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Pavement Assessment and management towards Smart and Safer mobility

Digital Twins for Roads
Development of Data Driven Models

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Smart Pavements

Digitalisation

Machine Learning

Digital Twins

Artificial Intelligence

Resilience

Sustainability

Asset Management

Carbon Neutral

Decarbonisation

Net Zero

Climate Change

Carbon Foot Printing

Circular Economy

Asphalt Circularity

CONTENT

- Defining a digital twin, a brief history of digital design
- Design twinning for roads – a case study from the London Orbital M25
- Operational twinning – a case study from Transport For London (TfL).
- Maintenance twinning – incorporation of condition and maintenance data to the network model

INTRODUCTION

- Digital design not ‘new’ in civil engineering, neither are physical prototypes
- Digital twins are a ‘hot’ topic right now – every marketing department for every vendor will give you a different definition!
- Much debate within the literature re: definition
  - Digital twin definitions vary by context, a flight control system for a drone is very different to a smart building is very different to a factory.
- Briefly recap of history
  - Explain how we got to where we are
  - Why there is some cynicism from the engineering community, and
  - Explore how twins are being used in industry and for research

A brief history of digital design (1)

- Early Finite Element Modelling on computers in the 1950’s at the Bell and Boeing labs for aerospace. Becomes more widespread in the 1960s.
- Volumetric modelling in CAD emerges in the 1980s

  (NB: parametric design tools have been available since the 1950’s, but not really ‘cad’ as we would know it)
- Model based design (CAD/CAM) becomes the dominant paradigm for product creation in the 2000s.
- In construction, Building Information Modelling (BIM) with higher dimensionality becomes commonplace in the 2010s – e.g., the UK BIM strategy (2011) and the UK BIM framework in 2019

A brief history of digital design (2)

- Digital design not 'new' in civil engineering
- Building and construction differs from other design work
  - Every bridge is bespoke, few (major) buildings are identical
  - Jets and automobiles - incredibly complex systems, but fundamentally one design replicated hundreds or millions of times, so small optimizations can scale accordingly
- Key drivers for digital design have also been economic
  - UK BIM strategy in 2011 - pitched to reduce costs by up to 20% through better collaboration between partners across the design lifecycle.
  - Optimisation though avoiding repetition and providing clarity for communication with contractors, designers, and clients.
- Now using these tools for design optimization
  - Net Zero CO_2, noise abatement, just-in-time materials use, etc

Digital Twin versus Physical Twin

- Use of physical models very definitely nothing new for civil infrastructure!
  - When the first engineers built the first roads, they probably started small and scaled up.
- Numerous examples in history in all areas of engineering and construction

Analogue Simulation – ‘Physical’ Twin

- Sagrada Familia Basilica in Barcelona
- Hanging Chain Model of the Sagrada Família, Anton Gaudi C.1889
- Using the catenary curve of loaded chains (string and sandbags) to optimise arch angles (load bearing features) within the church.
- Changes to the model cause instant re-optimisation.
- Replicating loads like this - ferocious calculation for a modern computer
- Visualisation of the interior is something we’re only seeing now with the use of game engines like Unity and Unreal.

The Analogue to Digital Shift

Passion Façade of Sagrada Família Barcelona (from Wikipedia.com).

Topologically optimized, 3d-printed shelving bracket from Printables.com.

- Digital models and tooling (detailed models and complex optimizations) – previously prohibitive or impractical
- Hyperbolic example – computationally cheap (sophisticated physical modelling – cost prohibitive)

Physical versus Digital Simulations

Physical models require little data, but deep domain knowledge and huge amounts of expertise. They are complex and non-generalizable.

They can represent complex and non-linear relationships in an intuitive qualitative way (even for non-experts).

Data driven (numerical) models can require large datasets but have comparatively lower model complexity than physical alternatives.

Equations to help understanding of inputs, outputs and processes which model represents. Outputs are generally abstract and unintuitive (FEA without physical representation (output view) – just matrix with PDE).

So, what are digital twins?

Many formal definitions and the state-of-art is in flux.

Generally assumed to require a model of a physical ‘thing’ - although ‘design twins’ are common in the Civils space as we move to a ‘BIM to TWIN’ design approach.

Generally assumed to include real-time data feeding back into the model – but when we’re talking about infrastructure, ‘real time’ can mean seconds, days, months, or even years before data changes.

So, what are digital twins?

- Intuitive understanding probably better than a strict definition (which will probably change).
- Many of the attempts at a definition focus on use cases and applications rather than digital twinning as a methodology.
- Definition for our purposes - a digital representation of a ‘thing’, where the status of the digital representation changes to reflect the status of the physical object.
- OR – a virtual model of a physical object or system with a bidirectional relationship between the physical and virtual object.
- A digital twin is NOT a clone.

Defining Digital Twins

- You might have real time data feeds, your data might have latency of a day or a week or a year. Ideally, infrastructure shouldn’t change drastically too often.
- You might have automated or bi-directional control to some degree.
- AI and ML models can provide insight, but that depends on the quality of the model and the data.
- High fidelity 3D models can be helpful, but a VR headset may not help you diagnose a signal failure – more abstract visualizations can be helpful.
- None of the above ‘Define’ the twin. Potential features supporting use cases of the twin. Defining characteristic is the data model.

Digital Twins for Roads

- Design versus Operational models – we can think of this as 'new assets' versus 'existing assets'
- In road terms:
    - Design model is often integrated with BIM
    - Operational model often integrated with a network model
        - Operational models may support smooth operation of the network, maintenance operations, or both.
        - Operational models may also be integrated with traffic management systems –the 'smart city' paradigm, to minimize disruption on the network and manage incidents.
        - Maintenance models generally incorporate PMS data, to manage investment, identify issues with respect to asset condition, and schedule interventions on the network.

