This approach focuses on maintaining safe interaction distances dynamically rather than enforcing rigid exclusion zones. To achieve this, we implement a multi-agent system based on robotic control principles, enabling coordinated decision-making among autonomous agents. The system is designed to simplify safety management in complex and unstructured environments, such as construction sites, where human–machine interactions are frequent and unpredictable. By abstracting safety behaviors from specific agents, the proposed framework remains flexible and scalable, making it adaptable to diverse robotic platforms and operational scenarios.

Summary of the work carried out

In addition to simulating machines and accident scenarios, we developed custom hardware capable of extracting human state data through wearable sensors. A major contribution of this work is the implementation of heavy machine behaviors within a laboratory setting using robotic manipulation. The simulation framework supports collaboration among up to four machines performing a single task, while real-world experiments were conducted with up to two robots and two human participants, limited by laboratory space and inter-robot communication latency. Abstracting heavy machinery as robotic manipulators enabled precise control and repeatable experimentation, allowing key aspects of complex construction environments to be realistically modeled. This abstraction has resulted in a modular and extensible platform suitable for studying human–machine collaboration and safety.

Image 1. Implementation of robotic control with robotic manipulators and humans during a collaborative task

Major outcomes and significance

This work is significant for improving human safety in complex, dynamic environments where humans and machines operate in close proximity, such as construction and industrial settings. By focusing on proactive collision avoidance, compliant behavior, and guaranteed separation, the proposed approach directly addresses high-risk human–machine interactions that are difficult to manage with traditional rule-based safety systems. Treating humans and robots within a unified, agent-agnostic framework enables more natural and predictable interactions, reducing unexpected behaviors that can compromise safety.

A key strength of this work is its modular architecture, which allows individual components such as perception, control, decision-making, and human input modeling, to be independently improved, replaced, or adapted to different tasks and environments. This modularity supports scalability, long-term maintainability, and deployment across diverse platforms without redesigning the entire system.

Equally important is the emphasis on minimizing the simulation-to-reality (sim-to-real) gap. Reliable transfer from simulation to real-world deployment is essential for safety-critical systems, as discrepancies can lead to unsafe behaviors. By using realistic multi-agent simulations and control strategies that generalize well to physical systems, this work increases confidence in real-world performance. Overall, the approach contributes toward safer, more adaptable, and ethically grounded human–machine collaboration in complex environments.

Future directions

Future work will focus on enhancing both simulation platforms and real-world implementations to advance the system from Technology Readiness Level (TRL) 4 to TRL 5. This includes improving the fidelity of simulated environments, increasing the robustness of control and perception modules, and conducting more extensive validation in relevant operational settings. Additionally, a comprehensive evaluation of hardware requirements will be undertaken in parallel with an in-depth examination of ethical constraints related to human input, such as safety, autonomy, transparency, and consent. Balancing sensing, actuation, and computational capabilities with ethical considerations will be critical to ensuring that human–robot interaction remains safe, acceptable, and aligned with regulatory and societal expectations.

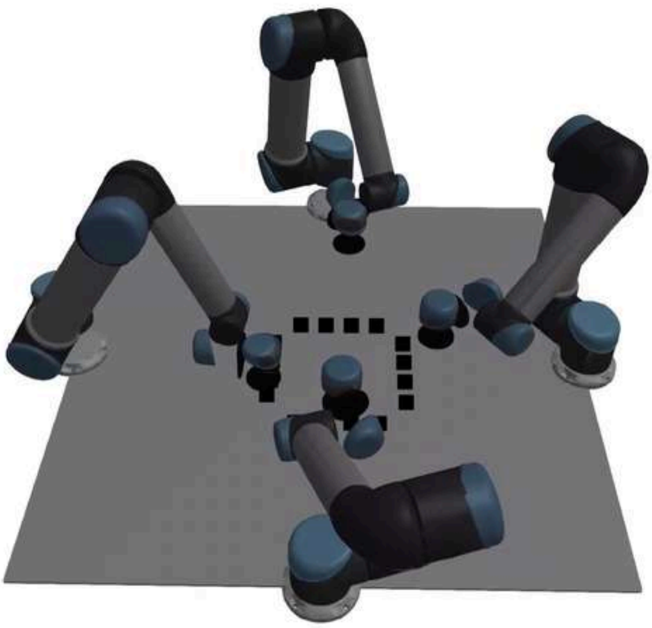


Image 2. Simulation of robotic control using simulators upto 4 robots during a collaborative task

