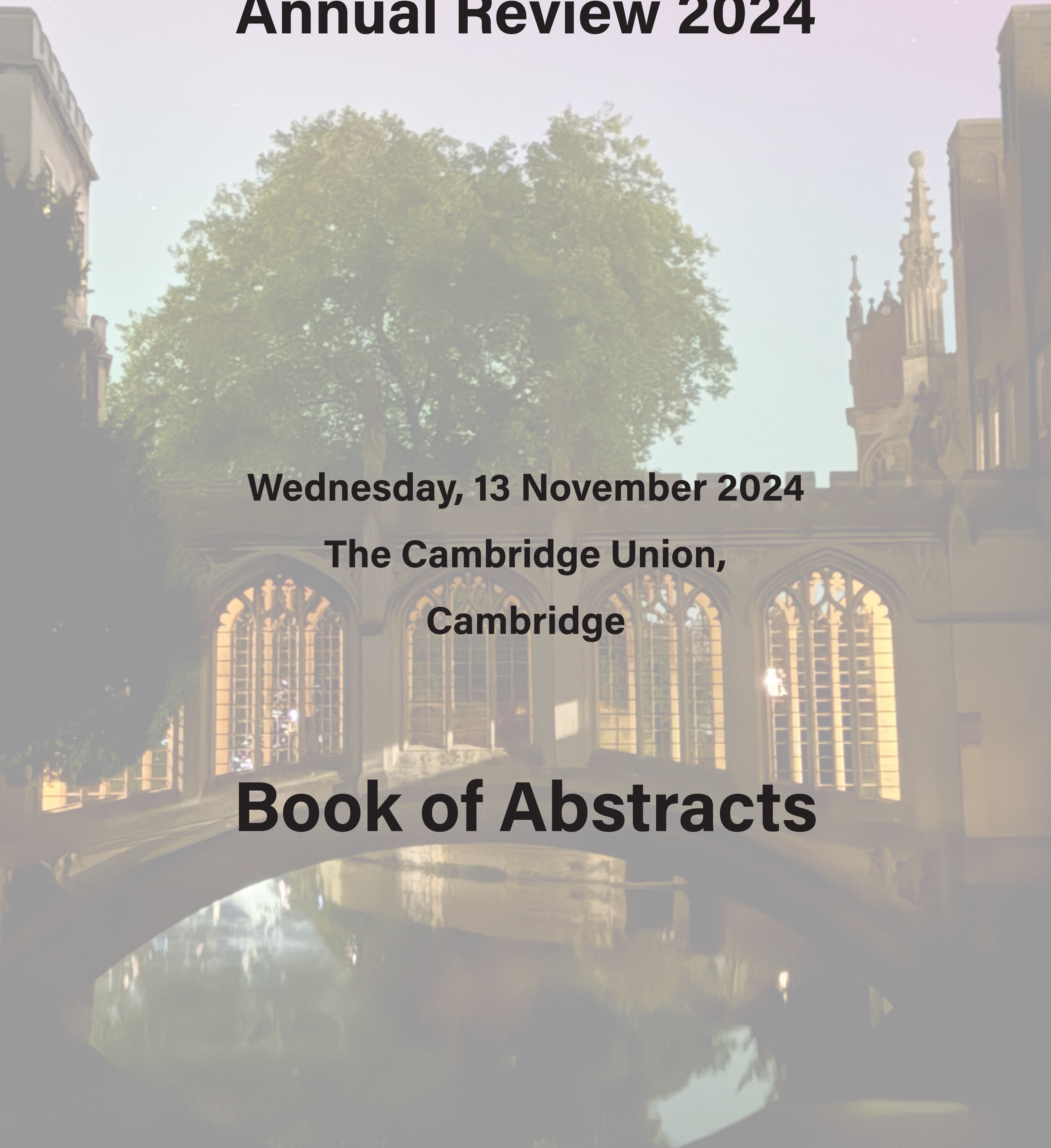
UNIVERSITY OF CAMBRIDGE

LAING O'ROURKE CENTRE *for* CONSTRUCTION ENGINEERING *and* TECHNOLOGY

Digital Roads of the Future
Annual Review 2024



Wednesday, 13 November 2024

The Cambridge Union,

Cambridge

Book of Abstracts

Foreword

Smart Materials is the overarching theme of my research activities with a focus on decarbonisation, digitalisation and environmental protection. Most recent initiatives included Digital Roads Prosperity partnership, Future Roads COFUND Fellowships, Resilient Materials for Life Programme Grant and the National Research Hub DARe.

Research activities presented in this book of abstracts include the development of enhanced repair materials for robotic pavement maintenance, development of low carbon cementitious pavement materials, carbon capture and storage in pavements, circular economy approaches to road projects excavation wastes, enhanced carbon calculations, advanced data-driven analyses and interpretation of road performance data, lessons learnt from international standards and pavement designs, advanced sensor technology for early stage corrosion detection, and life cycle and material flow analyses of future decarbonised and resilience transport infrastructure scenarios.

This work has been carried out by a fantastic team of SRAs, PDRAs, Research Fellows and PhD students.

Professor Abir Al-Tabbaa
Professor of Civil & Environmental Engineering
Department of Engineering
University of Cambridge

It is useful, I think, to consider sustainability from two perspectives. First, sustainability can be a feature in other scientific areas – where research adopts principles of sustainability and is directed towards more sustainable outcomes. Second, as a specialist area of endeavour, sustainability forms a field of research that deals with the interaction between natural, social and technical systems, and establishing methods for understanding what good outcomes look like. This is the perspective that shapes the research of Future Roads Sustainability Fellows.

We have four fellows leading projects under this theme. These cover: transport modelling with a focus on climate hazard impacts – starting with flooding, with the intention of expanding to other hazards (Jie Liu and Zizhen Xu); advancing carbon data management across the highways sector – building on existing capabilities and taking a wider systems view (Jinying Xu); and, determining equality, diversity, and equity outcomes for active travel infrastructure – a project that has recently leveraged wider digital skills available within the DRF programme (Khashayar Kazemzadeh). A particularly rewarding aspect of these projects has been the industry relationships that have been developing, and how these has shaped the direction of the projects and secondment opportunities.

Dr Kristen MacAskill
Associate Professor in Engineering, Environment and Sustainable Development
Department of Engineering
University of Cambridge

In recent years, our research group has seen remarkable growth, both in capacity and quality, as numerous funded projects have advanced to full implementation. This dynamic mini-ecosystem, hosted at the Civil Engineering Building in West Cambridge, promotes a collaborative space where researchers, academics, and industry partners unite, creating valuable and innovative synergies.

Co-locating like-minded individuals has inspired forward-thinking initiatives and cutting-edge research across multiple themes. I am honoured to lead this pioneering work in technology development within civil engineering, where the continuous exchange of ideas with colleagues and partners powers pioneering growth and advances the visibility of our research.

As our projects mature, their impact is becoming more evident, and we anticipate a profound influence in the near future. I invite you to explore this collection of abstracts, which encapsulates the pioneering spirit of our research group and the promising path forward.

Professor Ioannis Brilakis
Laing O'Rourke Professor of Civil and Information Engineering
Department of Engineering
University of Cambridge

The future of infrastructure is intertwined with advances in robotics, where digital roads serve as a transformative platform. As our society shifts towards smarter, more sustainable solutions, robotics research plays a pivotal role in redefining road construction and maintenance.

Central to this vision is the concept of human-in-the-loop robotic systems, enhancing decision-making, efficiency, and adaptability. By actively involving human expertise, these systems foster sustainability and scalability, addressing complex challenges in road infrastructure. Collaboration with smart material scientists enables the development of adaptive, resilient materials, while partnerships with digital twin researchers allow for real-time monitoring and predictive maintenance.

This synergy not only drives advancements in autonomous robotics but also accelerates the transition to sustainable, responsive road networks. Together, these research efforts create a digital road ecosystem that integrates human insight with cutting-edge technology, laying a foundation for resilient and adaptable infrastructure in an ever-evolving world.

Professor Fumiya Iida
Professor of Robotics
Department of Engineering
University of Cambridge

Our partners

Digital Roads Prosperity Partnership is supported by the Engineering and Physical Sciences Research Council (EPSRC), part of UK Research and Innovation (UKRI) Grant [EP/V056441/1]

FUTUREROADS has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101034337.

Table of Abstracts

Digital Twin for Sustainability: driving value for digital innovation and decision making with AI

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Digitalization in the construction industry offers unprecedented opportunities to enhance sustainable project delivery. Companies struggle to manage the time, cost, safety, environmental impacts and quality dimensions of projects. Digital Twin (DT) and Artificial Intelligence (AI) have been widely applied in other industries, such as the automobile and manufacturing sectors. Existing literature has explored the benefits and challenges of adopting DT and AI in construction; however, there is no clear guidance about how the industry can best leverage the technologies to design their specific sustainable solutions. Despite the readily available technologies, local authorities and private corporations are still plagued by little understanding of digital transformation, hence unavoidably delaying innovation progress.

This research project thus aims to work with industry partner: Far East Consortium (FEC), to investigate spilling over values from DT and AI in construction. The research project has three overriding research aspects: 1) AI-driven whole life cycle assessment twinning in buildings; 2) digital building planning and approval DT system for smart bidding decisions; and 3) ethical use of AI and data governance for responsible development.

1) The first aspect centres on the urgency to reduce carbon emissions from buildings by DT platform and AI analytics. Whole life cycle assessment (WLCA) is a widely accepted methodology to facilitate the design and construction of net zero buildings. Previous studies have examined the advantages and drawbacks of integrating Building Information Modelling (BIM) and WLCA. Nonetheless, being a static model, BIM-based WLCA displayed several challenges, including the predicaments of dynamic data update, trustworthiness in data transfer and inconsistent WLCA measurements. To address the barriers, this research will investigate the integration of WLCA and DT to enable real-time simulations and dynamic data flow throughout the building life cycle. It will first explore the trends of DT-based WLCA, develop a methodological framework, and followed by verification in FEC residential buildings.

2) Apart from the environmental aspect, digitalization of planning and approval plays a significant role in optimizing resource planning and bidding decisions. This research aims to address gaps about inefficiencies in building permit applications and enhance transparency in the approval procedures by DT. The findings will provide insights about “what” DT information is necessary to automate building permit applications and “how” project managers can exploit DT to enhance their confidence in winning the bids.

3) The above two research themes illustrate the growing trend of supplementing construction decisions with digitalized tools. It is therefore crucial to ensure the ethical use of AI-driven DT platforms. Studies concerning cybersecurity of open-sourced data, data ownership among stakeholders and intellectual property infringement along supply chains, are not yet comprehensive to bolster users’ trust when applying the technologies, thus limiting their wide adoption. The final aspect will discuss how industry leaders and local authorities can make ethical and informed choices by AI and build trust with one another in the digital transformation era while maintaining their data privacy.

The three research aspects will combine both academic theories and practical case studies at FEC asset for developing frameworks that push the next wave of sustainable development with DT and AI.

D-Hydroflex: Digital solutions for improving the sustainability performance and FLEXibility potential of HYDROpower

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D-Hydroflex is a €4.5 million EU collaborative research project with 17 partners from 8 counties. Increasing demand for flexibility and sustainability in Europe's clean energy transition, driven by the growing share of renewable energy sources, has highlighted the need for enhanced efficiency and flexibility in hydropower systems. Digital Twin (DT) technology, which has already shown significant success in other industries, holds great potential for improving the operation, maintenance, and environmental sustainability of hydropower plants (HPPs). The D-Hydroflex project aims to revolutionise the operation and sustainability of hydropower plants by developing advanced digital solutions. Central to the project is creating a cloud-based monitoring and diagnostics centre, which will enable real-time insights into plant operations, predictive maintenance, and optimisation of HPP efficiency. By implementing DT for hydro units and dams alongside AI-based frameworks and biodiversity monitoring algorithms, D-Hydroflex enhances operational flexibility and environmental sustainability. The project responds to the evolving needs of the European energy system, facilitating greater integration of renewable energy sources (RES) while reducing hydropower outages.

The University College London and the University of Cambridge are collaborating on key aspects of the D-Hydroflex project, with a focus on developing and advancing DT technology for dam operations and maintenance. UCL's task involves defining the architecture of the DT platform to meet predictive maintenance requirements, ensuring information interoperability, data integration and established models from BIM and GIS environments like IFC and CityGML. The architecture outlines DT platform components, interfaces, data repositories, and exchange formats, including protocols for information transmission and business workflows. Meanwhile, the University of Cambridge is working on automating the creation of geometric DT by leveraging point cloud, visual, and thermal data to generate detailed object-oriented models of dam structures. Cambridge team develops AI-driven methods for detecting dam components and creating converters for DT platforms, rigorously testing system performance across use cases to set benchmarks for future applications.

Innovations will be demonstrated in seven operational HPPs across five European countries—Spain, France, Poland, Romania, and Greece—validating tools for predictive maintenance, anomaly detection, hybridisation with hydrogen production, and smart grid integration. D-Hydroflex's outcomes promise substantial environmental benefits, including reduced CO2 emissions, improved RES penetration, and support for EU decarbonisation goals.

Automating Construction and Maintenance of Road Geometric Digital Twins

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The research focuses on automating the process of constructing and maintaining geometric digital twins (GDT) of highways and other roads using large-scale spatial and visual datasets to reduce related costs and enable further applications such as performance optimisation, failure prediction and future scenario modelling.

Problem statement: Road construction is one of the fields where poor performance is observed, with many cases of construction costs overrunning. The growing population will increase the demand for roads, which are already in heavy use. It is important to construct and operate road infrastructure in such circumstances efficiently. There is evidence to suggest that road digital twins have high potential to boost the performance of the road construction industry in terms of cost, time, quality, safety and sustainability metrics.

Methodology: We present an automatic framework for creating and maintaining a road GDT in the form of a 3D model of road objects and their relationships. The proposed framework takes as input a coloured point cloud and relevant information such as road type and asset location upon availability. The framework is composed of context- and location -aware segmentation techniques for scene understanding in point clouds and the meshing method to convert point clusters to 3D meshed and coloured road objects. In the maintenance part, we proposed using an instance-aware point cloud change retrieval method to detect changes, match changed instances, and update the GDT. In this project's scope, frequent highway assets are identified for prioritisation.