Digital Twins for Road Design

- There is a push for 'BIM-to-twin' as what is included in a BIM environment has increased (schedules, budgets, sustainability factors).
- A key asset management concept - the design should support the full lifecycle of the infrastructure, from conception, through operation, to decommission.
- The BIM model can be considered the starting point of the digital twin for new assets. Industry BIM vendors (Bentley, Autodesk) are shaping understanding of digital twins in industry.
- Much of the focus of these tools is for buildings - not transportation networks.

BIM Primer (Business as usual)

- Whilst ostensibly a tool for 3D modelling of buildings, BIM has increasingly expanded to include detailed scheduling for the project including (4D BIM), Budget - including construction options (5D BIM), and sustainability (6D BIM).
- In addition, BIM capability of an organization is described in terms of levels – from Level 0 (non-collaborative 2D drafting) to Level 2 (Collaborative design in a Common Data Environment).
- There is an aspirational BIM level 3 where data is open and shared regardless of vendor or consumer utilizing open standards.
- It's a BIG DATA question. Who owns the data and what is its value/cost?

Design Twinning for Roads


J10 M25 London Orbital

- Busiest junction of the busiest road in the UK, with > 270,000 vehicles using the junction daily.
- Immediate vicinity of the junction:
  - Site of Special Scientific Interest,
  - Special Protection Area,
  - Ancient woodland,
  - Scheduled monument,
  - Several listed buildings, and
  - Resides within the London green belt.
- A preferred layout selected mid 2017 (designs by Balfour Beatty and Atkins).
- Detailed environmental surveys and monitoring to assess impact of the infrastructure
- Detailed traffic models (evaluation of smart motorways)
- Data sharing between all stakeholders; designers, the UK government, City of London officials, environmental groups – in a single common data area.

Image rendered in Unreal 5 using imported BIM models

- Detailed design was produced involving (submitted for planning in June 2019):
    - Creation of dedicated slip-lanes,
    - Widening of the A3,
    - Reshaping the existing roundabout, and
    - Providing an additional running lane.
- Detailed schedules for construction work and mitigation measures to minimize the environmental and traffic impacts were included, with:
    - Just-in-time construction details for bridge decks and deliveries to minimize closures, an
    - Reforestation on the level of individual trees to replace those affected.
- Planning consultation then ran for almost 2 years as additional groups were consulted
- In January 2021, the UK secretary of state for transport requested a special consultation to assess the environmental impacts and the necessity of the infrastructure following COVID-19. The integrated models allowed for rapid re-running with revised parameters and a response issued.
- Approval was issued by the secretary of state in March 2022.

Design Twinning Observations

- The key functions of a ‘design twin’ is to allow optioneering of design options, optimization of design, and to facilitate consultation with related experts and stakeholders.
- Existing design organizations and tool developers are actively working in this space, leading to well intentioned muddying of the waters with regards where BIM stops and a Twin begins.
- Don’t underestimate the importance of rapid iteration and consultation tools – in this instance, consultation took far longer than design!

Digital Twins for Existing Infrastructure

- More existing than new infrastructure
- A very different approach to digital twins for design infrastructure (complexity and scale).
- Existing infrastructure is far more variable than new infrastructure (age, condition, construction methodology).
- Often looking at network scale rather than individual asset scale.
- Focus is often on reality capture –
  - Remote sensing such as LIDAR for road layout and surrounding context,
  - Road condition surveys through both sensor and visual inspections for condition data,
  - Traffic camera data (GPS data from partners, Tomtom & Google).
- Road networks have particular challenges for real time monitoring due to driver behavior.

Operational Twinning

Transport for London (TfL)

- TfL manages the integrated transport network for London (both rail and road, tube and buses)
  - 80% of all journeys are by road,
  - On the road network TfL manage 6,400 traffic signals, around 21,500 bus stops, 1,800 highways structures, and around 50,000 roadworks projects per year.
- There are significant key challenges for a manager of existing infrastructure looking to build a digital twin.
- The focus here is on operational management, not condition.