This work demonstrates an agent-agnostic framework for multi-agent collaboration in which humans and robots are treated equivalently, enabling intuitive behavior shaping of both through simple parameter tuning. The proposed approach guarantees a minimum separation of approximately 20 cm while supporting active avoidance and compliant interactions. A VMC-based implementation with conflict-resolution capabilities detects deadlocks through force-balance analysis and resolves them by negotiating task priority with minimal communication, reducing the probability of robots becoming stuck in a block-placement task from up to 61.2% to zero. The decentralized design ensures scalability and robustness, allowing agents to seamlessly swap roles and adapt to changes in team composition. This was validated experimentally with up to two robots and two humans, and in simulation with up to four robots. Finally, the results highlight that subtle human cues provide valuable information for coordination and safety, underscoring the importance of incorporating such cues into human–robot interaction systems.

HIGHWAY INTELLIGENT TRAFFIC CONTROL SYSTEM BASED ON VEHICLE–ROAD COORDINATION AND MULTI–AGENT TECHNOLOGY

Dr Yue Xie
Marie Skłodowska Curie FUTUREROADS Fellow
Assistant Professor/Lecturer at the Loughborough University, UK

This project develops an intelligent highway traffic control framework based on vehicle–road coordination and multi-agent decision-making. It treats the highway as a coupled cyber–physical system in which vehicles and infrastructure interact under partial observability and distributed control. The approach integrates multi-agent reinforcement learning with optimisation and heuristic layers to deliver reliable, constraint-aware control in mixed-autonomy traffic. The framework targets reduced congestion and travel time, improved throughput and stability, and lower energy use and emissions. It is evaluated in simulation across diverse operational scenarios, including incidents, demand surges, and temporary traffic management, to produce actionable guidance for deployment.

Scientific concept and goals

This project explores how to achieve intelligent highway traffic control through vehicle–road coordination and multi-agent decision-making, aiming to improve network efficiency, resilience, and sustainability under realistic operational constraints. The scientific concept is to model the highway as a physical-digital coupled system where vehicles (autonomous and human-driven) and infrastructure (sensing, signalling, variable speed limits, and lane control) interact dynamically, with limited observability and distributed control authority.

The main goal is to develop a multi-agent traffic management framework that integrates reinforcement learning with optimisation and heuristic decision layers. Reinforcement learning supports sequential, interactive control in mixed-autonomy environments, while optimisation components help enforce constraints and improve reliability and sample efficiency. The framework targets measurable outcomes including reduced congestion and travel time, improved throughput and stability, and lower energy consumption and emissions.

A second goal is to extend the coordination framework to electric and connected vehicles, where routing decisions interact with charging availability and road conditions, motivating energy-aware scheduling and multi-objective trade-offs.

The project is validated through simulation-based evaluation across diverse scenarios, including mixed traffic, incidents, demand surges, and temporary traffic management. Deliverables include a unified modelling and control architecture, validated policies that generalise across scenarios, and practical insights into when coordinated multi-agent control provides clear advantages over conventional, decoupled traffic management.

Summary of the work carried out

During the FUTUREROADS fellowship, I developed and evaluated an intelligent highway traffic control concept based on vehicle–road coordination based on digital-twin framework.

I established a unified modelling view of the highway as a physical-digital twin system linking traffic flow, vehicle behaviour, and infrastructure control actions (e.g., speed management and lane-related interventions). On this basis, I formulated decision problems that connect network-level performance objectives (travel time, throughput, reliability) with sustainability objectives (energy use and emissions), and designed simulation scenarios to stress-test performance under incidents, demand surges, and temporary traffic management conditions.

Technically, I explored a layered approach that combines (i) multi-agent reinforcement learning for sequential, interactive control under decentralised observations, and (ii) optimisation and heuristic components to enforce constraints, provide interpretable baselines, and improve reliability where purely learned policies can be brittle. This supported systematic comparison between learning-based coordination and structure-aware optimisation.

A major strand focused on electric and connected vehicle operations. I developed multi-objective formulations that couple routing with charging/energy scheduling and examined mobility–energy trade-offs in coupled power–traffic networks. This resulted in peer-reviewed outputs on multi-objective evolutionary optimisation for EV routing and on collaborative routing with charging/discharging scheduling, as well as exploratory work on mixed-autonomy traffic with wireless charging using reinforcement learning.