Key findings: We presented a fully automatic solution for addressing a crucial step of segmenting the objects and meshing them to create road GDTs that benefit from context and location awareness. As a result, we showed how data-driven solutions can be navigated by basic prior knowledge of road nature for point cloud segmentation and how these segmented point clusters could be represented in 3D as meshes. Our approach with location awareness yielded a high mIoU of over 91% on average for the challenging road furniture objects in the CAMHighways dataset. Moreover, we show that context awareness alone is beneficial as well: non-ground mode, along with the trajectory-based partitioning and precomputed eigenvalues and normals, leads to 86% mIoU for all the above ground objects. Our unsupervised module in the line marking segmentation achieves 77.4% mIoU, contributing toward a holistic approach to digital twinning of the most frequent road objects.

Conclusion: As a result, our solution opens the door for a wide range of industrial applications, offering a fast, cost-effective automatic alternative for digital twinning. We establish a foundation for multiple use cases, including asset management, road network planning, predictive maintenance, visualisations through immersive reality and various simulations. These applications promise to enhance efficiency and consequently foster more environmentally friendly processes through reducing emissions from travelling and road maintenance works.

Automated Geometric Digital Twin Construction for Existing Buildings

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The Architecture, Engineering, Construction, and Operation (AECO) industry is a cornerstone of economic growth and a key player in shaping environmental sustainability. Yet, it remains hindered by outdated information management methods, resulting in inefficiencies that slow progress in productivity and sustainability. Digital Twins (DTs) have emerged as a transformative solution, offering unprecedented opportunities for enhanced decision-making throughout the building lifecycle-from design and construction to operation and maintenance. Despite this promise, most existing buildings, constructed before digital technologies, lack DTs, and their design models often fail to represent as-is conditions accurately. The crux of the problem lies in creating geometric DTs (gDTs), which involve capturing the as-is geometry of buildings through Point Cloud Datasets (PCDs). This process, though critical, is labour-intensive, hindering the broader adoption of DTs, particularly in maintenance and operation phases.

In response to this challenge, this work introduces an innovative and automated framework for the digitisation of building geometry from PCDs. The framework comprises three pivotal components: space detection, relation detection, and object detection. Space detection leverages empty blob detection and expansion to model volumetric spaces from PCDs, identifying complex architectural features like non-convex spaces, walls, doorways, and windows. Relation detection combines line-casting, distance-based approaches, and context-aware classification to detect primitive surfaces and establish topological relations between building elements, constructing a coherent geometric graph. Object detection integrates data-driven and model-driven approaches to detect and generate volumetric models for common building objects. By stitching together the results of space, relation, and object detection, the framework ensures a comprehensive, interconnected digital model with improved accuracy and consistency.

The impact of this framework on the AECO industry is profound. By automating the labour-intensive process of gDT creation, it drastically reduces the time required for manual modelling by up to 90%, slashing both costs and labour demands. This makes the creation of DTs for existing buildings not only feasible but also highly efficient, opening the door to widespread adoption across the industry. The framework's ability to model complex spaces and detect intricate topological relationships with precision ensures that the resulting gDTs are accurate representations of their real-world counterparts. This, in turn, enhances the management of building operations, contributing to smarter, more sustainable, and better-maintained environments.

The societal impact is equally significant. By streamlining gDT creation, this framework helps drive the AECO industry toward greater sustainability, efficiency, and resilience. With more buildings benefiting from accurate DTs, energy consumption can be optimized, maintenance can become predictive, and operational efficiencies maximized. This approach contributes to a future where cities are more sustainable and resilient, supporting both economic growth and environmental stewardship.

Conceptual framework for advanced digital planning permissions and building permits through road digital twins

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In times of resource scarcity, maximising the utilisation of existing resources becomes crucial, particularly in sectors facing shortages of skilled workers or materials. This necessity extends beyond traditional perspectives, prompting a focus on leveraging road digital twins (RDTs) to enhance efficiency in planning and building permit (PBP) processes. PBP processes are vital for ensuring compliance and safety in the architecture, engineering, and construction (AEC) industry but are often manual and time-consuming, leading to project delays. While there's increasing interest in automating code compliance, there's a recognised need for more holistic research. Digitalisation holds promise for improving PBP processes, yet its implementation faces challenges, including stakeholder involvement and sector complexity. Despite the potential of digital twins to streamline processes, research on their application in PBPs remains limited, with little exploration of efficiency gains through adjacent data sources like real-time data. The project is particularly aligned with Sustainable Development Goals (SDG) 11 and 9, as it contributes to creating sustainable, resilient infrastructure for urban environments and advancing innovation in transport and construction processes.

The research concept proposed aims to explore the integration of RDTs into PBP processes through a structured approach. This concept consists of four main steps. Step 1 involves identifying and developing information packages (IPs) by gathering relevant data that links RDTs and PBPs. Examples of IPs include site development assurance, accessibility of land, and regulatory compliance. Step 2 focuses on knowledge management, organising the gathered information into a structured system such as an ontology. Step 3 conducts an uncertainty analysis, examining uncertainties in PBP processes and building a robust decision model. Step 4 evaluates the business case, aiming to generate value for stakeholders by offering services like automated querying of required information for building permits. The starting and expected end TRL levels for the project starts with TRL 2 and will increase to TRL 5 in Step 4.

For investigating Step 1, qualitative empirical data was gathered through expert interviews and focus group workshop. As an interim result, four main categories could be identified. The first category is construction-based, which addresses impacts on construction sites for roads and various permit processes which are caused by building permits (e.g., road closure, heavy vehicle passing) that could be integrated. This category also highlights the challenge of managing two distinct information silos (infrastructure and buildings) within construction projects. The second category is regulation-based, which emphasizes regulatory considerations, for example related to parking spaces and the provision of charging stations, reflecting the adaptation to new infrastructure needs. The third category, transport planning/modeling-based, centers on transportation interventions required for developments (e.g., submission of transport peak models due to a new building), implying work carried out by specialists (in urban planning or transport engineering) within the planning department. The fourth category is design-based, which focuses on how road design can be influenced, particularly by aspects such as visibility in curves and junctions. This category could include considerations for autonomous vehicles, ensuring they navigate effectively. These themes collectively highlight the initiative's comprehensive approach to advancing road and transport infrastructure in the context of digital innovation and future needs.

The research anticipates uncovering insights that could revolutionise PBP processes by integrating RDTs effectively. By addressing questions regarding use cases, management elements, and risk mitigation, the study seeks to enhance decision-making, efficiency, and transparency throughout the building lifecycle. The research expects to provide valuable solutions, such as reducing time delays, increasing certainty in construction management, and facilitating accurate decision-making for stakeholders involved in PBP processes. These findings are poised to have significant implications for both research and practice, potentially transforming how PBP procedures are conducted and benefiting various stakeholders in the AEC sector.

In conclusion, the research concept offers a promising avenue to bridge the gap between PBP processes and RDTs, aiming to improving the efficiency and transparency of PBP processes and to enhance decision-making processes. By systematically exploring the integration of RDTs into PBPs, the study seeks to break down information silos between different domains, while acknowledging potential limitations such as data restrictions and international perspectives, this research endeavour holds the potential to offer innovative solutions that could reshape how PBP processes are conducted, benefiting both stakeholders and society as a whole.

The industry secondment for this project is planned with Ordnance Survey in the project's second year.

Industry secondment needs: Sector, 1 or 2 sentences secondment proposal.

Acknowledgements: We thank the participants of the focus group and the interviewees for their valuable insights.

Planning of Road Digital Twins: A pathway to achieve Net Zero in Road Infrastructure

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A Digital Twin (DT) is generally defined as a reciprocal model of the physical asset that contains a feedback loop to the real-life system. It is widely implemented in fields such as aerospace, roads monitoring, agriculture, etc. National Highways have been working on Digital Roads which aims to include DT of all roads in the UK. DT of roads is helpful for long term planning and more effective asset strategies, therefore nation-wide companies are now shifting focus in the automated planning process for roads.

Planning of Road Digital Twins is a new focus in the industry for sustainability and faster initial design. Methods such as Multi-Criteria Decision Making (MCDM) and Geographical Information Systems (GIS) are used to assist in urban road planning. These methods are widely implemented on newly built roads but often neglect environmental factors and feasibility of the urban space. Planning of Road DT will be able to assist in complex and sustainable planning given the limitations of the environment.

To investigate the planning of digital assets, the planning of physical assets in infrastructure will be first studied. This provides a wide array of dataset for further implementation as well as the experience in planning. Given the volume of the data, DT would be best analysed using cutting-edge technologies such as Machine Learning (ML) and Deep Learning (DL). The business outlook of the project also needs to be evaluated so that the project will be better adopted by the industry. The research targets at showcasing the sustainability and financial aspect of the industry with different scopes of road projects. With the final product of the research being a framework, to facilitate compatibility and feasibility, the software management and interface design will also be taken into consideration.

During the MRes year, the main tasks would be to a). roadmap the planning process for physical assets for dataset preparation and references. b). identify the key criteria for digital asset planning c). familiar myself with DT of roads and other information technologies and d). provide a feasible business model for the framework. With the solid understanding of the road industry, the PhD will build upon the MRes year and focus mainly on framework development. With the support of the industry partner, the framework will be validated using various planning cases for its accuracy and robustness.

This research aims to provide the industrial partner a framework to decide the planning at the preliminary stage of the design process. Planning options will be identified according to the carbon emission during the process as well as the time-efficiency. The optimal solution with the least greenhouse gas emissions during the construction process and service would be provided.

In addition to reduction in construction emission, the framework will reduce on-site visit with improved accessibility and accuracy. This would also lead to a smaller carbon footprint to achieve Net Zero in road infrastructure.

This project is funded by the Future Infrastructure and Built Environment Centre for Doctoral Training. The incoming industry partner is to be confirmed soon.

Maintaining Geometric Building Digital Twins from Spatial and Visual Datasets

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One of the greatest challenges faced by the Architecture, Engineering, and Construction (AEC) industry is poor project performance due to the lack of timely progress monitoring and quality control during the construction stage. A Digital Twin (DT) can serve as an information repository for storing and sharing an asset's properties over time with all AEC stakeholders for managing a building project throughout its lifecycle. Keeping the geometric DT dynamic by detecting, segmenting, and recording the as-built geometry data of building object instances from the on-site collected Spatial and Visual Data (SVD) by leveraging the Design Intent (DI) is a core step in automating and standardising progress monitoring and quality control. However, there is no state-of-practice solution that can automatically keep geometric DT updated based on the DI during the construction stage. Seven core knowledge gaps are: 1) lack of performance evaluation of commercial software; 2) missing frequency analysis of building object class utilisation; 3) challenge in cluttered and occluded scenarios of as-built PCD; 4) challenge in handling distinct geometric deviations in terms of position, orientation, and scale between DI and as-built instances; 5) challenge in updating DT's geometry for building instances with various shape complexities; 6) challenge in non-Manhattan-world buildings; 7) challenge in recording the as-built status for a geometric DT's maintenance.

The first and fundamental objective of this research aims to identify the most crucial building object classes, focusing on their frequency and the labour intensity involved in their representation for DT construction and maintenance. This analysis aims to prioritise these object classes based on their significance in the building's DT, thereby optimising the time and effort allocated to a DT's updating and maintenance. After this, the main and technical objective of this research is to develop a framework that can automatically, efficiently, and precisely detect, segment, match, and update as-built instances within these most frequent building object classes from PCD by leveraging as-designed models. The research considers the differences between as-designed models and as-built instances, thereby the proposed solution takes advantage of some attributes from DI but does not fully depend on it. The following research questions have be answered: 1) How to ensure that all relevant points corresponding to the DI instance are automatically selected and segmented from the as-built PCD? 2) How to reduce the effect caused by significant clutter and occlusions in PCD for instance detection and segmentation? 3) How to leverage the DI model as prior knowledge to support instance detection and segmentation from SVD when there are distinct deviations between as-designed and as-built instances in terms of position, orientation, and scale? 4) Is it possible to develop a method that can adapt to different object classes with various shape complexities and non-Manhattan-world types? 5) How to record and update as-built instances into a DT to reflect the timestamped physical building conditions?

The experiment results on detecting, segmenting, and tessellating as-is geometry data of top frequent object instances, including planar and curved walls, columns, pipes, elbows, and heating terminals, show that the proposed solution can handle the geometric DT updating of object classes with various shapes in different complex environments. Overall, the updated geometric building DT can significantly reduce manual checking time, leading to faster project progress monitoring and quality control at the construction stage. As the proposed solution can be implemented at different timestamps during the building's construction, the discrepancies between DI and as-built status can be detected and reported timely. It can help avoid costly rectifications in the later stages of construction.

Highways Maintenance and Renewal Scheduling Exploiting New Data Sources and Digital Twins

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The UK spends over £5 billion annually on road maintenance, but current cyclical and reactive approaches are hampered by outdated systems and rigid budgets. With the push towards sustainability, including National Highways' Net Zero by 2040 initiative, there's a growing need for data-driven solutions like Digital Twins (DTs) and predictive analytics. However, current practices struggle with inconsistent data integration and overly complex approval processes, resulting in inefficiencies in resource allocation and decision-making, particularly for service providers like Amey. This research seeks to develop a framework that leverages novel technologies to optimize road maintenance, improving decision-making, resource allocation, and aligning with sustainability goals.

To tackle the identified challenges, the approach focuses on four key areas: data integration, streamlined approval processes, high-level optimization, and sustainability in a cohesive and data-driven manner.

- Data Integration and Damage Assessment (1st year): By standardizing data from various sources, such as sensors and visual inspections, damage can be accurately quantified, enabling a preliminary importance rating for each task. This rating helps prioritize tasks based on urgency and resource needs, allowing for efficient resource allocation and a quicker response to critical maintenance issues.

- Streamlined Approval Processes (1st-2nd year): After the initial priority rating, the data will enter a traditional multi-tiered approval process. The approach automates key stages, reducing procedural delays. Supervisors maintain oversight through a digital dashboard, guided by automated decision principles, ensuring a balance between automation and essential manual interventions. This approach minimizes delays and enhances overall operational efficiency.

- High-Level Optimization Using Digital Twins (2nd-3rd year): Once the approval process is complete, the focus shifts to the operational level, where DT technology supports complex multi-objective optimization. Historical data informs predictable elements, such as resource productivity and material needs, while adaptive and machine learning algorithms respond to real-time changes in site layout and route planning. Uncertain factors, such as external risks, are managed using probabilistic models to maintain flexibility. This optimization framework, validated through field trials with Amey and corresponding data sources, significantly enhances decision-making and improves operational efficiency.