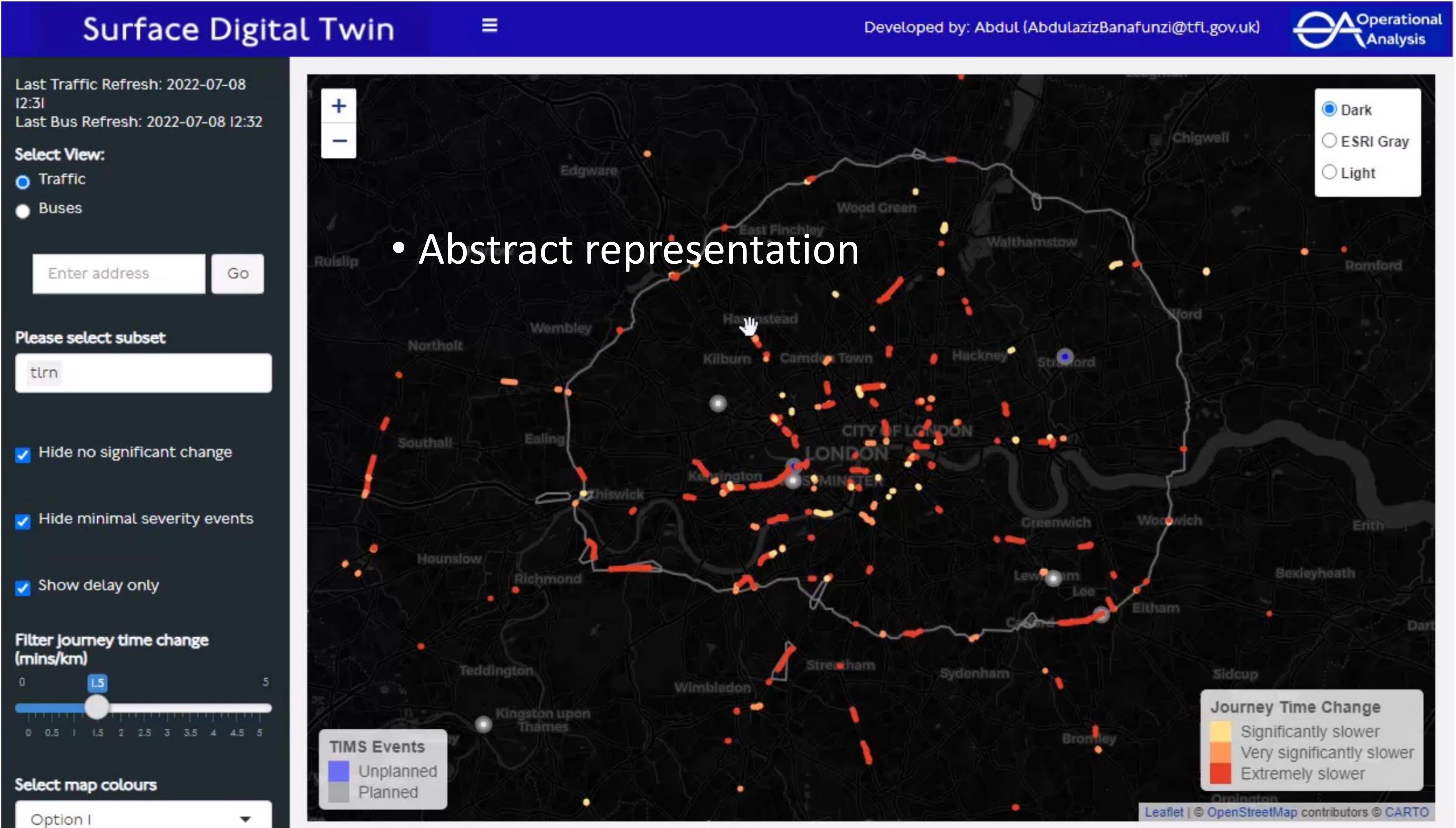
Context for Digital Twin Data

London Road Network – Challenges

Operational Analysis

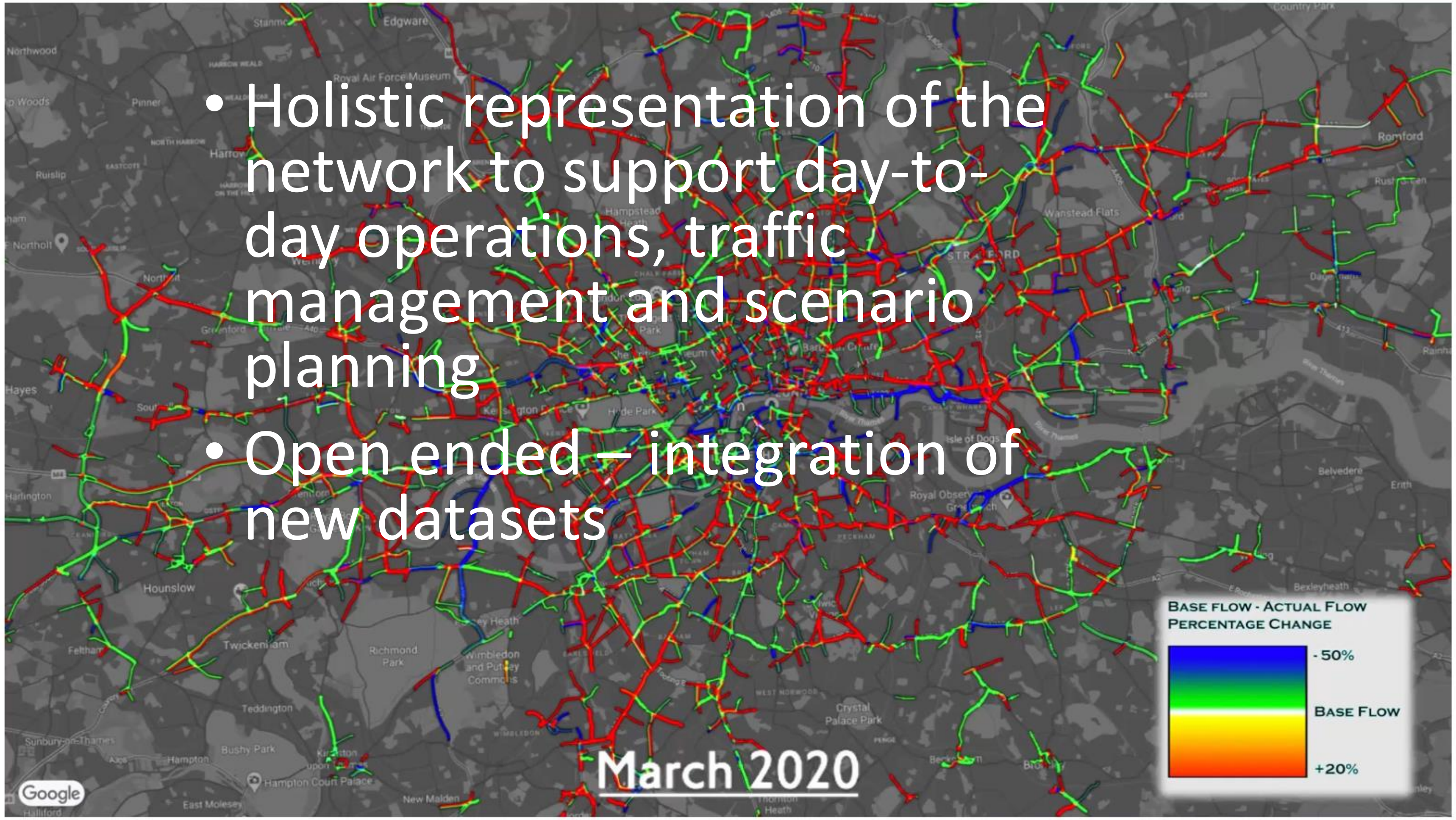
Factors that make it difficult to deliver effective intelligence	Data	Network Attributes	Network Properties
	Poor quality data Poor spatial and temporal coverage Lack of **Cycle, Ped and freight** data **Poor innovation** in sensors and new data ▪Understand network outcomes but not what influences them	**Open network** with little control over demand **Heterogenous road layout** especially London **Dynamic** changes in network design and layout Don't know how to **measure demand and capacity** effectively	**Stochastic** properties of traffic because they are driven by driver behaviour Exhibit **"Emergent behaviour"** and the **same values for many measures** can be arrived at **for different traffic assignment configurations** on the network

