Government Office for Science

Future of Tunnelling

Future of Tunnelling: High-level review of emerging technologies

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Acronyms

AI	Artificial Intelligence
AR	Augmented Reality
BIM	Building Information Modelling
DfMA	Design for Manufacture and Assembly
GO-Science	Government Office for Science
GPU	Graphical Processing Unit
GGBS	Ground Granulated Blast Furnace Slag
HSEW	Health, Safety, Environmental and Welfare
IoT	Internet of Things
IP	Intellectual Property
LLM	Large Language Models
MEP	Mechanical, Electrical and Plumbing
MiC	Modular Integrated Construction
MiMEP	Multitrade integrated Mechanical Electrical and Power
NUAR	National Underground Asset Register
SDG	Sustainable Development Goal
SMART	Stormwater Management And Road Tunnel (SMART Tunnel),
STEEP	Social, Technological, Economic, Environmental, and Political
TBM	Tunnel Boring Machine
VR	Virtual Reality

Executive Summary

Arup have been commissioned by the Government Office for Science (GO-Science) to undertake a high-level study into the emerging trends and technologies in tunnelling at scales from trenchless drilling to large transport tunnels.

The space below the surface provides society and the economy with a range of uses, which are set to increase in variety and criticality over the coming decades. This high level study forms part of the Go-Science foresight project: Future of the Subsurface. Qualitative and quantitative empirical research based on interviews and a survey was obtained to provide contextual insights on the future of tunnelling in the UK, focussed on emerging technology and the associated opportunities and challenges. Given the relevant wide-ranging topics and literature, a scope and study approach was defined to be commensurate with the study budget.

Recent technology developments have been categorised within the following taxonomy: robotics, materials, artificial intelligence (AI), building information modelling (BIM) and design, prefabrication, 3D printing, wearables and mobility, virtual/augmented reality (VR/AR), drones, sensors and internet of things (IoT), blockchain, digital twins, excavation technology, investigation and sensing, energy, and data storage and processing. The current UK position has been summarised within the categories of investigation and sensing, design, tunnel construction methodology, operation, planning and powers to construct, repurposing and reusing tunnels and shared use of tunnels.

Key opportunities for the application of technology in tunnelling of particular relevance to policy makers include:

- **Standardisation** of tunnelling components to create a 'kit of parts' approach to construction, and standardisation of the design and assessment process;
- **Data-driven design and construction planning** – facilitated by improved access to data to inform design, and improved use of AI and BIM, including improved integration between design, construction and operation. Develop and share a national digital twin, including ground conditions data, the National Underground Asset Register (NUAR) utility data, existing buildings and below-ground structures.
- **Excavation technology** innovation through accelerating the adoption of emerging technologies, particularly robotics. Incremental innovation of existing technology, and potential rapid innovation involving robotic excavation methods.
- **Construction materials** – focussing on sustainability; optimising concrete for tunnelling operations, including secondary cementitious materials and non-ferrous reinforcement materials. Increase the reuse of materials. Develop understanding of service life through investigating, modelling and analysis to extend the service life of tunnel assets.
- **Energy** – utilisation of tunnels to harvest geothermal heat from the ground through tunnel energy segments. Harvesting heat generated from tunnel use, such as rail. Sourcing construction plant fuel from renewable sources, such as hydrogen fuel cells and electric plant.
- **Operational requirements** – critically reviewing operational requirements to refine tunnels. For example, replacing human tunnel operation and maintenance with robotic technology could offer a reduction in space proofing requirements and tunnel diameter.
- **Shared use** – shared use of tunnels offers to reduce competition for subsurface space, reduce capital expenditure (CAPEX) and operational expenditure (OPEX) costs. Multi-utility tunnels in new developments and upgrades where possible. Utilisation of transport and energy tunnels for other uses such as utility infrastructure. Combined utility corridors.
- **Reusing tunnels and tunnelling equipment** – Reuse of tunnels, including by extending their service life, and by utilising abandoned tunnels for similar or new uses. Reuse of tunnelling equipment, including TBMs, on projects.