- Sustainability and Long-Term Planning (3rd year): Carbon tracking and electronic vehicle (EV) infrastructure are integrated into the framework, ensuring that maintenance decisions support both immediate efficiency and long-term sustainability goals.

The proposed framework, developed through advanced algorithms, literature review, and real-world trials aligned with industrial collaboration with Amey, promises significant improvements in operational efficiency. By integrating digital twins and AI-driven algorithms, a digitalised platform will be introduced, and it will enable real-time adaptation to changing conditions, optimizing resource allocation and enhancing scheduling accuracy in an integrated manner. These improvements will minimize downtime, streamline infrastructure management, and align with the UK's Net Zero goals, supporting a more sustainable and resilient road network.

Geometric Digital Twinning of Industrial Facilities

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Ageing industrial facilities often lack essential documentation, resulting in sub-optimal maintenance and breakdowns. Digital twins remedy this and assist in the operation and maintenance of industrial facilities. However, generating twins for existing facilities is a laborious and time-intensive process that outweighs the perceived benefits offered by the twins. Specifically, creating geometrical models from point cloud scans is particularly labour intensive. Furthermore, prior work on industrial facility modelling produce no more than a disjoint set of element point clusters and contain significant inaccuracies due to occlusions. A facility is a network of interconnected elements; having an accurate representation of the elements as well as identification of their relationships is vital for its operation.

This research explores the various gaps associated with the automated infrastructure digitisation process, with a focus on industrial facilities. Specifically, it focuses on the need for detection of element relationships, the need for higher precision and recall in the process of segmenting individual elements, and the need for the generation of geometric models with a high Level of Detail (LoD) in the presence of occlusions. A pipeline is proposed to address each of the above needs.

The proposed method takes segmented clusters of individual object instances generated from previous work as input and aims to output a comprehensive geometric model of the facility. This includes parametric modelling of individual elements through prediction and optimisation of model parameters, inference of relationships between elements using Graph Neural Networks (GNN), prediction of missing regions of elements caused by occlusions, as well as generation of high-resolution mesh representations of industrial facility elements.

Work conducted thus far has demonstrated the feasibility of parametric modelling of elbow, flange, tee and pipe elements to generate idealised geometries, as well as of inferring connectivity relationships between these elements with high precision and recall. Furthermore, a novel loss function for the comparison of point clouds has been introduced to aid in training 3D deep learning models, achieving SOTA results on completion of missing regions of point clouds. This research aims to build on these methods and improve segmentation performance as well as generate mesh representations of elements. Thus, the outcome of the research is intended to be an automated process of generating a geometric digital twin of an existing industrial facility that closely resembles its real-world counterpart. This, in turn, will make digital twins more accessible for industrial facilities, resulting in improved predictive maintenance and more efficient operations. This research is performed in collaboration with BP and AVEVA.

Constructing and Maintaining Geometric Digital Twins of Road Conditions

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Motorways provide essential connectivity between major locations. Today's road maintenance practice however requires intensive human input, which hinders the society's demand for drastic improvements in meeting future traffic demands, attaining carbon net zero and safeguarding zero harm on roads. To address the societal need to maintain undisturbed connectivity while achieving step-change advancements, digitisation provides a promising avenue. The current digitisation process however relies heavily on manual effort.

Hence, the research proposed here aims to enhance automation in creating a geometric digital twin (gDT) capturing the conditions of roads. The prospects of gDT for road conditions first hinge on ways to improve efficiency and reduce human effort in preparing and annotating real-life visual datasets. Where defects are rare or absent in the collected visual datasets, synthetic data will be needed to train a defect detector. With a curated and annotated visual dataset, development proceeds to identify defects in pavement and off-road assets discoverable from the prepared data and construct detectors to detect such defects. A fully functional gDT should also include the ability to update the conditions of identified assets and output conditions in a tractable manner for further visualisation. As of now, the research has primarily advanced in the area of image annotation and synthetic data creation.

The proposed annotation pipeline reduces human effort in creating and reviewing labels by selecting the most informative images for review, leveraging unlabelled images and mimicking past manual corrections. The pipeline adds three additional components to the existing two-stage Mask R-CNN: consistency regularisation, an active learning scoring module and an automatic correction module based on past human-reviewed pseudolabels. The pipeline yields approximately 25% savings of manual mouse clicks from fully manual labelling and gains by an average of 40% in average precision and recall from the original Mask R-CNN.

The proposed synthetic data creation pipeline targets to create instances that preserve fine features in pavement defects with relatively lean computing resources. Adopting synthetic data will help alleviate severe class bias observed in the original datasets and improve the detector performance. The pipeline involves cropping patches of different pavement images as the style and carries out style transfer with real defects using FastPhotoStyle which does not need extensive training. This technique significantly improves the alignment of defects to the destination images, evaluated by both qualitative observations and quantitative FID metrics. Future work may include creating rare defects on off-pavement assets for building an all-round on and off-road defect detector.

The overall annotation and synthetic creation pipeline increase automation and reduce manual labour in annotating and creating data for defect detector training. The expedited data annotation and synthesis alleviate the burden of preparing data for creating a gDT and the overall digitisation process.

A review of trustworthy requirements for road digital twins

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Digital Twins (DT)have been recognised as a powerful tool for whole-life management of road infrastructure in an intelligent, sustainable, and resilient manner. On the way forward, however, the road infrastructure stakeholders are still faced with the challenge of how to ensure the DTs work trustily. An untrustworthy DT would produce inaccurate information and decision-making, resulting in high financial costs, inefficient road management, and safety concerns. To address this challenge, this research analyses the current state of the DT paradigm and classifies the potential factors that will impact the trustworthiness of DTs. The analysis and classification take into consideration the functionality layers of DTs and the operational requirements in road infrastructure management. Accordingly, the practical approaches that can be adopted to resolve the identified trustworthiness issues are thoroughly reviewed and systematically integrated into a framework designed to ensure the appropriate and trustworthy use of a road DT.

The proposed framework not only addresses technical aspects but also aligns with operational practices, providing stakeholders with a practical roadmap for designing and deploying trustworthy DT solutions in the road sector. Specifically, the developed trustworthy framework is underpinned by three key pillars: precision, transparency, and cybersecurity. Precision is highlighted as a primary concern, with the study illustrating the importance of accurate data collection, synchronisation, and the application of machine learning for enhancing model accuracy. Transparency is underscored through the need for explainable Artificial Intelligence (AI) and Machine Learning (ML) models, ensuring that decisions are understandable to users, thereby building trust. Cybersecurity is identified as a critical aspect, with the study addressing the vulnerabilities inherent in cloud-based systems and the necessity of safeguarding against data tampering and unauthorised access. Together, these elements form a robust framework aimed at enhancing the trustworthiness of road DTs, ultimately contributing to more effective and reliable infrastructure management. It is strongly envisioned that this developed framework will serve as valuable guidance for the design and construction of robust and trustworthy digital twins, helping mitigate risks and enhance the overall effectiveness of road infrastructure management.

Alignment with SGD: This research contributes to SDG 9: Industry, Innovation, and Infrastructure and SDG 11: Sustainable Cities and Communities.

Project TRL: The current research is positioned at a TRL 1-3, focusing on basic principle observation and experimental proof of concept.

ChatTwin: Enabling LLM-Based Natural Language Interactions with Infrastructure Digital Twins

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Infrastructure management, particularly of road systems, faces significant challenges such as data inaccessibility, leading to increased costs, sustainability concerns, and safety hazards. Despite substantial investments in the United Kingdom (UK) and elsewhere, efficient management of such systems remains challenging, primarily due to the complexities of integrating and analysing large amounts of data from diverse data sources for informed decision-making. Digital twins have been developed as unified platforms for such data integration and analysis. However, the human interfaces of these digital twins present another layer of complexity, particularly for infrastructure professionals with limited expertise in computer systems. This situation shows the urgent need for more accessible and user-friendly interfaces with digital twins to support effective infrastructure management. This research addresses this gap by proposing an integration of Large Language Models (LLMs) with infrastructure digital twins, aiming to improve the accessibility and interpretability of the complex data within infrastructure digital twins, thereby facilitating better decision-making processes.

This study introduces an innovative system, referred to as ChatTwin, which leverages LLMs to enhance interactions between human operators and infrastructure digital twins. Focused on road systems, the system is designed to perform five primary tasks: data visualisation, data summarisation, digital twin modification, model visualisation, and work schedule inquiries. The system employs natural language prompts for user interactions, which are then categorised and processed to retrieve relevant data from the digital twin. This information, combined with the initial prompts, is fed into an LLM to generate outputs that include Python-based commands, natural language summaries and/or visual representations. A prototype digital twin of a road system, incorporating various data types such as geometry data, time-series sensor data, and defect information, was developed to validate the approach.

The integration of LLMs with digital twins enabled effective natural language interactions, thereby bridging the gap between complex domain knowledge/data and intuitive user interfaces. The system demonstrated proficiency in accurately categorising tasks, processing and visualising data, summarising information, and executing digital twin modifications within simulated scenarios. The findings highlight the system's capacity to enhance user-centricity in the lifecycle management of infrastructure, streamlining decision-making and interactions across different stages, with a particular emphasis on operations and maintenance.

The study presents a significant advancement in infrastructure management through the novel integration of LLMs with digital twins. This approach not only improves data accessibility and interpretability but also has the potential to streamline and transform decision-making processes in infrastructure management. The results demonstrate the utility of LLMs in bridging existing gaps in digital twin interactions, suggesting further research directions such as refining user feedback mechanisms, expanding task capabilities, and integrating multi-turn interactions to better address the complexities inherent in infrastructure management.

A Quality-aware Road Digital Twin Using Multi-modal Data

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The evolution of remote sensing and multi-sensor technologies has led to the generation of multi-modal data, facilitating diverse representations of a singular scene. Ground Penetrating Radar (GPR) employs electromagnetic pulses to probe the subsurface of road pavements. LiDAR captures 3D data along with the intensity of road assets. RGB cameras provide insights into colour, texture, and edge details. Thermal cameras detect infrared radiation emissions from roads. Fusing these data modalities yields a holistic understanding of scenes and offering precise platform and sensor orientations. The sensors used to capture different data modalities can be mounted on different platforms including aerial, hand-held, static and mobile.

While multi-modal data fusion offers significant potential, it also faces challenges due to inherent differences in coordinate systems across various sensors. Addressing these discrepancies typically begins with co-registration and alignment of data modalities, a topic widely explored in fields such as computer graphics, autonomous driving, and robotics, often using advanced learning-based techniques.

Despite this progress, there remains a gap in comprehensive literature on multi-modal data fusion within digital twins (DT) for road infrastructure, specifically considering the semantic aspects of data. LiDAR data, due to its high density and accuracy, serves as the primary modality for constructing geometric digital twins.

Other modalities can be fused with this modality to improve the quality of the outputted geometric DT. The strategy to fuse these modalities considering their level of abstraction and the quality parameter to evaluate it are subjects of this research. Different sources of unknowns can affect the data and the fusion model. Therefore, the quality parameters should be investigated carefully to fit the target of DT. Since the proposed solution is implemented on data collected from mobile ground platforms, it is essential to manage the algorithm's complexity to maintain efficiency.

By creating data-driven virtual models, the digital twins enable real-time monitoring, and predictive analysis to enhance the sustainability, efficiency, and longevity of infrastructure systems. Digital twins enable real-time analysis of traffic patterns, identifying and predicting congestion points and inefficient routes. By suggesting optimal routes or adjusting traffic signals dynamically, they reduce vehicle idling and fuel consumption, leading to lower emissions. Digital twins track the lifecycle of infrastructure components, prevents premature replacements, and reduces resource consumption and waste. Lifecycle assessments enable better understanding of environmental impacts, leading to more informed material choices toward reducing embodied carbon. Through continuous monitoring, they allow timely repairs, reducing the need for resource-intensive replacements. This results in fewer materials consumed over time and lowers the carbon footprint associated with construction and repair activities, which hasten reaching NetZero. Furthermore, by enhancing material reuse, asset adaptation and readaptation built environments, digital twin supports green infrastructure and circular economy.

UNIVERSITY OF CAMBRIDGE

DIGITAL TWIN ENABLED CONSTRUCTION PROGRESS MONITORING AND QUALITY CONTROL

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Digital Twin technology is transforming the management and monitoring of construction projects, enabling automation in progress tracking and enhancing quality assurance. Traditionally, construction site inspections have relied on site managers and field specialists, often requiring significant manual effort and time. To address these challenges, this research introduces a Digital Twin-based methodology for automating progress monitoring and improving quality control on construction sites.

Our approach utilizes laser-collected 3D point cloud (PCD) data for progress monitoring and quality assessment. By conducting comparative analyses between the as-built PCD data and the pre-determined design geometry and schedule, our system identifies discrepancies in building compliance. This integration allows for precise geometry and schedule deviation detection, facilitating timely corrective actions and ensuring project milestones are met efficiently.

The proposed method also incorporates the Building Information Modelling (BIM) model to further enhance progress tracking. By continuously comparing the construction site's 3D point clouds with the BIM model, we provide insights into the construction status, predict completion times, and enable semi-continuous progress monitoring. Our system, integrated with the Digital Twin platform, ensures a comprehensive view of project progress and quality, streamlining decision-making and project management processes.

Extensive experiments conducted on a real-world construction dataset demonstrate the efficacy of the proposed method. By leveraging non-contact sensing technologies like 3D laser scanning, we ensure more reliable and detailed data for monitoring, surpassing traditional 2D cameras in accuracy and effectiveness. This approach marks a significant advancement in automated construction management, paving the way for more efficient, informed, and proactive project oversight.

Beyond its immediate construction applications, this research offers broader commercial and societal impacts. The developed Digital Twin framework can be extended across various industries, including infrastructure, urban planning, and facility management, where continuous monitoring and real-time data analysis are essential. By enabling faster detection of design deviations and enhancing quality control, our system could reduce costs associated with rework and project delays, benefiting stakeholders from contractors to developers. Moreover, this technology supports the trend toward smart cities and sustainable construction practices, providing scalable, data-driven solutions that foster resilient, high-quality urban environments.