- Abstract representation

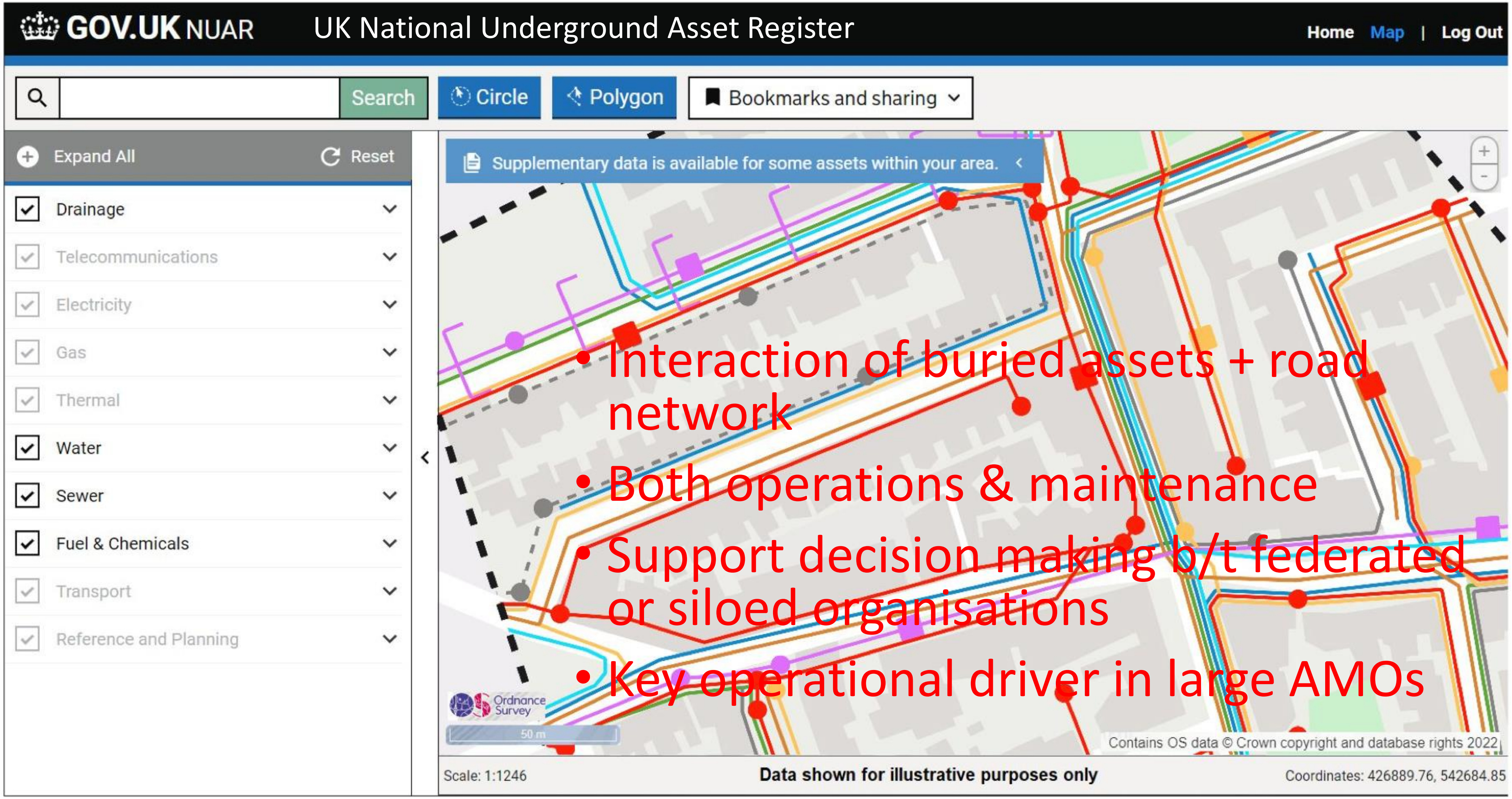


4. Visual Layer

Visualisation of our data allows us to make better decisions in the future.
e.g., COVID impact on traffic flows in London



- Holistic representation of the network to support day-to-day operations, traffic management and scenario planning
- Open ended – integration of new datasets



- Interaction of buried assets + road network
- Both operations & maintenance
- Support decision making b/t federated or siloed organisations
- Key operational driver in large AMOs