To stimulate and sustain an ecosystem for technology development and adoption, a strong pipeline of tunnelling projects and related planned work is crucial. Key challenges to technological development and implementation identified include:

- Contractual arrangements resulting in a risk-averse environment stifling innovation;
- Prolonged and complex assurance processes;
- Lack of access to data, such as existing ground conditions and subsurface assets;
- Industry or project focus on the wrong technology, leading to loss of confidence and distraction from appropriate technology;
- Social factors constraining the adoption of technology, such as resistance to change or technology and drivers to optimise design leading to unique designs that constrain standardisation;
- Shared use of tunnels limited by safety concerns, differing requirements and commercial risk;
- Matching supply with demand across topics such as reusing tunnel assets or harvesting energy; and
- Complexity and gaps in policy on the ownership of underground space.

Opportunities for further work to develop this study include a detailed literature review, extending the engagement with the tunnelling industry, including the supply chain and academia, and broadening the study to include the impact of the future contextual environment within technology will be developed and implemented.

1. Introduction

Arup have been commissioned by GO-Science to undertake a high-level study into the emerging trends and technologies in tunnelling at scales from trenchless drilling to large transport tunnels.

The space below the surface provides society and the economy with a range of uses, which are set to increase in variety and criticality over the coming decades considering population growth, emerging technologies, the need to decarbonise, food, water and energy security, and the impacts of climate change[1]. The aim of the study is to inform future scenarios for subsurface use and the potential need for more coordination and regulation to unlock value in the use of underground space, focussing on tunnels. This Future of Tunnelling study forms part of the Go-Science foresight project: Future of the Subsurface[1].

The study methodology is described in Section 2 and findings of the study are summarised in Section 3 following the headings of the Government's Rapid Technology Assessments[2] to facilitate the onward dissemination of the study to government bodies and other stakeholders. Context for tunnelling in the UK is briefly outlined in Section 3.1.

Tunnelling, in the context of this study, encompasses the broad range of activities required for the design, construction and operation of underground works relating to tunnels, shafts, caverns and associated underground structures[3]. A tunnel constructed in the modern era is a system of components (e.g. structural linings, walkways) housing systems (e.g. communications, power, ventilation) within a broader system (e.g., a railway or a sewer network); tunnels are generally considered in this context of a broader system. This study focuses on the structural component of the system, i.e. tunnel structures and tunnel construction.

This Rapid Technology Assessment considers physical and digital technologies and enablers of these technologies that have the potential to lead to significant gains in tunnelling productivity, quality, cost and health, safety, environmental and welfare (HSEW) improvements.

2. Study methodology

2.1 Outline

The study was performed using both a qualitative and a quantitative empirical research approach to obtain contextual insights of the future of tunnelling in the UK, focussed on emerging technology and the associated opportunities and challenges. Given the relevant wide-ranging topics and literature, a narrow scope and study approach was defined to be commensurate with the study budget.

Given that the majority[4] of the world's tunnels use tunnel boring machines (TBMs), this study focussed on tunnelling use cases that are currently undertaken using TBMs in particular. Emerging technology has been the focus of the study, touching on trends that could impact the adoption of emerging technologies. In particular, technology that aligns with the current trajectory for UK tunnelling to tunnel faster, cheaper, safer and with lower embodied and whole-life carbon. Future wider contextual trends that significantly impact the trajectory of the future of tunnelling are beyond this scope, and are referred to in Section 4.

This section outlines the key components of the research methodology.

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[1] Future of the Subsurface project summary at https://www.gov.uk/government/publications/future-of-the-subsurface/future-of-the-subsurface#:~:text=1.-,Overview,the%20impacts%20of%20climate%20change.

[2] Rapid Technology Assessments are published at https://www.gov.uk/government/collections/rapid-technology-assessments

[3] The International Tunnelling and Underground Space Association (ITA-AITES) provides useful contextual information on tunnelling: https://tunnel.ita-aites.org/en/

[4] In the absence of a definitive compilation of UK tunnelling projects, a list of tunnels in the UK collated on Wikipedia was reviewed, of which 77% completed since 2000 were constructed using TBMs.

2.2 Approach

2.2.1 Data Collection

Data was obtained through interviews, primarily internally with the Arup global tunnel skills network, and an industry survey. A detailed literature review was not undertaken and would be beneficial to develop and test the findings of the study.

Expert Interviews

A series of in-depth interviews were conducted with participants selected from diverse group of Arup's industry experts, aiding in understanding nuanced perspectives of leaders in the field. The experts were chosen based on their extensive experience, knowledge and involvement in various aspects of tunnel construction, design and management and to provide global coverage. The map below shows the geolocation of the participants interviewed.