To align with FUTUREROADS' digital infrastructure agenda, I also contributed to work on trustworthy AI-supported digital twin frameworks for road operation and maintenance, connecting decision outputs to auditable, maintainable operational pipelines.

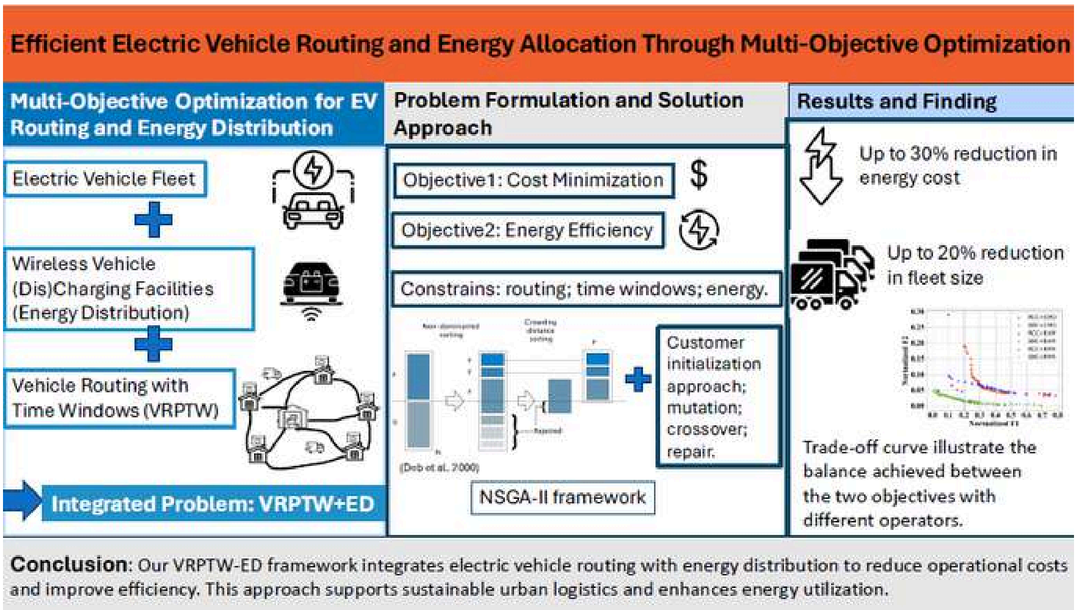


Fig 1. Efficient Electric Vehicle Routing and Energy Allocation Through Multi-Objective Optimization

Major outcomes and significance

A key outcome is an optimisation framework for EV routing that integrates logistics objectives with energy constraints and improves feasibility through constraint-compliant initialization. This delivers a practical algorithmic route toward scalable, deployable EV fleet operations, aligned with FUTUREROADS' sustainability agenda. This outcome is published in Applied Soft Computing (2025): A multi-objective evolutionary algorithm with constraint-compliant initialization for energy transport and urban logistics in Electric Vehicle Routing.

Then I extended the scope from routing alone to joint routing and charging/discharging scheduling in coupled power–traffic networks, formulated as a multi-objective problem. The significance is enabling system-level coordination across transport and energy infrastructure, which is essential for EV penetration at scale. This is published in IEEE Internet of Things Journal (2025): Collaborative Routing and Charging/Discharging Scheduling of Electric Autonomous Vehicles in Coupled Power-Traffic Networks: A Multiobjective Approach.

To support deployment realism, I contributed to a trustworthy AI-supported digital twin framework for road operation and maintenance, linking optimisation outputs to auditable operational pipelines: Development of a trustworthy AI-supported digital twin framework for road operation and maintenance.

Overall, the fellowship's significance is a coherent research line connecting multi-objective optimisation, energy–mobility coupling, and trustworthy digital road operations, with validated methods and peer-reviewed dissemination.

Future directions

Future work will focus on advancing the traffic management framework into a deployable **multi-agent system** that remains robust under mixed autonomy, partial observability, and operational constraints. A first direction is to develop hierarchical and hybrid multi-agent architectures, where infrastructure agents (e.g., speed and lane control) coordinate with vehicle agents (routing, compliance) through structured communication and constraint-aware decision layers. A second direction is to improve generalisation and safety, using offline and imitation learning from historical operations, domain randomisation, and safety filters to guarantee stability during incidents and temporary traffic management. Third, I will investigate multi-objective multi-agent learning that explicitly balances mobility, emissions, and energy use, and quantifies coordination benefits versus control authority. Finally, I will connect the multi-agent policies to a digital-twin evaluation loop for scenario generation, stress testing, and continuous calibration, enabling credible evidence for National Highways-aligned field trials and incremental deployment.