OMICRON: Towards a more automated and optimised maintenance, renewal and upgrade of roads by means of robotised technologies and intelligent decision support tools

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The OMICRON project is a €5 million EU initiative to transform asset management for European roads through an Intelligent Asset Management Platform. Bringing together 16 partners from seven countries, OMICRON focuses on optimizing road infrastructure—construction, maintenance, and upgrades—via four pillars: digital inspection technologies, a BIM-oriented Digital Twin (DT), a Decision Support Tool (DST), and advanced construction solutions. Central to OMICRON, the Digital Twin will streamline and automate road management tasks traditionally handled manually. Connected to the DST, it enhances efficiency across the road network, covering pavements, bridges, tunnels, and lighting systems. This integrated approach promises significant improvements in road asset management.

Within the OMICRON framework, two specific tasks are undertaken by the University of Cambridge.

The first task focuses on designing and integrating a road Digital Twin that leverages digital inspection data and other sources, ultimately creating a maintenance Decision Support Tool for infrastructure managers. The expected outputs include a functional Road Digital Twin, an operational Decision Support System, and IT tools that enhance decision-making processes.

The second task aims to replace costly, imprecise manual vehicle inspections with advanced technologies, integrating LiDAR, RGB, and near-infrared sensors. Computer vision and SLAM algorithms will enhance data processing and 3D mapping, while OMICRON's platform will securely store and manage comprehensive road condition data for improved accessibility.

Key anticipated outcomes of OMICRON include enhanced safety for road users and maintenance personnel, increased road network capacity, improved efficiency in intervention processes, and a reduction in overall maintenance costs. The technologies developed will undergo demonstration in a virtual environment, followed by four real-world demonstrators located in CEF corridors in Spain and Italy, ultimately achieving a Technology Readiness Level (TRL) of 7.

Optimal Construction Management and Production Control

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BIM2TWIN involves a multidisciplinary consortium of partners, bringing together expertise in monitoring technologies, artificial intelligence, computer vision, information schema and graph databases, construction management, equipment automation, and occupational safety. The Digital Building Twin (DBT) platform will be tested across three demonstration sites in Spain, France, and Finland. BIM2TWIN is a €6 million EU collaborative research project with 17 partners from 8 countries.

The project develops a lean-based DBT platform for construction management to reduce waste, optimize schedules, and cut costs. It enhances situational awareness through a closed-loop Plan-Do-Check-Act (PDCA) process. Key features include unified data acquisition, complex event processing, and a Project Status Model (PSM) for real-time monitoring of schedules, budgets, quality, and safety linked to the Building Information Model (BIM) for seamless transitions from construction to operation phases.

Two significant tasks are undertaken within the project.

The first task focuses on capturing and preprocessing on-site data, encompassing the import, registration, and compression of 3D and 2D data from various acquisition technologies. This includes scaling, orienting, and intelligently compressing data, such as point clouds and solid vector geometry, to prepare for subsequent interpretation and merging.

The second task emphasizes progress monitoring through the development of automated procedures and software prototypes. This task aims to detect meaningful point clusters, probabilistically assign object labels, identify expected but missing objects, and update the corresponding activity progress status. Additionally, it measures spatial properties of detected objects—such as length, width, and flatness—and compares them against design specifications and tolerance limits.

BIM2TWIN unites a multidisciplinary team to develop a cutting-edge DBT platform, transforming construction management with lean principles. Current progress-monitoring practices rely on manual visual inspections, requiring human interpretation of scanned data. BIM2TWIN proposes an innovative software prototype to automate as-built geometry capture (point clouds) and register it into the BIM, automatically detecting inconsistencies (TRL 6). By testing across demonstration sites in Spain, France, and Finland, the project aims to set new benchmarks in efficiency and oversight, ultimately enhancing quality, safety, and economic viability in construction.

Construct and maintain a highway digital twin from multi-modal data

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Highways serve as fundamental infrastructure within the transportation network, with road freight accounting for 79% of domestic movement in the UK in 2018 and cars, vans, and taxis representing 88% of passenger kilometres in 2021. Emerging from the manufacturing sector, digital twins have gained prominence in the infrastructure domain, particularly within the Architecture, Engineering, and Construction (AEC) sector. A digital twin is universally acknowledged as a representation linking an asset or system, offering transformative potential for enhancing lifecycle processes of transportation infrastructure, such as highways, railways, and bridges. Despite the promise, challenges persist in efficiently constructing useful digital twins from diverse data sources due to manual reconstruction efforts, disjointed data linkage, and insufficient data structure design.

This project aims to automate digital twin construction and maintenance using Artificial Intelligence (AI) methods applied to multi-modal data, encompassing laser-scanned point clouds, RGB images, thermal images, and ground-penetrating radar (GPR) data. Leveraging the capabilities of deep learning in processing point cloud and image data, the project has amassed a substantial annotated dataset suitable for training models, necessitating high-performance computing resources.

Based on the thermal data GPR data in CamHighway dataset, I generated thermal point cloud data for a road section and prepared the GPR data samples for training machine learning models.

The anticipated outcomes 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.

Alignment with SGD: This research contributes to SDG 9: Industry, Innovation, and Infrastructure and SDG 11: Sustainable Cities and Communities.

Project TRL: The current research is positioned at a TRL 4-5, focusing on validating key findings through controlled environments and stakeholder engagement.

RESTOR: Reuse of Structural Steel in Construction

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The steel industry significantly contributes to GHG emissions, with construction heavily reliant on steel. The £1.3M RESTOR project, in partnership with the University of Birmingham, addresses this by developing methods to maximize sustainable, low-energy reuse of structural steel from demolished buildings. Traditional recycling is energy-intensive, yet while 87-93% of steel is recycled, only 7-13% is reused, highlighting a major opportunity for reducing environmental impact.

The RESTOR project promotes sustainable construction by reusing structural steel. It develops NDT-based models to assess reclaimed steel, optimizing reuse with machine learning. A key outcome is a web-based Digital Twin design tool on Rhino and AWS, using deep learning and generative design to help architects and engineers create sustainable structures from catalogued steel. The project aims for a TRL of 4, with a demonstration in an industrial setting. The University of Birmingham leads the NDT-based assessment, ensuring that reused steel components meet structural performance standards. Meanwhile, the Cambridge team spearheads the development of the generative design tool, integrating Building Information Modelling (BIM) to enable the seamless inclusion of reused steel components into the design of new industrial, residential, and commercial structures. By combining advanced NDT, generative design, and BIM techniques, the RESTOR project provides a comprehensive and scalable solution for structural steel reuse in construction.

RESTOR is leading sustainable construction innovation, targeting the iron and steel sector—currently the fourth-largest global CO2 emitter (2.6 Gt in 2019). This project supports the UK's post-COVID-19 recovery strategy by developing solutions that give the construction industry an international competitive edge. The Cambridge team has created a web app tool for structural engineers to streamline the inclusion of reused steel members in designs, expected to significantly reduce design time and encourage reuse. Using Deep Belief Networks and SIMP optimization, RESTOR addresses reuse challenges like buildability and quality assurance.

With an API-invariant architecture, the tool supports multiple model formats (IFC, STEP, RVT), aiming for widespread industry adoption. While still in early development, RESTOR envisions long-term benefits including reduced energy demands, lower GHG emissions, and progress toward the UK's 2050 net-zero targets.

Conclusion: This project not only provides essential tools for sustainable construction but also positions the UK at the forefront of global efforts to reduce emissions.

Funding Acknowledgement: This research is funded by EPSRC, led by the Universities of Birmingham and Cambridge.

Enhancing Road Digital Twins with High-Fidelity 3D Traffic Sign Reconstruction

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The study addresses the critical challenges in the 3D reconstruction of traffic signs for improved inspections and maintenance. Current traffic sign detection, recognition, and localisation practices are reviewed, highlighting significant research gaps and limitations. We propose a hybrid approach in utilising mobile mapping and image-based data to enhance the fidelity and level of detail.

The methodology involves a two-step process: initially producing a semi-automated script which reduces manual workload during 3D reconstruction and then performing several tests to assess interoperability with machine learning algorithms for full automation. The methodology also investigates integration with Industry Foundation Classes, the adoption of information user requirements and the robust data model design for Digital Twin implementation. Findings demonstrate the effectiveness of our approach in generating detailed, low-polygon models suitable for real-time updates, thus offering a promising direction for future research in procedural mesh generation and identifying novel pipelines for Digital Twin generation and updating.

Establishing Digital Twins Information Requirements for Highway Asset Maintenance

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Highway digital twins have emerged as powerful tools for asset maintenance, allowing for real-time monitoring and predictive analysis of infrastructure conditions. However, establishing the information requirements to implement these digital twins effectively remains a critical challenge. This research addresses this gap by identifying and delineating the essential information requirements to optimise highway digital twins for asset maintenance.

The methodology employed in this research involves a comprehensive approach that combines both quantitative and qualitative techniques. Initially, a thorough review of existing literature on highway digital twins and asset maintenance was conducted to identify standard practices and emerging trends. Subsequently, interviews and surveys were conducted with relevant stakeholders, including highway authorities, engineers, and technology experts, to gather insights into their information needs and preferences regarding digital twins. Data analysis techniques such as content analysis and thematic coding were then employed to distil critical findings and identify recurring themes.

Several essential information requirements for highway digital twins emerged through synthesising literature review findings and stakeholder input. Our model for establishing information requirements is based upon multiple road assets, each having their own maintenance stages influenced by several factors, and these factors are modelled based on time-stamped information requirements.

By delineating these requirements, highway authorities and infrastructure managers can better harness the potential of digital twins to improve maintenance practices, enhance operational efficiency, and ultimately prolong the lifespan of highway assets. Moreover, the emphasis on interoperability and data standardisation highlights the need for collaborative efforts and industry-wide standards to ensure the seamless integration of digital twin technologies into existing infrastructure management frameworks. Further research and development in this area are essential to address evolving challenges and capitalise on emerging opportunities in intelligent infrastructure management.

Alignment with SGD: This research contributes to SDG 9: Industry, Innovation, and Infrastructure and SDG 11: Sustainable Cities and Communities.

Project TRL: The current research is positioned at a TRL 4-5, focusing on validating key findings through controlled environments and stakeholder engagement.

Acknowledgement of Data and Collaborations: This research utilises the CAMHighways dataset, supplied for experimental purposes. Additionally, qualitative data has been gathered through interviews with experts from highway authorities and industry professionals.

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AEGIR: DigitAl and physical incrEmental renovation packaGes/systems enhancing envIronmental and energetic behaviour and use of Resources

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AEGIR is a 13.8M EURO collaborative project funded by Horizon Europe via UKRI, involving 28 partners across 10 countries. The AEGIR project aims to revolutionize the renovation and retrofitting processes for buildings by introducing a scalable, smart, and non-intrusive solution. The project's primary objective is to enhance the uptake of deep retrofitting techniques, targeting the creation of nearly zero-energy buildings.

By integrating innovative, industrialized plug-and-play envelope solutions with locally deployed renewable energy technologies, AEGIR provides a flexible and efficient method for improving building performance. This holistic approach is further supported by a digital ecosystem that enhances the entire construction workflow, from design through to operation, ensuring cost-efficiency and sustainability.

AEGIR seeks to address the pressing need for sustainable building solutions in different climatic regions across Europe. The project involves four demonstration sites, located in Spain, France, Denmark, and Romania, covering a variety of building typologies such as multi-family dwellings, educational facilities, and social housing. These sites serve as real-world testbeds for the innovative solutions, ensuring that the developed technologies are adaptable to a wide range of environments and user needs. By including a socio-economic model that provides new financial schemes, AEGIR not only focuses on technical innovation but also aims to create a sustainable business model for widespread adoption across Europe.

Within the AEGIR framework, two specific objectives are undertaken by the University of Cambridge.

- Address the data capturing and data registration of the onsite spatial and visual data from the building to automatically reconstruct the indoor building environments.
- Generate geometric digital twins of buildings automatically for renovation purposes.

Based on the objectives, a handheld scanning hardware device and corresponding software method are first designed for automated 3D point cloud reconstruction of buildings. This handheld scanning device and method facilitate the automated generation of 3D models of existing buildings, reducing costs and improving renovation efficiency. In addition, a novel pipeline is proposed for geometrical digital twin generation (Ag2DT) from point clouds to 3D model, structured in three key phases.

In conclusion, PointPix can reduce the time and cost for data collection, registration, and pre-processing. The Ag2DT automates the generation of DTs from point clouds and images, providing a comprehensive digital representation suited for building renovation analysis. The automatic digitization of the building accelerates the efficiency of the entire workflow, ensuring cost-efficiency and sustainability.

M-TABS: Muon Tomography for Assessing Bridge Structures

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Muon tomography, which utilizes the relatively long-lived muon particle to generate 2D and 3D images through Coulomb scattering, is being developed to detect nuclear materials and monitor underground carbon sequestration sites. Unlike traditional Non-Destructive Testing (NDT) methods—such as ground-penetrating radar, X-ray, and ultrasound, which can face limitations in data depth, 3D model integration, and operational intrusiveness—muon tomography offers a non-invasive approach with enhanced subsurface imaging capabilities. Standard surface-level scanning methods like Lidar lack these deep insights, making GScan's Muon Flux Technology (MFT) a valuable alternative for advanced infrastructure and security applications.

The M-TABS project focuses on advancing assessment methods for maintaining aging bridge structures, especially those made from prefabricated concrete. By MFT, M-TABS addresses the limitations of traditional approaches, providing high-quality data integration into 3D BIM formats to improve the inspection experience for operators and infrastructure managers. The project seeks to revolutionize NDT of built infrastructure, particularly bridges. Key objectives from the Cambridge team include optimizing data processing for faster scans, developing machine learning algorithms to enhance data quality, and ensuring seamless integration of MFT data with 3D models.

Expected outcomes include comprehensive, non-invasive bridge inspections that reduce maintenance costs, extend infrastructure lifespans, and generate revenue growth, with profitability projected by 2027 and substantial market expansion anticipated by 2030. M-TABS targets the global NDT market, estimated at £28 billion in 2021 and projected to grow significantly by 2026. The technology is set for a commercial launch by late 2026, offering over 300 annual NDT measurements with GSCAN's MFT system in the UK, with expansion plans for EU and US markets.

Funding Acknowledgement: M-TABS is funded by Innovate UK Smart Grants, led by GSCAN LTD.

A Framework for Automating Multi-scale and Multi-scenario Digital Twin Design for the Strategic Road Network

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Digital twins (DTs) are transforming infrastructure management by creating virtual representations of physical systems. The Strategic Road Network (SRN), managed by National Highways, is critical to the UK's road infrastructure, and modernising its maintenance, development, and operation is vital. While DTs for assets, processes, and defects have been manually developed, automating the creation of complex DTs across multiple scales—macro (entire road networks), meso (road sections), and micro (specific assets like traffic signs)—and simulating diverse operational scenarios remains underexplored.