Operational Twining Observations

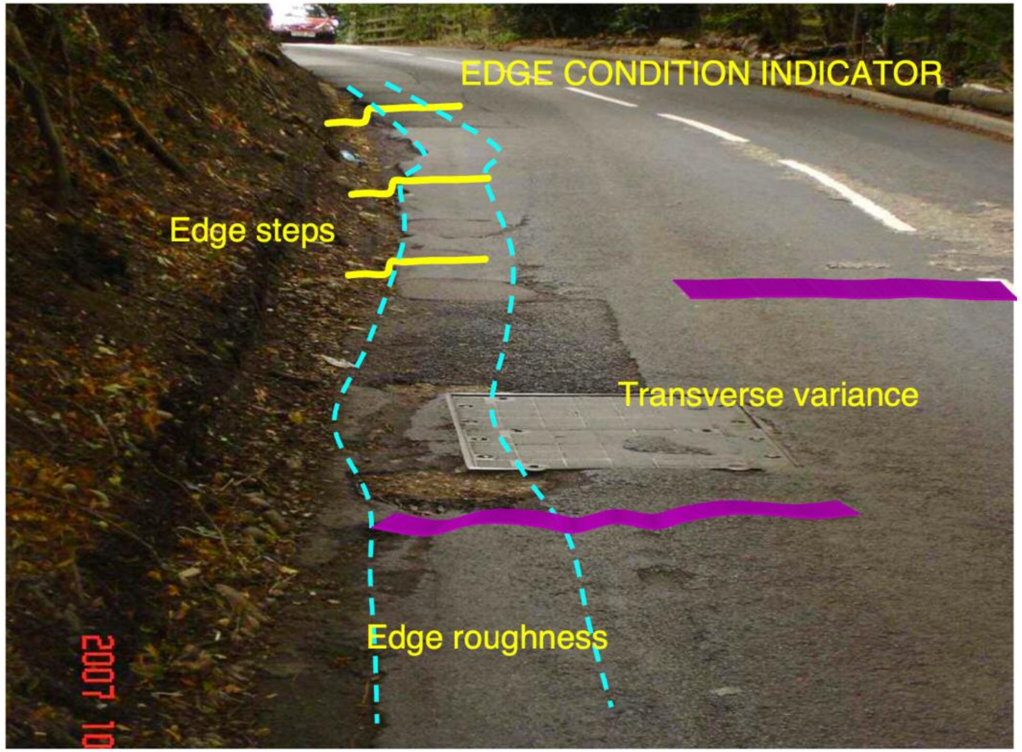
- Digital twins for Operations often tie into smart city or smart motorway concepts.
- Focusing on event detection and prediction. Moving to support planning decisions (traffic flow, routing).
- In contrast to BIM for design, operational twins have a GIS level network focus:
  - Creates, manages, analyses and maps different types of data
  - Location data, descriptive information, etc.
- Allow for effective communication between silos and teams – providing different views of a single source of the truth.

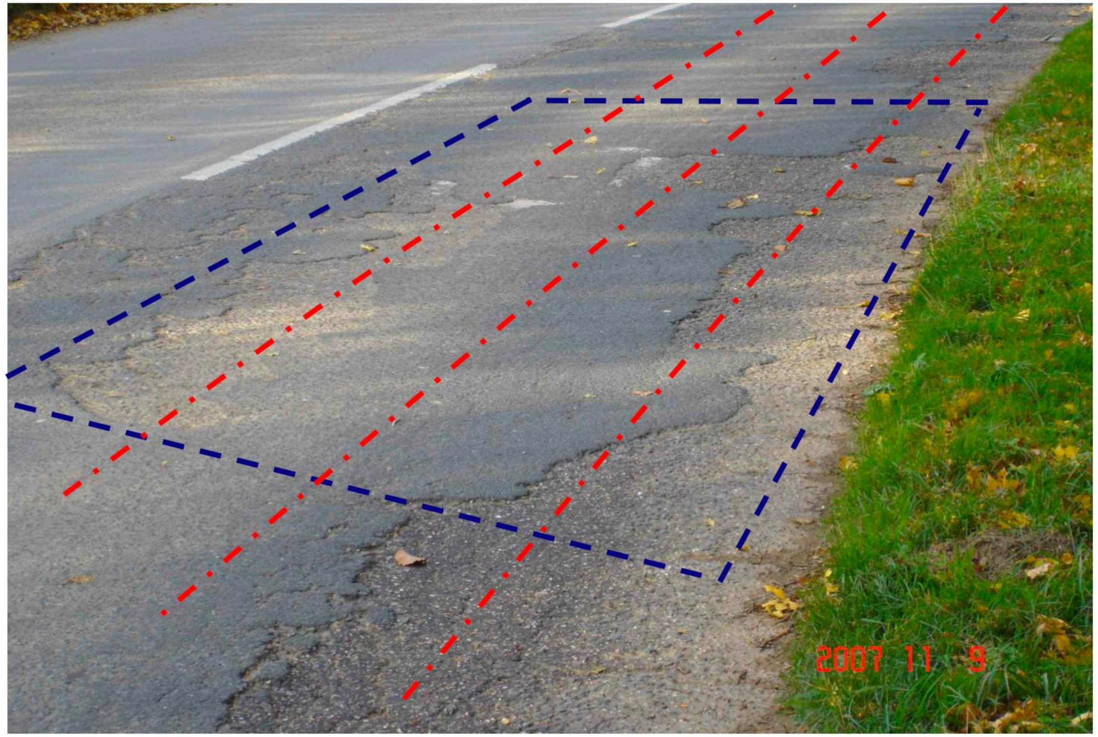
Maintenance Twinning

Digital twins for condition

- Road networks are hugely variable,
- Assets can vary by age and condition,
- Asset management organizations (AMOs) are often siloed (structures, drainage, Geotech, etc),
- Responsibilities can be federated (e.g., county/state borders, regional administration).
- ‘Single version of the truth’ – cross-asset, cross region models = Big win for AMOs
- Knowledge to stakeholders & prediction of outcomes