This project aims to developed an intelligent highway traffic management concept based on vehicle–road coordination and multi-agent decision-making. Highways were treated as coupled systems where vehicles, infrastructure, and energy services interact under partial observability and distributed control. Within this framing, I defined decision problems and evaluation pipelines that link mobility outcomes (travel time, throughput, reliability) with sustainability outcomes (energy use and emissions), and assessed performance under disruption scenarios relevant to operations.

A central contribution is the integration of energy-aware optimisation into transport control. The fellowship produced peer-reviewed advances in multi-objective evolutionary optimisation for EV routing and in collaborative routing with charging/discharging scheduling in coupled power–traffic networks, providing practical algorithmic building blocks for coordinated mobility and energy operations. Complementary exploration of reinforcement learning in mixed-autonomy settings supports the longer-term aim of scalable multi-agent coordination.

AI-ASSISTED UNCONVENTIONAL ROAD SURFACE MONITORING

Dr Xiang Wang
Marie Skłodowska Curie FUTUREROADS Fellow

Road transportation is an important component of transportation. Numerous roads to be monitored are a challenge for the management by the authorities. Untimely road maintenance endangers the safety of drivers and vehicles. Low-cost and high-efficiency road surface monitoring becomes an important target for FUTUREROADS. Conventional road surface monitoring systems have the disadvantages of high costs and difficulty to be improved. Automated driving shows potential for future road transportation. Will autonomous vehicles mounted with non-conventional sensors monitoring roads be a future road surface monitoring solution? This research will develop a low-cost road surface monitoring system mainly based on autonomous-vehicle-mounted sensors. The key research points are the advanced computing methods for analysing road surface conditions based on the data collected from the vehicles and developing unconventional sensors as complementary sensing components for road surface monitoring. Currently, an optical computing-based method is developed in simulation for analysing the road surface conditions as an advanced computing unit for road surface analysis. Soft sensors are developed for road surface profile monitoring. This research aims at realising a low-cost vehicle-mounted sensor-based road surface monitoring system, which is helpful to improve the driving safety of drivers and vehicles and improve road maintenance efficiency.

Scientific concept and goals

The scientific concept is to utilise vehicles as distributed sensing resources for road monitoring, acquiring road condition information through vehicle-mounted sensors and analysing this information using novel computational methods to enable efficient and low-cost road surface monitoring.

The core goals of this research are to:

1. Develop advanced computing methods for analysing road surface conditions using multi-source vehicle-mounted sensor data,
2. Design and integrate unconventional and soft sensors as complementary tools for road surface monitoring.

Summary of the work carried out

TThe work carried out in this research focuses on two directions, computing and sensing, for road monitoring.

For computing, an optical computing–based approach was developed for road surface condition monitoring. A physical optical reservoir computing framework was used to analyse vehicle-mounted acceleration data, enabling the inference of road surface fluctuation characteristics and roughness-related indicators without explicit road–vehicle modelling.

For sensing, a fibre-optic-based soft sensor was designed for deformation perception. The sensor was integrated into a deformable, translucent material and utilises optical dissipation and colour-based responses to capture spatial deformation information, such as bending direction and magnitude, providing a flexible and low-cost solution for deformation sensing.