Previous research on DT modelling has focused on specific disciplines, often addressing simple DTs with limited scenario and scale considerations. However, as infrastructure becomes more complex, scalable, interoperable, and context-driven DTs are increasingly necessary. Automating their creation, especially for vast infrastructures like the SRN, presents significant challenges due to the countless valid design solutions. Key research questions arise, such as: What constitutes an optimal DT design framework? How can we evaluate and choose the best design from multiple possibilities? What are the baselines for assessing these models? To address this gap, a framework for generating Pareto-optimal DTs across various scales and scenarios is needed.

This research proposes a novel framework to identify user and information requirements from stakeholders at local and national levels, and to develop a method for automatically generating trustworthy DT models and architectures, incorporating product, process, and resource information, aligned with the Centre for Digital Built Britain's (CDBB) Information Management Framework, and operating across multiple scales and scenarios. The methodology includes analysing stakeholder requirements, developing DT scoring metrics, and applying Pareto optimisation to generate and evaluate solutions.

The research programme will span 3-4 years:

- Year 1: Map current digital curation practices of a major highways network operator; review management objectives; categorise existing and emerging information types; propose a DT design automation framework, followed by initial testing.
- Years 2-4: Implement and test the framework; explore new insights from broader digital twin research; engage with industry partners to develop pilot plans and measure real-world outcomes.

In conclusion, this research will significantly advance the automation of DT design for large-scale infrastructure, promoting the digitisation and optimisation of road networks, ensuring productisation, interoperability with the National Digital Twin programme, information security, and futureproofing.

Geometric Digital Twin Construction, Updates and Inference from the Point Cloud Data Powered by A.I. and Linked Data Technologies

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Digital Twins (DTs) function as virtual representations of physical assets, processes, and systems, enabling stakeholders to visualize, monitor, and analyse assets with high precision. gDTs, specifically, focus on the static model components of buildings, capturing detailed geometric and attribute information for each element. However, current scan-to-gDTs methods are constrained by challenges such as inconsistent modelling techniques across different building components and difficulties in reconstructing occluded or hidden areas.

The research carried out in the Buildspace project investigates an advanced approach for the automatic generation and enhancement of geometric Digital Twins (gDTs) of buildings, utilizing point cloud data (PCD) from existing structures.

The primary objective of this research is to develop an integrated methodology for automated gDT generation and enrichment, incorporating occlusion completion and hidden object inference within point cloud datasets. The research targets three core components:

Occlusion completion and hidden object inference: Utilizing machine learning-based feature extraction and linked data technologies to infer occluded or hidden building elements within PCD;

Object-oriented gDT generation: Generating gDTs with spatially oriented representations of individual building components and their interrelationships; and

Semantic enrichment: Enhancing gDTs with semantic information through computer vision techniques and linked data.

This study initiates with a comprehensive review of existing practices, synthesizing current knowledge to establish an integrated framework for gDTs construction. Spearheaded by the University of Cambridge, the research advances automated gDTs generation using machine learning techniques with texture mapping (XYZRGBt) to support precise energy analysis. This dual approach—integrating data-driven methods with structured architectural knowledge—underpins a more holistic methodology for gDTs creation.

The methodologies and technical outcomes of this research will be applied within the BuildSpace project1 , which aims to develop multi-modal gDTs across four European pilot sites. These sites will leverage terrestrial data from IoT platforms, BIM solutions, and aerial imagery from drones equipped with thermal cameras and satellite-based geolocation (e.g., EGNSS and Copernicus). This multi-source data integration will support energy-efficient decision-making, while providing stakeholders with sustainability alerts and actionable insights. Consequently, a foundational framework is established for the construction, updating, and inference mechanisms essential for gDTs, advancing the accuracy and applicability of digital representations of physical structures in practical projects.

A Digital Twin-based Data Federation Framework for Managing Asset-process Interactions in Highway Infrastructure Systems

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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.

Alignment with SDG:

- SDG 9 Industry, Innovation, and Infrastructure,
- SDG 11 Sustainable Cities and Communities, and
- SDG 12 Responsible Consumption and Production.

Project TRL: the starting TRL (technology readiness level) of federated DT system is '1 Basic Principles Observed', and the expected end TRL is '5 Technology Validated In Relevant Environment'.

Industry secondment needs: I need to do an industry secondment in National Highways or Costain to learn the real practice of road inspection and maintenance, in order to understand the use cases and information requirements for devising a federated highway twin system. I would also like to do a secondment in Trimble to learn more about digital twin software development and applications.

Datasets: This project has received two datasets: (a) 3D road models in IFC4 from Costain; and (b) 3D road models in IFC4.3 from Trimble. This project has also received asset management (P-AMS) data from National Highways.

The initial test shows that the proposed digital twin framework and system prototype can be effectively used to query asset data distributed in different subsystems. IFC models are used as metadata models for connecting with the asset management system.

A graph-based approach for road digital twin

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The major problem to be addressed in the project is how to design road digital twins. This problem will be addressed by achieving the following four objectives:

(1) Objective 1: Identifying the specific information requirements for road digital twin

(2) objective-2: Developing a graph-based reference data library for road assets;

(3) objective-3: Developing an extensible, future-proof, and scalable road integration cloud architecture; and

(4) objective-4: Validating the proposed approach for road digital twinning.

These objectives are identified and scheduled logically, and, to achieve these objectives, the standard procedure specified in an international standard, ISO19650 organization and digitalization of information about buildings and civil engineering works, will be referenced.

To be specific, the following methods will be used: (1) Objective 1: Relevant literature will be reviewed and interviews/questionnaires with stakeholders, such as Jacobs and National Highways, will be conducted to learn the specific information requirements for future road management and define the road Foundation Data Model. (2) Objective-2: Graph-based technologies, such as Resource Description Framework (RDF) and labelled property graph (LPG), will be compared to select the proper graph technology for implementing the graph reference data library that is developed based on information requirements identified in Objective-1. (3) Objective 3: An extensible, future-proof, and scalable road integration cloud architecture will be developed by working with stakeholders, taking data fusion and data interoperability into consideration. (4) Objective 4: Real project data will be used to validate the effectiveness of the proposed approach for road digital twinning.

Alignment with SDG:

- SDG 9 Industry, Innovation, and Infrastructure,
- SDG 11 Sustainable Cities and Communities, and
- SDG 12 Responsible Consumption and Production.

Project TRL: the starting TRL (technology readiness level) of graph-centric DT is ‘1 Basic Principles Observed’, and the expected end TRL is ‘5 Technology Validated In Relevant Environment’.

Industry secondment needs: I need to do an industry secondment to learn the real practice of road maintenance, in order to create a data model for the road section, which can be used with property graph.

Datasets: This project has received two 3D road models in IFC4.3 from Trimble. The initial test shows that IFC road models mainly contains geometric information (> 98%), while the semantic information is less than 2%, which shows the need to enrich the semantics of road data models.

Defect Initiation Modelling for Predictive Maintenance via Spatial Smoothing

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Highways are critical to the economy of a country and their condition is directly connected with the safety and comfort of its users. Currently, transport authorities rely on routine visual inspection by a site crew, which is usually infrequent, expensive, time-consuming and without proper prediction and control over material usage and maintenance time. Repairs to roads are large scale disruptive processes that can close roads for extended periods delaying traffic and contributing to pollution. There is a pressing need for innovative road pavement maintenance designs that can streamline the data collection, the decision-making processes, and execution of maintenance processes while minimising disruptions and costs, ultimately contributing to more efficient infrastructure management.

Digital Twins (DTs) provide a platform to integrate vast amounts of relevant, real-time data. One approach to streamlining the maintenance process through efficient DT-driven methods is through predictive and proactive maintenance. Leveraging the data available in a DT of the highway, we perform spatial modelling with the aim of predicting the probability of various defects arising under different circumstances. A dataset is built incorporating defect counts in sites spatially partitioning National Highway's Strategic Road Network, as well as explanatory variables such as easting, northing, pavement age, surface material, length, traffic flow, and weather. Then, spatial smoothing is applied to the data, so that spatial correlation in the occurrence of defects and explanatory variables is taken into account.

The resulting model is integrated into the DT and adapted to be modular so as to inform decisions pertaining to specific time periods, locations, and defect types. It is a significant step towards implementing predictive and proactive maintenance, which majorly reduces associated costs, inefficiencies, and risks associated with the widely employed reactive maintenance. This model is also to be used in KPI and decision modelling in order to assess and quantify these improvements.

Deriving Handcrafted Road Asset Condition Forecasting and Forensic Maintenance Processes

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There is a new need for better controlling and monitoring processes for existing road maintenance techniques, measuring their performance to address budgetary constraints and to bring existing systems to a higher standard. By focusing on data science methods that monitor Key Performance Indicators (KPI's) such as money, safety, sustainability, time and quality, the efficiency of current and future methods can be strengthened to run within existing constraints. Processes from product information in the digital twin can also be derived to enable direct control of robotic maintenance and repair operations.

This project focuses on data science and machine learning methodology essential in synthesizing a digital twin with new materials, and measurement techniques for road assets, along with providing the means of control for robotic monitoring and communication, exploiting data rich feedback and new materials. This involves investigating state-of-the-art processes for highway maintenance treatments, summarising current capabilities and their implementation into the digital twin. Spatial modelling can then be performed for distributions of defects and repairs, identifying, and fitting spatial models to a constructed dataset, and investigating how the strategic road network can be broken down spatially into several sites, identifying the explanatory variables for each of these locations.

The data acquired in these stages will then be used to predict forecasting failures. State-of-the-art deterioration curves will be explored for pavement performance measures. They'll also be studied for individual defects and their systems, noting how diseases can be inferred from them and how the causes of these diseases can also be pinpointed from these deterioration curves. Decision models are then investigated and developed along with the application of the five KPIs into the digital twin, leading to a prototype implemented into the existing systems. This is in conjunction with a list of guidelines for data collection and monitoring, identifying data requirements for digital twin maintenance for various road assets and how these can be fulfilled using efficient modern tools.

The findings from this stage of the project will then lead to further optimisation algorithms on the existing KPIs and decision models, generating detailed maintenance treatment schedules with required resources and assets. Once a design automation prototype is created, optimal maintenance processes can be automatically derived into high level human readable instructions and low-level, machine-readable instructions.

DIgital Twin and Knowledge Graph-based Road Maintenance Decision-making

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Roads serve as the primary mode of transportation for individuals, and their maintenance is adversely affected by a shortage of skilled professionals, including manual and professional roles such as civil engineers. This skills shortage has raised concerns among industry professionals regarding its impact on budgets, project viability, and delays in maintenance, leading to further deterioration of road assets. The current road maintenance processes heavily rely on expert knowledge, making them susceptible to skill shortages.

Hence, this research proposes the integration of digital twins and knowledge graphs to address skills shortages in road maintenance preparation and operation processes. Leveraging Large Language Models (LLM) for information extraction, constructing knowledge graphs using Neo4j, performing knowledge fusion, data matching through similarity calculations, and providing candidate treatment recommendations through knowledge graph reasoning, this study aims to develop reliable and automated decision-making methods for road maintenance.

By utilizing knowledge graph-based approaches, this research seeks to mitigate skills shortages, reduce dependence on expert knowledge, and enhance the efficiency and effectiveness of road maintenance activities.

Digital Twin-Driven Structural Health Monitoring of Roads

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Road infrastructure plays a critical role in facilitating mobility, supporting economic activities, and promoting social development. Hence, it is important to maintain the high performance of roads by conducting timely maintenance and rehabilitation activities. In order to formulate accurate maintenance and rehabilitation strategies, a digital twin of roads can be used to identify the latest health condition of roads in service. In this process, an essential step is to obtain the structural health information of existing roads, which will be addressed in this study. At first, a physics-based model which can simulate a Non-Destructive Testing (NDT) method of roads will be developed by using a semi-analytical approach. Then, the developed model will be used to generate a database which contains the structural parameters and corresponding predicted NDT results of roads. At last, the generated database will be used to develop a data science-based technique which can identify structural parameters of roads in service based on NDT results, and the identified structural parameters will be used to evaluate the structural health and predict the remaining life of existing roads. The digital twin of roads with the latest structural health information can help formulate the most suitable maintenance and rehabilitation strategies, which ensure the good service performance of roads. The objective of this study aligns with the Sustainable Development Goals by making road infrastructure resilient to traffic loads and environmental factors (Goal 9), promoting economic growth due to enhanced mobility (Goal 8), and improving people's quality of life (Goal 3).

The starting Technology Readiness Level of this study is Level 3, which corresponds to the understanding of the NDT method from theoretical perspectives. The expected end Technology Readiness Level is Level 8, which indicates the integration of the developed technique into the commercial design of the NDT device. The NDT measurements from the TRL company can be used to validate the accuracy of the developed technique. To assess the compatibility of the developed technique with existing pavement management systems, a secondment at National Highways could be arranged.

Using class descriptions to classify inspection texts with minimal training data

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Modern Large Language Models (LLMs) are pretrained over a large corpus of texts, allowing to acquire a basic understanding of the semantic structures of natural language. Further fine-tuning is often required to adapt the generalized models to a specific task, such as classification with a custom dataset. However, as with most deep neural networks, a large amount of training data is required for the models to attain acceptable levels of performance. Road management creates a vast amount of unannotated textual data, which would be infeasible to manually annotate for every natural language processing (NLP) task. This limits the application of recent advances in NLP in extracting information from road textual sources.

Inspired by few-shot learning methods, where models take advantage of only a few training data, a description-based classification technique is proposed for texts. The description of classes acts as inherent information, or priors, for the classes, which can be used to guide the classification of texts. This alleviates the need for a large quality of labelled data. Class descriptions can be manually generated by experts, or can be extracted from annotation guidance for human operators. These descriptions would be matched with input texts to output similarity scores, which are used to classify the inputs.

Experiments are ongoing. However, early results indicate that significant improvements are brought by utilizing class descriptions in classification. Compared to traditional classification techniques, improvements can be as much as 50% with only 30 training data per class. Experiments are underway to determine optimal training conditions, in addition to how the amount of training data would affect model performances in this setting.

This project has the potential to unlock LLMs for use in road management in a scalable and flexible fashion, as there is a low requirement on training data. In addition, class descriptions can be used as a means of incorporating human expertise in classification, as they can be generated by domain experts.