Reality Capture – Ground Truth

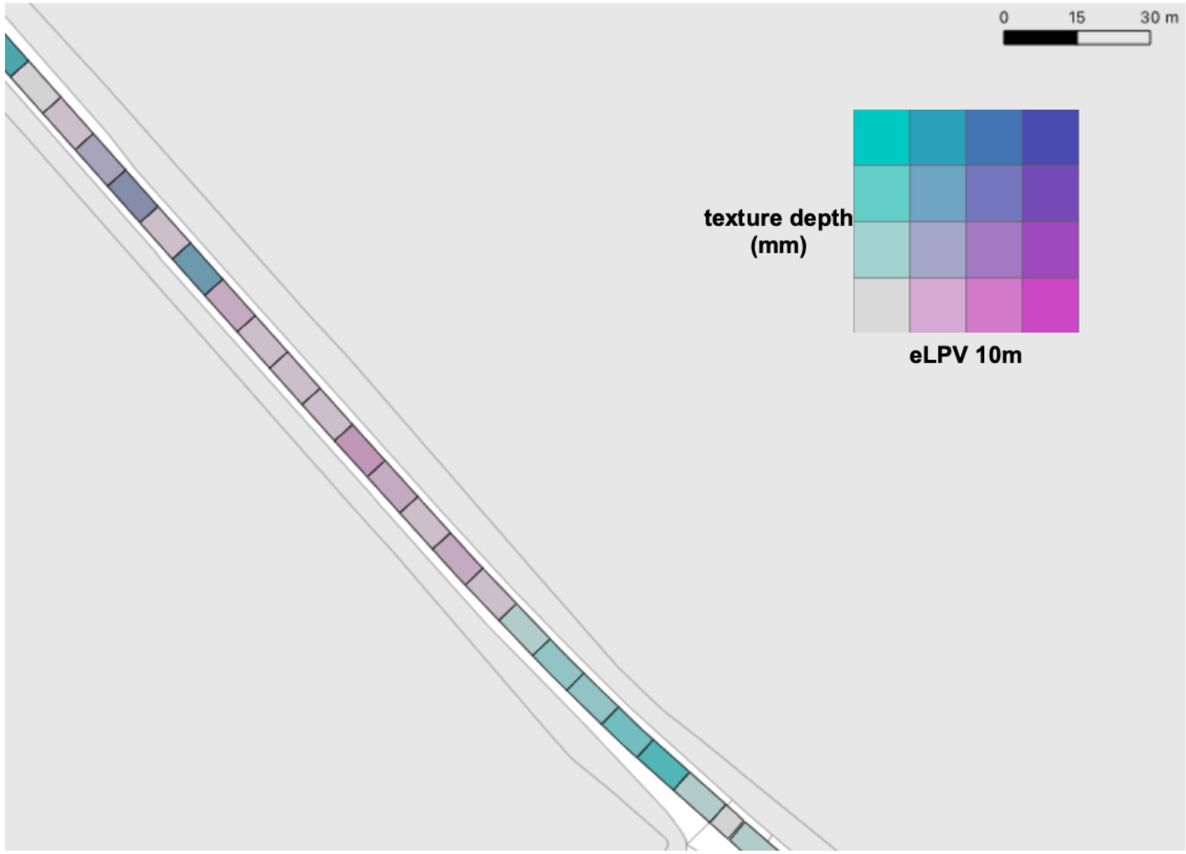




Reality Capture – Ground Truth

- Sources to establish road condition:
  - Visual inspections and traffic-speed surveys (e.g., TRACS and SCANNER in the UK) - road roughness, surface texture depth and rutting (potholes, bumps, cracks, and other defects).
  - Computer vision for defect detection, (e.g, VAISALA, Atkins Theia).
  - Business as usual for over 30 years.
- Commonly recorded in a Pavement Management System:
  - International systems and standards (Belman, UKPMS, Viagerenda).
- Fundamental purpose of PMS is to optimize budges for maintenance and investment.

Condition Data – Spatial Context



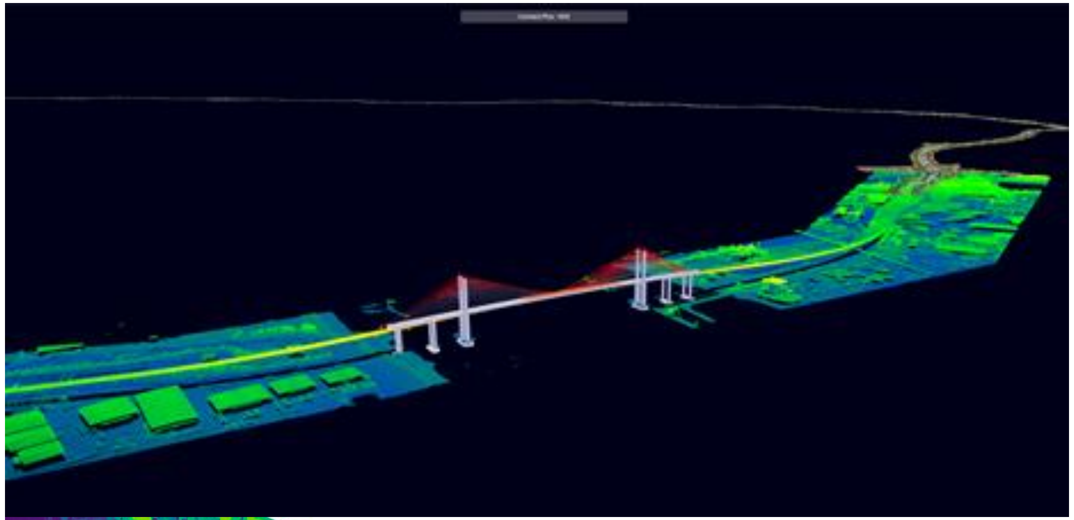
- Integration of PMS systems with GIS systems (maintenance sections correlated to network model)
- Example – UK Ordnance Survey Data to condition (PMS data)