Figure 1 - Map showing location of expert tunnelling interviewees

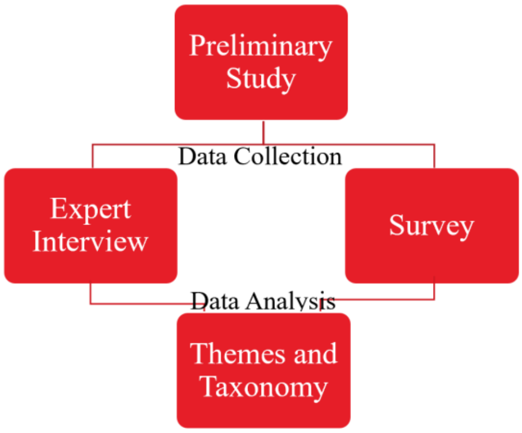
Survey

A preliminary survey was conducted of over 100 tunnelling professionals, comprising views from Arup tunnel designers from the UK and internationally, British Tunnelling Society members, and tunnelling professionals from the American tunnelling industry. The survey was designed to be comprehensive, covering a wide range of topics including potential technological advancements and its impact on the tunnelling industry, to supplement the in-house research and identify emerging technology outside of the UK.

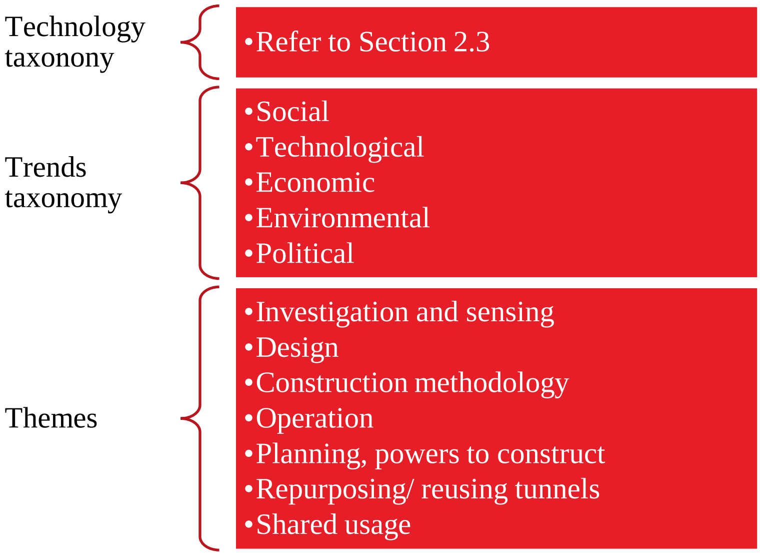
Wider and systematic engagement with the tunnelling community is recommended by Arup to develop and test the findings of study, and to help avoid a bias of opinion. This would include further engagement with key stakeholders directly, such as the British Tunnelling Association and the International Tunnelling Association.

2.2.2 Data Analysis

Qualitative data were transcribed and analysed to identify recurring themes and taxonomy. Quantitative data were analysed to discern trends and opinions within the industry. The data collected were cross-referenced to identify common and divergent viewpoints, allowing for a balanced and holistic analysis. Refer to Appendix B for the survey results. The following sections present the findings and recommendations for next steps.



Evidence was collated in a database and categorised as follows:



2.3 Technology and trends taxonomy

A technology taxonomy developed for this high-level study is outlined in Table 1.

Technology Taxonomy	Description
Robotics	Use of highly automated machines to carry out activities traditionally undertaken by humans.
Materials	Innovative use of eco-friendly materials and waste products to replace natural materials to achieve sustainable, green materials.
Artificial Intelligence (AI)	Artificial Intelligence (AI) involves using digital technology to perform tasks commonly associated with intelligent beings including: (a) machine learning (b) computer vision (c) natural language processing (e) knowledge-based systems (f) optimisation (g) automated planning and scheduling.
Building Information Modelling (BIM) & Design	Building Information Modelling (BIM) is a digital representation of physical and functional characteristics of a built asset utilised to create and manage the information in planning, design and construction of the project throughout its whole life cycle. Design incorporates the planning, specification and communication of project requirements.