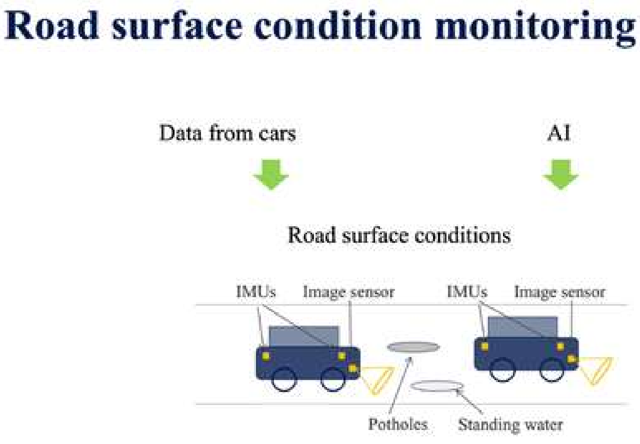


Fig 1. Vehicle-mounted sensor-based road surface monitoring system

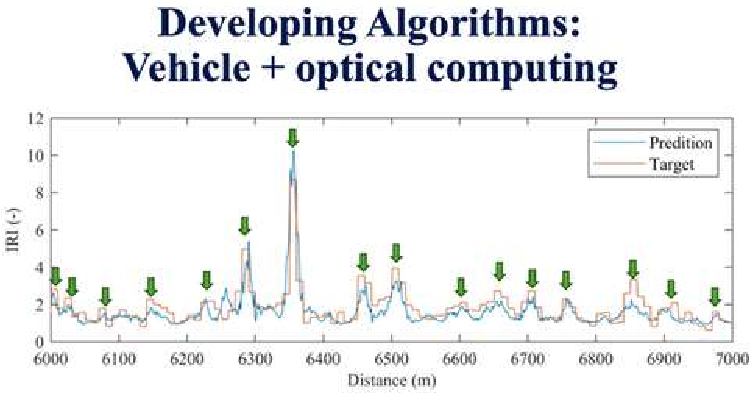


Fig 2. Developing algorithms for road surface monitoring

Major outcomes and significance

This research has delivered two major outcomes with quantitatively demonstrated performance, supporting the feasibility of low-cost, vehicle-based road monitoring and deformation sensing.

First, an optical computing–based road surface monitoring method was successfully developed and validated. Using a physical optical fibre–based reservoir computing framework, road surface fluctuation slopes and international roughness index (IRI) were predicted from vehicle-mounted acceleration data. The results show that approximately 90% of road surface fluctuation peaks and valleys were correctly identified. For road roughness evaluation, the prediction accuracy of the 100 m averaged IRI reached about 86%, while the accuracy for 10 m IRI segments was approximately 73%. These results demonstrate that the proposed optical computing approach can reliably extract meaningful road surface information from low-cost vehicle sensors, without relying on explicit road–vehicle dynamic models.

Second, a soft fibre-optic sensor for deformation perception was designed and experimentally validated. By embedding a dissipative optical fibre sensor pair into a translucent soft material, spatial deformation information was successfully captured through optical dissipation and colour-based expression. Quantitative inverse estimation showed that bending angles and displacements could be reconstructed with a root-mean-square error of approximately 13.9° for angle estimation and 0.9 mm for displacement estimation under controlled deformation. The sensor demonstrated clear directional sensitivity and repeatable responses, confirming its capability for deformation monitoring in soft and flexible structures.

The significance of this work lies in its demonstration that both road surface conditions and structural deformation can be monitored using unconventional sensing and computing approaches with quantified performance. The optical computing results show that high-level road condition indicators can be inferred with accuracy comparable to data-driven methods. The soft sensor results demonstrate a lightweight and low-cost alternative to conventional deformation sensing, with direct optical perception of spatial states.

Future directions

Future work will focus on advancing road surface monitoring through both algorithms and sensing technologies. Advanced algorithms will be developed to analyse road surface conditions using data from vehicle-mounted sensors, improving robustness and real-time capability by designing optical computing methods. In parallel, tyre-like sensors will be designed to directly interact with the road surface, providing complementary information for road surface monitoring.

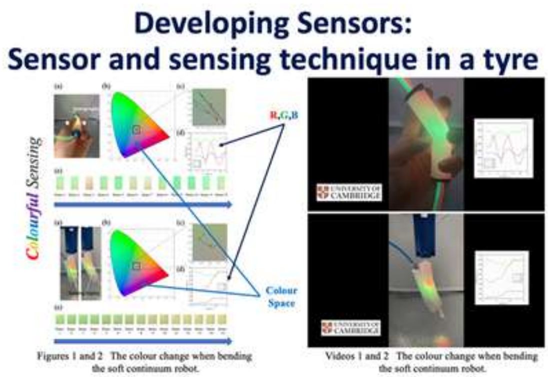


Fig 3. Developing a sensor and sensing technology in a tyre

By developing the sensor and computing methods based on the optical methods, the feasibility and performance of the road surface monitoring system have been investigated, which gives the potential for vehicle-sensor-based road surface monitoring. Future work will focus on advancing data-driven optical computing algorithms and developing tyre-like sensing technologies to further improve the accuracy, robustness, and feasibility of road surface monitoring.