Understanding the role of different cementitious blends on chloride transport behaviour

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The 2014 Infrastructure Cost Review underscores a saving of 3.4 billion pounds annually by deploying suitable infrastructure monitoring strategies. This is also validated through recently observed bridge damages, including York's Lendal Bridge and Bristol's Vauxhall Bridge, highlighting the need for continuous corrosion monitoring, a majority of which is due to chloride ingress.

However, the present monitoring strategies detect corrosion only after the onset of corrosion in the steel reinforcement, signifying the start of structural damage. To this effect, predictive monitoring of corrosion can help select suitable corrosion preventive strategies that can be deployed before the onset of structural damage, resulting in significant cost savings. Predictive corrosion modelling can be achieved by utilising the information on the concrete cover's in-situ state to model the probability of rebar corrosion. This requires a thorough understanding of the cementitious materials used, their interaction with other concrete ingredients and the chloride transport behaviour within the concrete system.

The available literature limits the above information to Ordinary Portland Cement (OPC). Hence, a gap can be observed for existing and emerging low-carbon materials, like Fly Ash (FA), Slag and Limestone Calcinated Clay (LC3) based cement. In addition to the above, several parameters, including the pH of the concrete system, temperature, external loads, etc., influence the chloride transport behaviour, whose correlation and order of importance are yet to be understood by the research fraternity.

The current study proposes a systems classification approach for the influencing parameters followed by experimental investigations to understand their combined influence on the various cement types. The parameter classification is based on the physical concrete boundary - 'Concrete' and 'Outside-concrete' systems. The 'Concrete' system is further divided into three sub-systems, namely concrete phase composition, pore structure and pore solution composition. Further, experimental investigations are undertaken to relate a few of the identified parameters, within the concrete phase composition and the pore structure sub-systems with the chloride transport behaviour. To this effect, the gas permeability test and the Rapid Chloride Migration Test (RCMT: NT-Build 492) were performed for five different kinds of mortar systems, namely, OPC, FA, Slag, LC3 and Alkali Activated Cement (AAC).

The diffusion of chloride is directly proportional to permeability (parameter under pore structure sub-system). Hence, it should result in lower diffusion coefficient values obtained from RCMT (Dnssm). However, this was not observed for FA and AAC. Furthermore, LC3 was shown to have a very sharp reduction in Dnssm values over a period of 14 days. These observations were explained by highlighting the difference in mortar compositions and were further extended to understand its relationship with parameters like permeability and Dnssm values. The study concludes with the need to first identify the order of importance for the influencing parameters, including stress, temperature, and pH, and then develop the models for those correlations, which can ultimately help in predicting corrosion before any structural damage.

A Decarbonisation Pathways of the UK Road Infrastructure: Pavement maintenance and repair strategies

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The ongoing transitions to address climate change, the shift towards mobility as a service, evolving travel patterns post-pandemic, and increasing extreme climate conditions are driving inevitable changes in infrastructure assets. Recognizing road infrastructure as both essential to national economic and social development and a major contributor to greenhouse gas emissions, this stresses the need for environmentally sustainable approaches for infrastructure planning, development, and maintenance to meet the UK Net Zero target.

This study aims to conduct a Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) to assess the long-term resource needs and carbon footprint associated with the construction, maintenance, and repair of local and strategic road networks. Two case studies, focusing on the A120 (with a mix of concrete and asphalt pavements) and Cambridge County Council's local roads will be used to assess current business as usual practices to identify key carbon and material hotspots across the infrastructure lifecycle. The analysis will explore opportunities to adopt low-carbon materials, improve resource use, implement resource circularity principles and incorporate low carbon technologies for both local and strategic road networks. This will enable the development of prospective scenarios based on polices and strategies for road infrastructure maintenance and repair activities to assess the environmental trade-off of different pathways to Net Zero.

The study will highlight the potential benefits and limitations of sustainable materials and methods, providing insights into more environmentally responsible road infrastructure strategies and roadmap for implementation. This work will contribute to inform decision-making for transport planners and policymakers, enabling them to make more environmentally responsible choices for road infrastructure. The study will not only highlight the trade-offs between various materials and processes but will also offer recommendations for transitioning to low-carbon infrastructure, contributing to the achievement of Net Zero in transport infrastructure. This research is part of the National Research Hub for Decarbonised Adaptable and Resilient Transport Infrastructures (DARe), in collaboration with Newcastle University, University of Glasgow, Heriot Watt and Anglia Ruskin University. The initiative aims to find viable pathways and solutions for a transition to a resilient, Net Zero transport system.

Enhanced concrete road repair materials

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Many concrete highways are nearing or exceeding their designed service life, necessitating effective repairs to maintain functionality and safety. Minimising highway closures—which are costly and disruptive—is a significant challenge in highway maintenance. Therefore, durable repairs that improve safety and reduce the frequency of maintenance are highly desirable.

This work presents the development of enhanced concrete road repair materials via the addition of selected microfibres to two commercial repair materials: Rapid Set Cement All (RS), a rapid-setting cementitious material known for high early strength, and Roadware 10 Minute Concrete Mender (RM), a fast-curing, polyurethane-based material. The research determined the maximum fibre content for optimal extrudability and crack filling, assessed the mechanical performance of the materials, and evaluated them as repairs in damaged concrete specimens.

The study found a limit on the volume of fibres that could be added to the materials while maintaining extrudability and effective crack filling, but that the addition of fibres at these limits enhanced the material's performance as repairs. Specifically, RS enhanced with 0.6% polyvinyl alcohol fibres (1–2 mm in length) demonstrated as a repair under flexure, a 30% increase in ultimate strength and toughness, twice the ductility compared to plain RS, and under slant shear loading, a 30% increase in ductility, 40% higher toughness, and considerable residual strength. RM with 1% glass fibres (1–2 mm in length) as a repair under flexure exhibited twice the ductility, over 30% greater toughness, and four times the residual strength compared to plain RM; under slant shear loading, it showed over 30% higher ductility and slightly increased toughness. The enhanced performance of these materials as repairs suggests they can lead to longer-lasting repairs, improving safety and reducing maintenance costs.

By providing repair materials that are extrudable, effective at crack filling and exhibit enhanced performance, this work can lead to practical, longer-lasting concrete repair solutions, improving highway safety and reducing maintenance costs

Net Zero Emissions from Road Infrastructure: A Critical Review on Carbon Offsetting Strategies for Their Practical Positioning and Thrust Areas

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The construction and upkeep of road infrastructure, encompassing the procurement of raw materials to the operation of construction equipment, gives rise to a carbon footprint that accounts for 24% of global energy-related emissions and 74% of the transportation sector. In light of the pressing climate crisis and the global commitment to achieve net zero emissions, it is imperative to identify and address the sources of carbon emissions stemming from road infrastructure. This entails identifying the emission pipeline and prioritising strategies for mitigating their environmental impact. This research provides a review of existing and ongoing research in the construction industry to mitigate significant emissions from their respective sub-sectors, with a focus on road infrastructure.

The strategies for achieving net zero emissions that are examined in the rstudy are closely tied to the three primary materials employed in road infrastructure - concrete, steel, and asphalt. These materials together represent the primary source of emissions from road infrastructure, during their production and transportation. The carbon reduction methodologies include the utilisation of low carbon cements, alternative supplementary cementitious materials, the incorporation of recycled aggregates, the transition to low carbon intensive warm-mix asphalts and bio-binders, and the exploration of sustainable steel alternatives. Furthermore, a section of the review also examines ongoing research on carbon capture and storage, with a particular focus on the potential for carbon storage in construction materials through various modes of cement, mineral, and aggregate-based carbonation.

The strategies reviewed are thoroughly examined in relation to the practical application of real-world road infrastructure, considering various factors such as codal restrictions, technological and market readiness, and user acceptance. This analysis highlights the need for further development of certain strategies, particularly those with high potential for carbon reduction but that are currently in the early stages of readiness for implementation. The research also discusses on the carbon offsetting of these technologies, considering their reliance on non-renewable energy sources and the lack of life cycle assessment studies to substantiate their environmental impact.

The study delineates that a timeline-oriented methodology for net zero emissions from any infrastructure ought to encompass two primary components: firstly, a reduction in the quantity of CO2 emitted, and secondly, the capture or offsetting of the emitted CO2. It underscores the necessity of carbon capture within infrastructure, in tandem with emission reduction strategies, in order to achieve net-zero emissions. The study further highlights the paucity of practical and scalable techniques for capturing or removing emissions directly from road infrastructure. It emphasizes the necessity of developing diverse absorbents based on hybrid materials that can surpass the limitations of current carbon absorbers. It also recommends a comprehensive and multi-faceted strategy that includes a life-cycle assessment for net zero emission approaches. This would require identifying hybrid strategies that incorporate complementary techniques to mitigate the limitations of each other.

With several promising road schemes and projects aimed at creating a sustainable road network across UK, the systematic review presented in the study, which critically evaluates the merits and drawbacks of each technology, can assist in selecting the most effective blends of net zero emission strategies, by combining the advantages of each and surpassing the standalone processes.

Towards Net Zero Roads: Integrating Climate Resilience and Low-Carbon Materials in Pavement Design

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One of the critical factors for the broad adoption of low-carbon materials in infrastructure is ensuring long-term performance and durability under varying climate conditions. As climate change intensifies, pavement designs must account for increased temperature variability, precipitation patterns, and extreme weather events, all of which accelerate deterioration and maintenance needs. By focusing on resilient materials and designs that stand the test of time, the construction industry can reduce both carbon emissions and lifecycle costs, paving the way for sustainable, durable infrastructure that supports Net Zero goals.

This study utilizes data from the Long-Term Pavement Performance (LTPP) program, which has been collecting extensive pavement performance data across various U.S. states since the 1990s. By examining data on pavement layers, traffic loads, climate conditions, and observed distress, we aim to understand how climate impacts pavement deterioration over time, especially in regions with climates comparable to the UK and translating the data insights into actionable strategies for the UK. By analysing performance patterns under diverse climate conditions, the findings will identify materials and design that not only minimize environmental impact during production and installation but also extend pavement lifespan, reducing the frequency of repairs and associated emissions.

Furthermore, these findings will be utilised to inform the decision making in A382 design considerations, especially with low carbon materials. These findings will also be used to form a comprehensive basis for climate-adaptive design recommendations. Leveraging both the LTPP dataset and A382 project data, the study aims to develop a set of design principles for achieving Decarbonised, Adaptable, and Climate-Resilient Road Infrastructure. These principles will support stakeholders in making informed choices about material selection, structural design, and maintenance strategies, ensuring that future road infrastructure not only withstands changing climate conditions but also actively contributes to decarbonisation efforts. This research is funded by Decarbonised Adaptable and Resilient Transport Infrastructures (DARe) National Hub, which aims to find viable low carbon and resilient pathways and solutions for transport systems.

Zero waste geopolymer pavements

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The expansion of highway construction and repairs poses significant challenges to the global supply of natural resources exacerbated by substantial mineral waste generation from construction activities. Despite efforts via initiatives like warm mix asphalt and waste prevention and recycling, there remains a pressing need to explore innovative solutions to minimize waste and reduce reliance on new aggregates. This study explores the feasibility of transitioning towards zero waste and carbon neutrality in pavement construction by revisiting conventional methods and embracing underexplored alternatives like in-situ recycling and low-carbon binders. Thus, the approach involves a comprehensive strategy aimed at achieving zero-waste pavements through utilizing recycled aggregates such as reclaimed asphalt pavements (RAP) and crushed concrete aggregates (CCA) into rigid pavements with the aid of geopolymer cement. The methodology begins with identifying available resources, waste streams, and potential trial sites, followed by laboratory development focused on designing geopolymer-based binders and concretes using both natural and waste materials. Final section will focus on incorporating the waste aggregates into the geopolymer and understanding it behaviour. The resulting products will undergo testing to meet industry standards, with a life cycle assessment (LCA) to determine the most viable options for potential field trials.

Preliminary results indicate that a compressive strength of 40 MPa (7-days) is achievable for geopolymer mortars made with natural aggregates and commercial metakaolin (MK). The targeted concrete and binder are expected to achieve strengths of 40-50 MPa after 28 days of curing, which makes the results promising.

In conclusion, this study presents a promising pathway for sustainable pavement construction by advancing the reuse of RAP and CCA with geopolymer cement. This innovative methodology not only addresses critical environmental issues but also paves the way for economic and technological advancements in sustainable construction. By strategically implementing these solutions, the construction sector can foster a culture of sustainability, reducing resource dependency and waste generation while achieving durable, eco-friendly pavements.

Alignment with SDG: SDG 9: Industry, Innovation, and Infrastructure; SDG 11: Sustainable Cities and Communities; SDG 12: Responsible Consumption and Production; SDG 13: Climate Action

Project TRL: TRL 3-6 for start and end period

Industry secondment needs: Proposing to conduct asphalt-geopolymer compatibility and adhesion studies at University of Nottingham

Datasets: N/A

Roads Fit for a Changing Climate: an analysis of rutting using the LTPP database

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With a changing climate, pavement rutting is forecast to become a more serious threat to the safety and longevity of our roads. Research into addressing this challenge has been described as inadequate even though the consideration of rutting in maintenance triggers and asset management is only going to increase in importance. To explore this problem, data mining techniques to establish association rules for pavement rutting among many factors. Similar techniques have been used in previous studies for exploring thermal cracking and structural failures, but not for rutting.

Long-term pavement performance (LTPP) data was used to make suggestions for reducing rutting in a changing climate. Three stages of analysis were undertaken, utilising Grey's Relational Analysis, Apriori Algorithm and two case studies of road sections with a high rutting development rate (RDR). There were no conclusive relationships deduced between RDR and any of the variables within the categories of climatic, traffic or pavement structure, and there were not any association rules that linked more than two variables with high support and confidence. This demonstrated that rather than high RDR occurring when traffic and climatic conditions are sub-optimal, high RDR occurs when the design is sub-optimal. The factors that cause design to be sub-optimal are complex and are not demonstrated through just the variables used in this study: traffic ESAL (Equivalent single axle load), surface layer thickness, binder layer thickness, base layer thickness, subbase layer thickness, E* (dynamic modulus), dynamic viscosity surface layer, dynamic viscosity binder layer, bitumen content surface layer, bitumen content binder layer, mean annual precipitation, mean annual temperature, max 7-day temperature. One of the factors that was not considered is the requirement to trade-off between different modes of deterioration, whereby asphaltic properties may be selected to reduce cracking or ravelling instead of rutting. It was shown that engineers are capable of maintaining low RDR without excessive requirement for maintenance, but appropriate design assumptions must be made to ensure this.