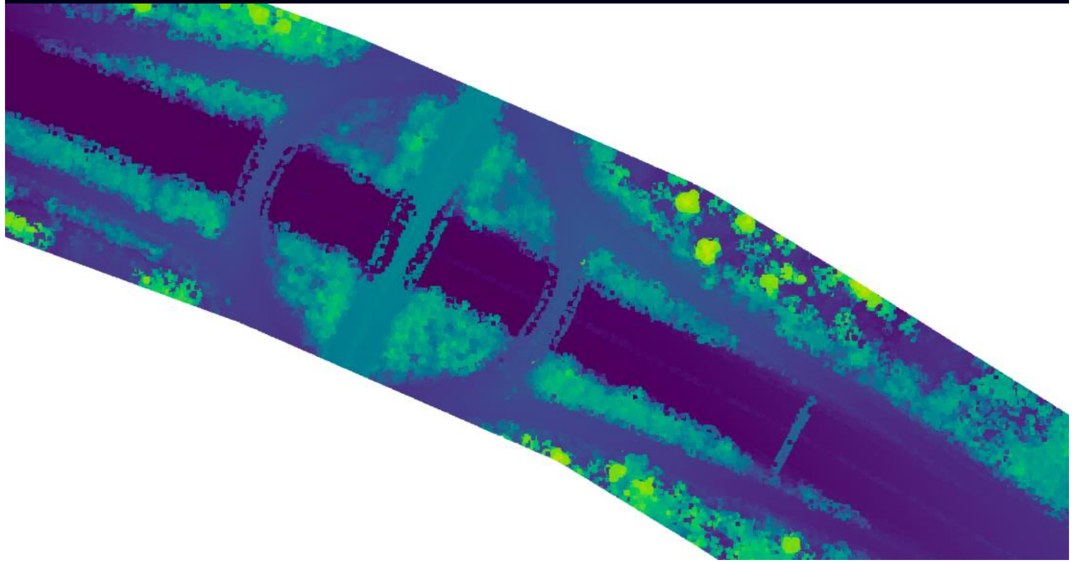
- Common network model with incorporated other novel datasets
- Drone (or satellite) LIDAR data for remote monitoring of assets

Digital Twins - Bringing datasets together

- Topology (LIDAR),
- Network models (GIS)
- BIM models (design teams)
- Sensor data (e.g, traffic, weather)
- Condition from PMS

To create a single view of the asset portfolio – reduce costs, improve service (safety), improve decision making.





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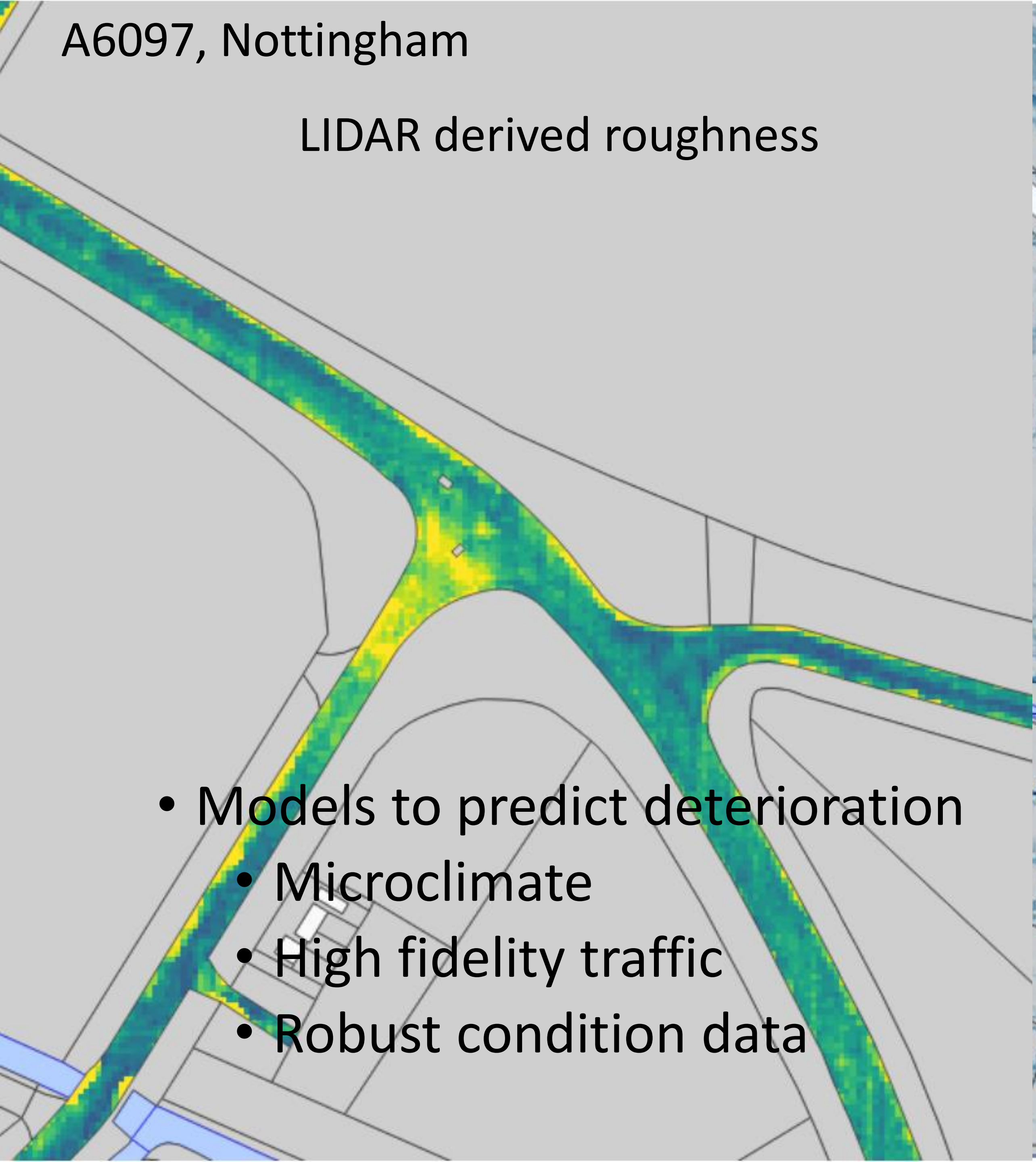