PUBLICATIONS

PUBLICATIONS

PROGRAMME LEVEL

Book of Abstracts

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Policy Response

- Defining the Digital Road Manager - Public Consultation Response, 2024, University of Cambridge, UK

DIGITAL TWINS / DATA SCIENCE

Policy Response

- Varun Kumar Reja, UK 10-Year Infrastructure Strategy – Consultation Response, University of Cambridge, 2025

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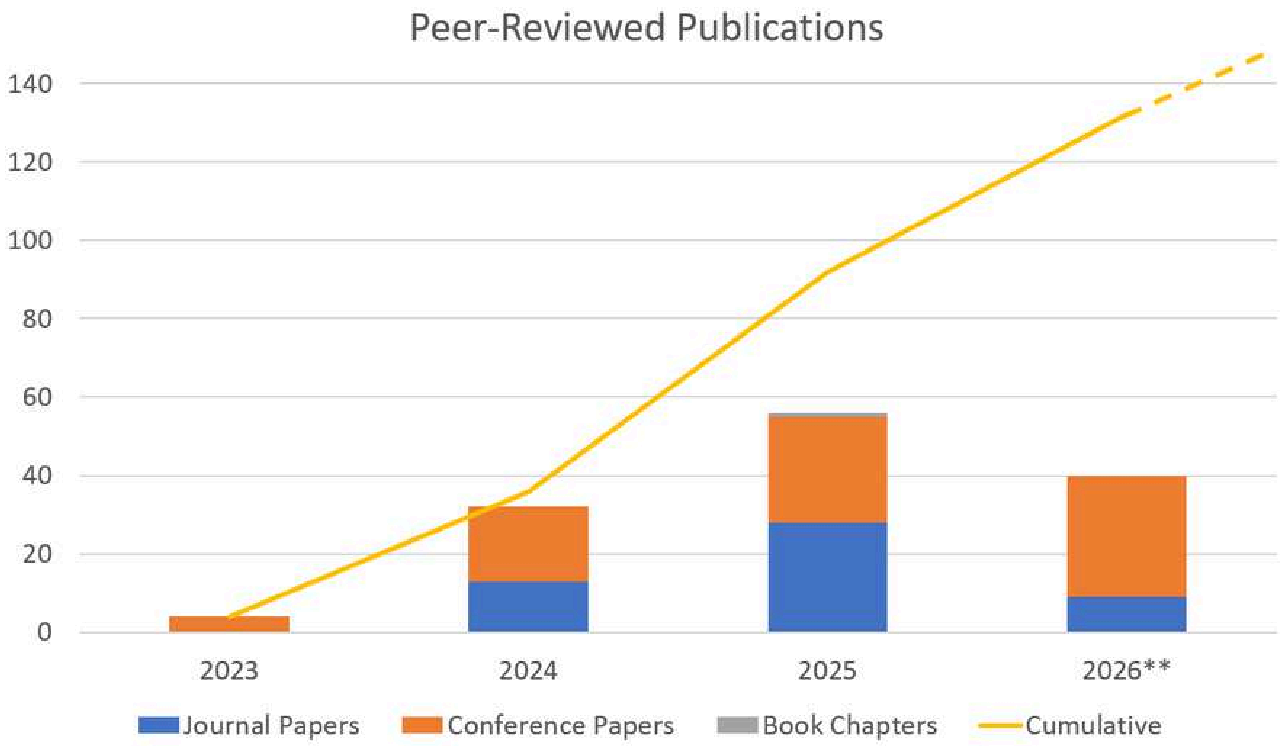

80% journals ranked Q1*

*SCImago Jorunal Ranking,
top 25% journals in subject category

138 publications**

**as of July 2026

17 joint publications with industry partners**

COLLABORATION PARTNERSHIP

COLLABORATION

INDUSTRY PARTNERS

Industry engagement is a defining characteristic of FUTUREROADS and is delivered through a network of 24 industry partners who contribute throughout the entire fellowship lifecycle, from identifying research challenges to supporting the implementation and impact of research outcomes.

Industry partners are also key co-funders of the programme, making substantial financial contributions to support fellowships, training, secondments, research activities, and programme delivery. This investment demonstrates the sector's commitment to developing future research leaders and accelerating innovation across the transport and infrastructure sectors.

Through a co-creation approach, industry representatives worked closely with academic partners to identify and define research and innovation challenges that formed the basis of the fellowship calls. This ensured that the programme addressed genuine sector needs and reflected future industry priorities.