The remainder of the PhD will include research into the rutting mechanisms as well as the pavement design and maintenance issues that contribute to rutting. Future pavement conditions will be modelled under various climate scenarios and suggestions for adaptation strategies will be produced to improve pavement resilience.

Bayesian Back Analysis of Pavement Layers Properties using Traffic Speed Deflectometer Measurement

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Pavement monitoring and health evaluation play a key role in highway operation and maintenance worldwide. As a result, extensive research has been devoted to improving pavement health evaluation methods. Determining the bulk material properties is one of the most critical steps in estimating a pavement's remaining service life. Although various strategies exist to estimate these properties, non-destructive methods remain the most popular choice. The Traffic Speed Deflectometer (TSD) is an emerging non-destructive testing instrument for evaluating the in-situ stiffness of pavements. However, TSD does not directly measure the stiffness properties; instead, it measures the slopes of vertical deflection at a set of points along the right rear wheel of a measuring truck trailer travelling at normal traffic speed. Therefore, TSD measurement data needs to be interpreted to obtain the in-situ stiffness of pavements, and back analysis is commonly employed for this task.

A typical back analysis requires three components: (i) a calculation model to simulate pavement responses under the dynamic TSD loading, (ii) TSD measurements, and (iii) a back calculation algorithm. The calculation model generates simulated pavement vertical deflections with a given set of stiffness parameters, which are then compared against the actual TSD measurements. The back analysis algorithm then iteratively adjusts the input stiffness parameters until the generated vertical deflections reasonably match the actual measurements. At this point, the calibrated stiffness values are considered representative of the in-situ pavement properties. Many algorithms have been proposed for this task. However, existing algorithms are often based on deterministic analysis, thereby overlooking the inherent uncertainties in material properties. In this regard, this work pioneers Bayesian probabilistic back analysis of TSD measurements. Bayesian back analysis considers both the inherent uncertainties in material properties and uncertainties in TSD measurements, thereby providing more comprehensive information of in-situ stiffness properties for decision-making.

This work starts from a parametric analysis that investigates the effects of uncertainties in surface, base, and subgrade layer modulus. The results show that pavement deflection is most sensitive to uncertainty in subgrade layer modulus, followed by base layer modulus and surface layer modulus. This ranking implies that back analysis of TSD measurement is most effective in estimating subgrade layer modulus and least effective for surface layer modulus. The dominant sensitivity to subgrade layer modulus makes the simultaneous back analysis of surface, base, and subgrade layer modulus a practical challenge. Bayesian back analyses using simulated TSD measurements are then carried out to corroborate these results. In practice, it is recommended to obtain subgrade layer modulus through other means so that surface and base layer moduli can be more effectively interpreted using TSD measurements.

Alignment with SDG: Improve pavement monitoring and health evaluation

Project TRL: Start: TRL 3; End: TRL 6

Industry secondment needs: I am currently on my secondment to quantify uncertain pavement material properties

Datasets: TSD measurement dat

Human-Robot Cooperation for Maintenance and Construction of Future Roads

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Construction and maintenance of roads are tedious processes involving a considerable amount of manual work. The personnel working at the construction site usually perform difficult tasks, e.g., lifting and moving heavy loads, and are often exposed to severe weather conditions. In this project, we propose a novel approach of human-robot social cooperation, where the human operator remotely orchestrates the robot. The robot performs the manipulation routines with objects and the roadside environment in a semi-automated manner. The proposed human-in-loop design will move the roadside workers to the remote offices, which reduces the negative effects associated with health and safety.

The applicant plans to develop the project in three steps.

First, the applicant will develop the haptic-enabled simulator that allows the human operator to manipulate objects simulated in a digital twin road construction or maintenance. The proposed simulator can be later used as a training platform to teach new staff members.

In the second stage, the algorithms developed for manipulation with a virtual environment will be implemented to operate a physical robot in a teleoperation setting. At this point, the main objective is to design control algorithms, as well as to develop an end-effector capable of sensing the physical contact and executing task-specific actuation.

The last stage is the development of the concept of human-robot cooperation, where the operator controls the robot through abstract motion patterns(orchestration) rather than by employing direct coordination through teleoperation. The proposed project has potentially a high social and scientific impact and involves multidisciplinary and international collaboration.

The goal and objectives of the project align with and is motivated by the UN's Sustainable Development Goals (SDGs), emphasizing human-centric approaches to aid in transitioning from Industry 4.0 to a more inclusive and equitable Industry 5.0. Particularly, the target SDGs are "8. Decent Work and Economic Growth", "9. Industry, Innovation and Infrastructure", "11. Sustainable Cities and Communities", and "12. Responsible Construction and Production". The project also makes the industry more inclusive to people physically less capable in manual labour jobs, which positively affects the "5. Gender Equality", and "10. Reduced Inequalities" goals.

This is a research level project with a plan to grow from TRL 1 (Basic Principles Observed) to TRL 3 (Experimental Proof of Concepts) level with possible cooperation with interested industry partners. The choice of the secondment plan will be made based on interest from the industry partners, as well as the available infrastructure and target application domain and expertise.

Pavement Maintenance Vehicle Design for Efficient Infrastructure Management

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Highways are critical to the economy of a country and their condition is directly connected with the safety and comfort of its users. Currently, transport authorities rely on routine visual inspection by a site crew, which is usually infrequent, expensive, time-consuming and without proper prediction and control over material usage and maintenance time. Repairs to roads are large scale disruptive processes that can close roads for extended periods delaying traffic and contributing to pollution. There is a pressing need for innovative road pavement maintenance designs that can streamline the data collection, the decision-making processes, and execution of maintenance processes while minimizing disruptions and costs, ultimately contributing to more efficient infrastructure management.

The research employs a multidisciplinary approach, integrating principles from mechanical engineering, materials science, and transportation engineering. Data collection involves the use of advanced sensing technologies mounted on maintenance vehicles, including Light Detection and Ranging (LiDAR), infrared cameras, Inertial Measurement Unit (IMU), temperature sensors, and ground-penetrating radar. These sensors gather detailed information about pavement conditions, including surface defects, subsurface damage, and material properties. Analysis techniques include data processing algorithms, statistical modelling, and simulation studies to assess pavement conditions and prioritise maintenance activities. Additionally, the methodology incorporates principles of vehicle dynamics and control to optimise vehicle performance and manoeuvrability during maintenance operations.

The research yields significant insights into the development of road pavement maintenance vehicles optimised for efficient infrastructure management. Findings indicate that the integration of advanced sensing technologies enables more accurate and timely assessment of pavement conditions, facilitating proactive maintenance interventions. Moreover, leveraging data-driven decision-making processes allows for the prioritisation of maintenance activities based on the severity and anticipated future deterioration of pavement defects. The research also highlights the importance of vehicle design considerations, such as payload capacity, mobility, and energy efficiency, in ensuring the effectiveness and sustainability of maintenance operations.

In conclusion, the development of road pavement maintenance vehicles tailored for efficient infrastructure management represents a crucial step forward in addressing the challenges of maintaining transportation networks. By leveraging advanced sensing technologies and data-driven decision-making processes, these vehicles can optimise maintenance strategies, minimise disruptions to traffic flow, and reduce the overall lifecycle costs of pavement assets. Moreover, the integration of sustainable design principles ensures that maintenance operations are conducted in an environmentally responsible manner. The implications of these findings extend beyond road pavement maintenance, serving as a model for the integration of technology and innovation in infrastructure management practices, ultimately enhancing the resilience and sustainability of transportation systems.

Control and Implications of Mixed Autonomous Vehicle-Infrastructure in a Heterogeneous Multi-agent System Framework

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Connected autonomous vehicles (CAVs) will be prevalent given the technology maturity and government promotion. Transportation system administrators and constructors should be prepared to leverage the controllability and potential of CAVs when they gradually permeate the roads in the near future. Current studies for CAVs usually consider either the control of a single CAV with human-driven vehicles (HVs), or collectively control among CAVs only. Moreover, their interactions with intelligent road infrastructure are investigated separately, which oversimplifies the heterogeneity among CAVs, HVs, and intelligent road infrastructure in the near future transportation system. Numerous challenges of heterogeneous multi-agent transportation systems, such as their interactions, partial controllability, and implications, are not addressed. This project will study the control and implications of a heterogeneous multi-agent transportation system mixed with CAVs, HVs, dynamic reversible lanes, and intelligent traffic lights. First, with awareness of the high spatial-temporal resolution and real-time characteristics of transportation systems, an efficient heterogeneous data fusion and multi-agent modelling framework will be developed. Second, optimal control policies for the heterogeneous multi-agent transportation system satisfying the safety requirements will be developed. Third, the opportunities and barriers to practical implementation and the implications for society and governance will be analysed. Through this project, we will push forward the technologies and insights of CAVs at dynamic reversible lanes and intelligent intersections and move towards a safer and more efficient system whereby CAVs can be highly leveraged.

Alignment with SDG: Goal 11 (Sustainable cities and communities)

Project TRL: TRL 3 (Experimental proof of concept)

Industry secondment needs: Real-world or simulated experimental platform for multiple autonomous vehicles

The Pavement Repair Robot as an Embodied Predictive Simulator

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Robotic manipulation faces significant challenges in adapting to novel materials and tasks, contrasting with humans' intuitive understanding and ability to internalise new scenarios. Current data-driven control mechanisms lack a comprehensive understanding of action policies, hindering adaptation to unfamiliar situations. In contrast, humans utilise analogies from previously encountered phenomena, demonstrating the importance of a deep understanding of the world's dynamics for robust interaction.

This research draws inspiration from the active participation and mental modelling observed in natural organisms. The proposed embodied predictive simulation diverges from traditional disembodied simulators by prioritising mechanical stability, real-time feedback, computational speed, and adaptability. While deep neural networks offer learnable models with potential for improvement, they exhibit limitations in adapting to unseen scenarios. Conversely, Newtonian mechanics is adaptable but lacks incremental learnability. In the specific context of highway maintenance, this study employs position-based dynamics for crack filling simulations, operating at approximately half real-time speed. Coupled with optimisation algorithms, this approach facilitates rapid discovery of automated crack sealing methods without physical experimentation. The simulation's ability to visualise hidden sub-surface material flows enables anticipation and understanding of new material effects.

This intuitive physics-based workflow proves adaptable to diverse liquid manipulation tasks, paving the way for future research on robotics in highway maintenance.

A Multi-Agent System for Heavy Machine Operation through Context-Aware Sensor Fusion

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Construction sites in the UK remain hazardous, responsible for over 20% of workplace fatalities. These incidents result not only in tragic loss of life but also in significant financial costs due to equipment damage and compensation claims. A key factor in many accidents is the limited situational awareness of heavy machinery operators and workers. There is a critical need to integrate Robotics, and Automation to improve safety on these sites, especially where automation is challenging due to the complexity and variability of the environment.

This project follows a three-stage approach to develop a smart, adaptable safety system for construction.

First, the project will identify specific safety requirements for construction workers by analysing common site hazards. Based on this, a digital interface will be developed, enabling workers to monitor risks in real-time. Next, an intelligent algorithm will allow the system to interpret construction site activity as work proceeds, enhancing its ability to anticipate risks and respond to dynamic changes. Finally, visual and audio alerts will be incorporated to deliver immediate feedback on hazards, making the system practical for high-traffic, limited-visibility areas.

Field testing will help refine this technology to address the unique safety needs of construction environments. Unlike manufacturing, where robotic systems are well-integrated, this project represents one of the first targeted applications of robotics for safety on construction sites. Once successful, this solution can transform industry practices, contributing to sustainable, resilient infrastructure and aligning with SDGs focused on safety, innovation, and sustainable cities.

Upon completion, this research will be deployed as a human-machine interface in work environments, control rooms, and on heavy machinery as a real-time tool to observe otherwise hidden areas, anticipate hazards, and help avoid them—all without replacing human oversight. The system's modular design will enable it to be adapted to different work sites.

This research establishes a smart interface between workers and machines, combining robotics and algorithms to manage complex, dynamic environments. For instance, if a machine operator needs an overview of a distant area, they can request a robot to capture a real-time image, ensuring safer conditions. Additionally, algorithms will support machine-to-machine communication, creating a network of "talking machines" that share critical information. Concepts like reinforcement learning, self-organisation, and embodied intelligence will make this a robust, responsive safety system.

Current Progress: Development has reached the simulation stage, involving heavy machinery, sensorized environments, multi-agent system (MAS) algorithms, and human factors such as emotions that could serve as cues to prevent hazards. Currently, the fellow is seeking an industry secondment to observe worker interactions with these systems, evaluate the feasibility of using robots in dynamic settings like construction and test the simulations in real world. Addressing these human-centred requirements will strengthen the system's integration and adaptability, ensuring a safe, collaborative, and practical solution for real-world applications.

Artificial intelligence assistant autonomous-vehicle-mounted sensors-based road surface condition monitoring system

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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 (RSM) becomes an important target for future roads. Conventional RSM 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 RSM solution? This research will develop a low-cost RSM system mainly based on autonomous-vehicle-mounted Inertial Measurement Units (IMUs) sensors.

Currently, the research is focusing on monitoring the international roughness index by civilian vehicles with sensors mounted on the vehicles. The international roughness index is a key index related to the performance of the pavement. One research journal paper and one conference paper are written with the scope of road surface monitoring of the international roughness index by sensors mounted on civilian vehicles. The other index that will be focused on is the friction of the pavement. The friction measurement will be used for the analysis of the detection of the onset of aquaplaning of the vehicles. Tires are the components of a vehicle that directly contact the road surfaces. The unevenness of the road surface and the friction of the road surface can be shown by the status of the tires. A tire sensor for road surface monitoring is developing based on optical methods to analyse the road surface details and relate the measured information for the road surface parameters.

Alignment with SDG: SDG Target 3.6 - halve the number of global deaths and injuries from road traffic accidents by 2030

The starting and expected end TRL levels:

TRL Level 1 (Starting): Basic Technology Research

TRL Level 3 (Expected): Analytical and experimental proof-of-concept

Industry secondment needs: Actively looking for secondment opportunities

Acknowledgement of dataset: No dataset used from Future Roads

Highway intelligent traffic control system based on vehicle-road coordination and multi-agent technology

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Global traffic congestion continues to intensify, leading to increased travel times, excessive fuel consumption, and escalating emissions. Addressing these challenges requires innovative solutions in traffic management and sustainable energy use. In this project, we introduce an intelligence traffic system aimed at integrating autonomous vehicle technology, advanced multi-agent coordination, and real-time data analytics to optimize highway flow and reduce congestion. Our proposed system can improve traditional traffic routing but also addresses the complex electric vehicle (EV) routing and charging problem, offering a model for efficient energy distribution by integrating EV charging with delivery fleet operations.