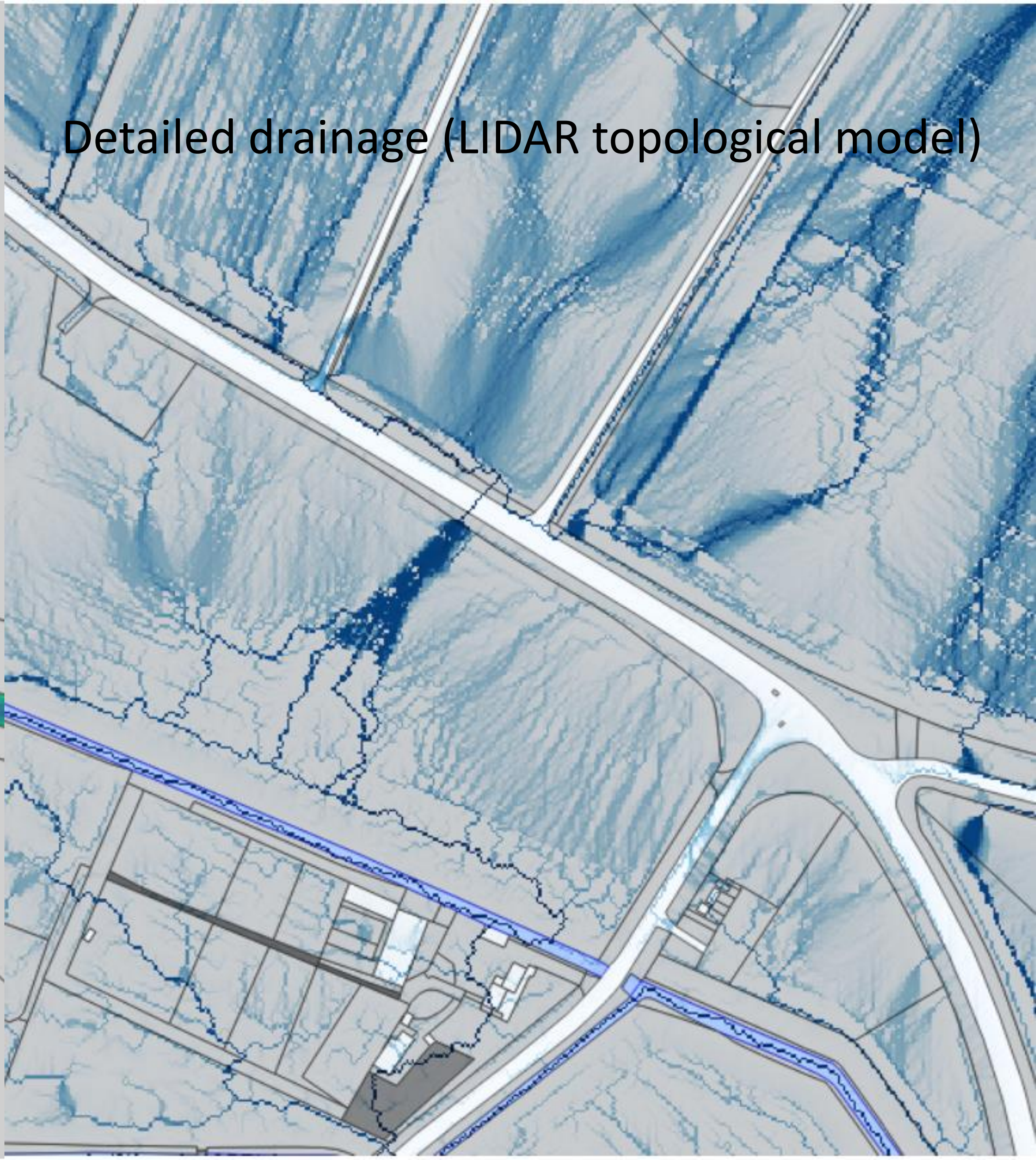

- Models to predict deterioration
  - Microclimate
  - High fidelity traffic
  - Robust condition data

Maintenance Twinning Observations

- Like the operational model, a maintenance model integrates with a network model.
- A maintenance model for pavements will (generally) incorporate the PMS data model of the AMO.
- This can be combined with other asset classes and the raw operational model to provide an organizational single source of truth.
- Inclusion of broader context can identify off-site risks such as drainage issues and off-site development.

Conclusions

- Broad definition(s) of digital twins (demystified based on application rather than methodology)
- UK case studies related to design, network operations and maintenance ‘digital twinning’
- The ambition is to combine these models (applications) – A unified digital twin for roads
- A key benefit of the digital twin paradigm is providing a single, consistent source of truth to an AMO.

Thank You