Industry partners played an active role in recruitment, serving on the Selection Committee. Following recruitment, they continued to play a central role in programme delivery by contributing to induction events, technical and professional training, workshops, and cohort-building activities. Through these activities, they provided valuable insights into industry challenges, innovation processes, sustainability, policy development, commercialisation, and the adoption of new technologies.

Industry representatives regularly delivered seminars, guest lectures, and technical talks, while also contributing to panel discussions, roundtables, and debates throughout the fellowship programme.

Partners hosted fellows for site visits and secondments, organised workshops and showcase events, provided access to facilities and operational environments, and shared real-world case studies and datasets to support research development and validation. They also invited fellows to participate in partner-led conferences, innovation events, and professional forums, creating valuable opportunities for networking, collaboration, and knowledge exchange.

Each fellow benefited from industrial supervision and mentoring through dedicated industry co-supervisors, who contributed to research direction, career development planning, secondment activities, and impact generation.

Industry participation also extended to programme governance. Industry representatives served on the Steering Committee, Supervisory Board, and Quality Assurance Group, contributing to strategic oversight, programme monitoring, quality assurance, ethics considerations, risk management, and the continued alignment of the programme with industry needs.

COLLABORATION

INDUSTRY PARTNERS

Collectively, the 24 industry partners have been instrumental in creating a vibrant and collaborative research environment that bridges academia and industry. Their sustained commitment has enriched the fellows' experience, strengthened the quality and impact of the research, and supported the development of the next generation of research and innovation leaders.

The FUTUREROADS team would like to express its sincere gratitude to all industry partners for their exceptional commitment, expertise, time, and support. Their active participation has been essential to the success of the programme and has created lasting benefits for the research community and the wider infrastructure sector.

national highways

"The Roads Research Alliance (RRA) gave the programme a broader industry base, a stronger route to impact and a collaborative structure that could help turn research into practical value. We are hugely grateful to the 22 founding industry members of the Alliance, whose commitment, insight and expertise helped create the momentum behind the RRA. Their willingness to share challenges, data, experience and practical know-how has been central to the success of the collaboration.

What makes the Alliance special is the combination of academic excellence, operator insight and industry commitment. It was never just about funding research. It was (and is) about creating a community with a shared purpose: to accelerate innovation and make sure great ideas have a pathway into real-world benefit for the roads sector."

Phillip Proctor - Head of Research, SES Quality, Standards, Research & Innovation at National Highways

COSTAIN

Department for Transport

COLLABORATION

INDUSTRY PARTNERS

ARCADIS

"A significant benefit of this collaboration has been the push for industry-wide standards. While bridging academic research to tangible industrial outcomes remained a challenge—at times impacting engagement from the industry side—the interaction between members and researchers proved to be of great value.

Bringing stakeholders together to exchange knowledge and experience was highly beneficial. The online sessions and presentations provided useful exposure to current challenges and innovative ideas for solving them."

Will Waller, Senior Director at Arcadis

AECOM

"FUTUREROADS Research Programme addresses current industry practical issues and future needs of resilience, digitisation and automation. The research themes align with National Highways' Connecting the Country - Planning for Long Term and Local Authorities key strategies, such as Sustainability, Smart Materials, Automation, Data Science and Digital Twins.

AECOM decided to join the programme as the research projects are proposed and driven by asset operators and managers, designers, contractors and materials and technology suppliers to provide sustainable road infrastructure. AECOM has contributed, supported and guided many research projects to solve practice issues facing our infrastructure future resilience."

Dr Bachar Hakim, Director – Infrastructure Technical Lead, Surface Transportation, Aviation and Ports Infrastructure at AECOM

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INDUSTRY PARTNERS

We got involved in the Future Roads program as it was clear that tried and tested approaches to managing our transport infrastructure were failing to keep up both with changing need and emerging technologies and solutions. Fresh thinking was needed, even if this presented us with challenges associated with how we turn research into deployable solutions.

From our perspective, the research has shown that there are solutions to many of the challenges we face, and that our ideas regarding how to overcome them were sound. It is unfair not to mention every piece of research, but if pressed I would suggest that the digital twin research, the research into flood modelling and the robotic systems research were particularly well received. Again, challenges remain but this work has shown us a way forward.

Prof Dr Matt Peck - Director of Innovation - Transportation at AtkinsRéalis

I find it really insightful to see first-hand how research and industry can combine to innovate in response to the key challenges our sector (and planet) is facing, by drawing on expertise and technological advancements.