Methodologically, we employ simulations across multiple traffic scenarios, including fully autonomous environments and mixed-traffic conditions where autonomous and traditional vehicles coexist. This approach allows for the testing of adaptive control algorithms in diverse settings, such as temporary road management and winter road maintenance, capturing the system's response under both standard and adverse traffic conditions. Through intelligent vehicle-to-infrastructure (V2I) communication, the system dynamically allocates charging resources based on vehicle routing needs, minimizing wait times and maximizing energy efficiency.

The proposed system should be able to mitigates congestion and reduces travel durations but also optimizes EV charging station utilization and streamlines energy distribution across the vehicle network, particularly benefiting fleet-based logistics. By enabling vehicles to interact with the electricity grid, the system facilitates energy-saving measures, contributing to overall sustainability efforts. Additionally, the system's strategic routing choices and optimized infrastructure use underscore its potential to support temporary and seasonal traffic requirements effectively. These outcomes underscore the promise of intelligent transport systems in delivering substantial societal, economic, and environmental benefits, and they lay a foundation for advancing adaptive, sustainable urban mobility.

Alignment with SDG: (Sustainability Development Goals)

Project TRL: TR3 (Experimental Proof of Concept)

Industry Secondment needs: National Highway for real-world scenarios of traffic management.

Acknowledgement of dataset: N/A

Exploring sealant flow perception through an agile flow cup test for robotic crack injection sealing

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Accurate robotic crack sealing (precise deposition of sealants) has been challenging due to the complex liquid flow behaviours in a random crack geometry. Recent advances in robotic liquid manipulation paves the way to tackling such problem through approximate yet computationally cheap and fast fluid simulations such as the position-based fluid (PBF) method, a particle-based fluid model. As the simulated (artificial) material parameters have no direct mapping from the real-world physical properties (e.g., viscosities, etc.), the simulator normally needs to estimate the material parameters using the facts/knowledge learned from a predecessor liquid manipulation task (e.g., stirring the liquid, etc.). Either through a time-consuming exhaustive trial-end-error parameter searching process or a quicker automated learning process (e.g., Bayesian Optimisation, etc.), one can reach a satisfactory simulation (most closely mimicking the physical material). However, such methods require a physical robot to be deployed in the predecessor task, which can be inconvenient or even inaccessible/unrealistic for crack sealing tasks under strict time or space limitations in the field situation.

This study proposes a liquid perception framework where an agile robot-free standardised flow cup test is utilised to capture physical liquid flow behaviour and transform it into a particle-based physics simulation intended for use in the robotic crack injection sealing task, enabling a real-to-sim-to-real workflow. The proposed framework combines the simulated flow cup test applying the PBF model with a Bayesian Optimisation process to automatically solve the simulated sealant parameters. The viability of the proposed framework can be examined by comparing the physical sealant injection performance (i.e., accuracy) with its counterpart using the perceived flow in simulation. A robotic crack sealing experiment is implemented in the lab and the results suggest that the flow cup test-based liquid perception is able to capture the sealant flow behaviour with an average accuracy of approx. 80-85% (up to 98% at the most) for identifying and predicting different sealant viscosities. It is believed that the flow cup test can be engineered into a special flowmeter that can be integrated into a field crack sealing robot for perceiving potentially dynamic sealant flow behaviour, and that the proposed framework has the potential to be applied to general robotic liquid manipulation tasks.

Assessing the impact of infrastructure and non-infrastructure factors on cyclist experience: A digital twin video experiment

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Cycling is a sustainable mode of transport that helps reduce traffic congestion and environmental impacts while promoting a healthier lifestyle. Despite these benefits, cycling constitutes a small share of overall transport in the UK, accounting for around 2 percent of trips, with a skew towards young male adults. Improving the cycling experience is crucial not only for increasing ridership but also for enhancing equity, diversity, and inclusion (EDI) in society. However, research in this domain remains limited, and there is a lack of nuanced understanding of how EDI factors influence cyclists' experiences with different interventions. This study evaluates cyclists' experiences across two types of facilities: on-road (shared with motorised vehicles) and off-road (dedicated to vulnerable road users). A digital twin model of a section of London is employed to simulate realistic cycling scenarios. The model incorporates various infrastructure elements such as pavement conditions, lighting systems, and security cameras, alongside non-infrastructure factors like time of day (day vs. night), to assess their impact on rider experience, particularly for women and older adults. Cyclist behaviour is then modelled in these different recorded scenarios, identifying preferences for infrastructure improvements among distinct groups of cyclists.

From a theoretical perspective, this research underscores the value of digital twin technology in creating real-world scenarios while allowing researchers to control and adjust individual parameters, such as modifying one element while keeping others constant. From a practical perspective, this study develops a cycling level of service index through the lens of EDI, offering valuable data to assess the appropriateness of current service rankings. The findings provide planners and policymakers with essential insights into prioritising cycling infrastructure improvements, ultimately enhancing the cycling experience for all. This aligns with the Sustainable Development Goals (SDG) by providing planners and policymakers with insights to prioritise cycling infrastructure improvements, contributing to more sustainable urban mobility (SDG 11) and supporting climate action initiatives (SDG 13) while enhancing the cycling experience for all.

The starting Technology Readiness Level (TRL) of this study is TRL 3, indicating that while the videos have been developed and are ready for testing, survey data collection has not yet begun. The expected end TRL is anticipated to be TRL 6, following successful data collection and analysis. The secondment could take place at TRL and will focus on collaborating with experts to advance the application of digital twin technology in cycling infrastructure. We thank TRL for providing the digital twin model used to develop the scenarios in this study.

The resilience of road networks to climate change: a case study of London and its surrounding regions

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Climate change alters global precipitation and temperature patterns, affecting the frequency and intensity of extreme weather events. Assessing and enhancing the resilience of Road Infrastructure Networks (RINs) to climate change is crucial for improving their capacity to withstand, adapt to, and recover from extreme weather conditions.

This study aims to: 1) Model cascading failures in RINs during climatic events; 2) Quantify the impact of these events on RIN performance; 3) Develop models to assess RIN resilience across various climate scenarios; and 4) Optimize resilience enhancement strategies from both "pre-disaster" (e.g., infrastructure maintenance and renovation) and "post-disaster" (e.g., infrastructure recovery) perspectives. This research contributes to building a reliable, resilient, and sustainable transportation system, enhancing the reliability, efficiency, and safety of daily travel.

This study focuses on t road network in London and its surrounding areas. We gratefully acknowledge industry partners — the Department for Transport, Ordinary Surface, National Highways, the Environment Agency and others— for providing essential research data that enable us to measure network resilience in the research area. An analysis of the vulnerability of the road network in the study area to heavy rainstorms has been conducted, with findings accepted for presentation at the "2025 TRB Annual Meeting". Following revisions, we plan to submit the conference paper to a journal soon.

This research aligns well with two Sustainable Development Goals: 1. Make cities and human settlements inclusive, safe, resilient and sustainable and 2. Take urgent action to combat climate change and its impacts. For the Technology Readiness Level, this project is expected to reach Level 4: "Component and/or breadboard validation in a laboratory environment." Real-world data is currently being used to validate the proposed models and methods. For instance, data on sampled flooding depths following heavy rainstorms and estimated Origin-Destination trips have been validated. In the next phase, we will assess the resilience of the road network to heavy rainstorms and other extreme weather events, aiming to produce more practical and impactful results.

Data science and advanced technologies for carbon management in highway projects

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Sustainability is the continued protection of human health and the environment while fostering economic prosperity and societal well-being. Specially, one of the most intriguing problems in sustainability is carbon measurement and analysis in infrastructure projects to meet the net-zero 2050 target. For future roads, carbon reduction is an inevitable theme to be addressed. This project will investigate data-informed sustainability decision-making in future roads, 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. 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 are developed.

Current progress: Research objective (2) finished and working on (3) and (4).

Alignment with SDGs: 9 Industry, Innovation and Infrastructure; 11 Sustainable cities and communities; 13 Climate Action.

Starting with TRL 1, expected end with TRL 6

Industry secondment: National Highways, starting 25 Nov 2024.

Climate resilience of national highway networks

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In the highway sector, resilience studies are under high priority to understand how prepared the current highway network is in the face of future severe weather events and its dependency on the related infrastructures. The proposed project aims to develop a system approach to assess highway resilience in the face of extreme weather events, with integrating geospatial analysis, risk assessment, and network analysis and evaluating potential cascading failure. Before conducting a resilience assessment for the nation-wide highway network, we conducted a regional case study for Greater London and surrounding areas. Flooding is selected as the major threat for highway network. Current efforts in data collection and modelling have successfully produced a geographical model and a network model of all classified highways. By intersecting the highway geographical model with the Environment Agency flood risk map, we identified the highway segments where flooding is expected to occur in 1 in 30 years, 100 years, and 1000 years event scenarios and the water depths have been sampled for each scenario. In addition to the highway floodings directly impacting the traffic, we also investigated the indirect impacts of the power-signal-traffic cascade due to inundated power substations as well as the highway visibility and slipperiness effect due to intensive precipitations. These three effects have been integrated into our traffic modelling, which allow estimating the average speed and travel time of the traffics on each of the highway segments. With the modelling, we created maps showing the hotspots with high vulnerability in terms of compromised travel efficiency during flooding events. Since the regional case study has proved the feasibility of our methodology, we are currently working on the next step to expand the research area from Greater London and surrounding areas to nationwide including England and Wales. Expanding the highway network increases the complexity and computational load. Considering that, we change the focus from traffic modelling to macroscopic network analysis, which measures community-level mobility (ability to travel to other places) and accessibility (ability to be accessed from other places) during flooding events. We are also particularly interested in the specific accessibility to critical services such as police station, hospital, and food market from local communities facing flooding events.

This research aligns with the United Nations Sustainable Development Goals (No.13 Climate Actions and No. 9 Industry, Innovation and Infrastructure).

The TRL level is expected to achieve 4 from 2. As of now potential secondments would be with National Highways (severe weather operation) and Atkins Realis (asset degradation modelling under climate change).

We acknowledge that National Highways has granted us the access to the HADDMS (now the new GDMS) where historical flooding data are being used for validation in the research.

Notes

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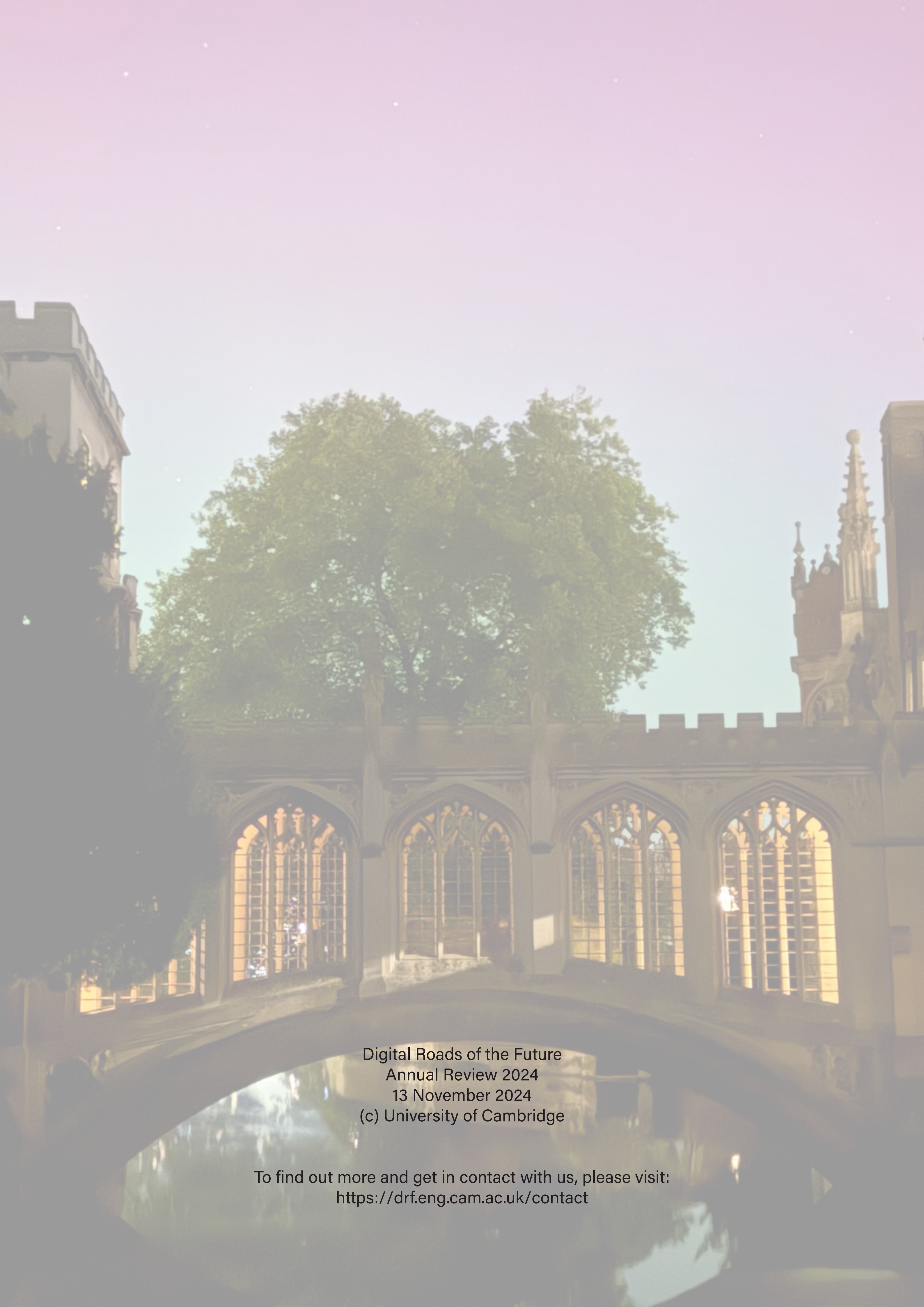

Digital Roads of the Future
Annual Review 2024
13 November 2024

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