Simon Hayton - Head of Engineering and Performance at AUREOS

Balfour Beatty joined the FUTUREROADS Programme to help accelerate innovation that strengthens the safety, resilience and sustainability of the UK's strategic road network. The programme enables collaborative research and real-world testing of solutions that reduce carbon, enhance performance and improve journey reliability. By working in partnership with industry, academia and National Highways, we gain early insight into emerging technologies and data-driven approaches, strengthening our ability to deliver smarter infrastructure and create measurable, whole-life value for customers, communities and the network.

Michael Schenk - Head of Demand, Operations & Innovation Planning, Balfour Beatty

COLLABORATION

INDUSTRY PARTNERS

Colas Ltd entered the programme in a supervisory capacity aligned with the second and third cohort of research fellows, across projects including structural condition monitoring, low carbon materials and network resilience.
It has been very rewarding for myself, and colleagues from different technical and analytical functions, to see the research directions evolve as the collaboration and mutual understanding between the industry and academic domains have strengthened.

The opportunity to engage directly with fundamental research is very different to the conventional R&D activity undertaken within the UK highways sector, enabling different perspectives to overcoming barriers to operational implementation of future innovations.

Dr Oliver Thomas - Innovation Manager, Colas

As an Industry Partner, joining the FUTUREROADS Programme has given Galliford Try a valuable platform to collaborate with leading researchers and industry peers, and gain access to valuable research all within the inspiring historic setting of Cambridge. As part of the wider National Highways Roads Research Alliance, we help ensure Cambridge led research aligns with National Highways' priorities for safer, more resilient and lower carbon roads, while also bringing real world industry challenges to the fore.
Our involvement in research reviews, industry days and technical training has strengthened our understanding of emerging technologies, and allowed us to contribute practical, construction focused insight to the development and testing of new innovations.

Ed Wells, Head of Digital Construction - & Phil Farrar, Infrastructure Highways Innovation Champion & Safety Hub Lead, Galliford Try

COLLABORATION

INDUSTRY PARTNERS

Jacobs

KIER

Ordnance Survey

"The FUTUREROADS Programme has been an invaluable opportunity to bridge research and real world impact. Ordnance Survey joined the programme to help shape the future of connected infrastructure, ensuring that our authoritative geospatial data underpins scalable, interoperable digital solutions. Our collaboration has enabled the translation of complex concepts, such as digital twins, into practical guidance that benefits industry. Highlights include joint work on national scale modelling and the development of resources on Digital Twins trust, which accelerate innovation and support more resilient, efficient infrastructure planning."

Dr Stefano Cavazzi - Principal Innovation & Research Scientist, Ordnance Survey

RAMBØLL

"Ramboll joined the FUTUREROADS programme to make a positive contribution to research that has the potential to transform roads in the UK, bringing cutting edge research through to tangible project outcomes. We have found the collaboration with the university, National Highways and industry partners to be a highlight of the scheme. There are still lots of challenges in linking research through to onsite implementation, but the shared purpose of doing so has been excellent."

John Armitage - Technical Director, Ramboll

SAP

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COLLABORATION

INDUSTRY PARTNERS

"Trimble joined this programme to bridge the gap between academic research and real-world industrial applications. Our goal was to collaborate with researchers to solve complex infrastructure challenges while connecting with other industry members to better understand their specific pain points and needs. A significant benefit of this collaboration has been the push for industry-wide standards. While bridging academic research to tangible industrial outcomes remained a challenge—at times impacting engagement from the industry side—the interaction between members and researchers proved to be of great value. Bringing stakeholders together to exchange knowledge and experience was highly beneficial. The online sessions and presentations provided useful exposure to current challenges and innovative ideas for solving them."

Dr Marianna Kopsida - Industry Manager at Trimble

"Trimble joined FUTUREROADS to ground cutting-edge research in industry reality. Collaborating with Mengtian Yin gave us early access to automated BIM classification and quality-assurance strategies that directly reduce manual rework. By testing these models within, we co-developed a practical "crosswalk" for National Highways' asset standards. This has accelerated our path toward scalable digital delivery. For Trimble, the benefit is a technically rigorous pipeline for asset handover and a deeper understanding of how emerging academic methods solve real-world data challenges."

Kieran Mulvey-Customer Success Manager at Trimble

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* as of July 2026

Acknowledgements

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.