Technology Taxonomy	Description
Prefabrication	Fabricating structures or structural components in advance of bringing them to site.
3D printing	Sequentially layering materials via computer-controlled processes to create three-dimensional shapes.
Wearables and mobility	Technology within devices that are mobile and/or worn by people that interact with other systems.
Virtual Reality/ Augmented Reality (VR/AR)	VR/AR technologies in construction are used to enhance the perception of reality to plan, design, execute and monitor projects by overlaying digital information on the visible world (AR) or displaying immersive digital models.
Drones	Drones are un-manned flying airborne devices used to gather data, enable communication and increase efficiency on construction sites.
Sensors and Internet of Things (IoT)	Use of sensors and Internet of Things (IoT) to enable real-time monitoring and predictive maintenance of construction sites and equipment by detecting changes in the environment and connecting to the internet, prompting an action.
Blockchain	A system that tracks transactions across a peer-to-peer network providing a shared and unchangeable ledger that is transparent and highly secure.
Excavation technology	Use of technology to remove soil, rock and other materials for purposes such as tunnelling, site preparation, foundation construction, utilities installation etc.
Digital twins	A digital representation of a physical object or system that is updated to reflect changes in the physical object or system.
Investigation and sensing technologies	Technologies to improve safety, efficiency and capability in investigating the geotechnical and environmental properties of the ground and structures.
Energy	Utilising innovative and sustainable sources of energy and materials to improve the sustainability of construction projects.
Data storage and processing	Advances in technology to process, analyse and manage large or complex set of information, increasing efficiency and productivity.

Table 1 - Technology taxonomy

3. Rapid Technology Review

3.1 Introduction

The global output for tunnels and underground space in 2019 was £110bn, and its growth is twice as high as other global construction sectors. The UK's share of this was an output of £843M, with £3.1bn worth of work in the pipeline[5]. Advances in tunnelling technology are crucial to enabling this growth, and new innovations will need to be adopted and matured to match this demand.

A demand for longer and larger tunnel bores (>18m diameter) for underground space creation is apparent, as is an increase in demand for smaller diameter microtunnels (<4m diameter) to serve utilities. More resilient in-tunnel communications systems, mechanical, electrical and plumbing (MEP) and control systems are required to support increasingly more complex construction and operations, however, tunnel fit out is beyond the scope of this study. Emerging use cases for tunnels such as hyperloop have the potential to increase the need for tunnels and impact the requirements for design and construction of tunnels. Reuse, retrofit and mixed use of these underground spaces is becoming increasingly important to sustainably use the subsurface.

Tunnelling technology advancement is viewed as being incremental rather than comprising frequent step changes and, although there are disruptive technologies that are showing potential for rapid change, innovations building on established tunnelling methods of construction and established engineering practice dominate. Tunnel technology development is being seen across the whole tunnel asset lifecycle, from planning and design, operations and maintenance, through decommissioning and reuse. Emerging technologies, maturing research and development, and a changing workforce with new technology skills is bringing forward innovation. Positive outcomes demonstrated by the wider global tunnelling industry demonstrate that where more equitable risk share contracting and legislation is present, this has proven key to lowering the barriers to the adoption of new technology, ideas and approaches, enabling productive innovation to be realised within real-world tunnelling projects.

Evidence collated for this high-level study is summarised in Appendix A, including references to key sources.

3.2 Recent developments

Recent global developments within each technology taxonomy category are captured in Appendix A and below:

- **Robotics** – Robotic technology has been adopted at various stages of the tunnel construction process, from pre-construction investigation and sensing, construction stage segment production and handling through to TBM maintenance and robotic cutterhead disc changing, and post-construction maintenance and inspection of tunnels. The application of robotics within the manufacturing and mining industries to more general tunnelling projects is an emerging theme. Market disruption using many small robotic excavators to replace traditional excavation methods has been proposed. Robotics offer health and safety benefits by removing or supporting operatives in undertaking traditionally manually intensive and repetitive tasks.

Robotic inspection of UK Power Network tunnels (UKPN, Arup, 2023)

- **Materials** – There is a particular focus on sustainable structural materials, such as cement replacement in concrete, including emerging research into calcined clay. A future lack of current cement replacement materials, such as ground granulated blast furnace slag (GGBS), is a widely accepted challenge. Use of steel fibre reinforcement has emerged as routine practice, with future use of macrosynthetic fibres instead of steel, bio-based self-healing concrete, and cement biotechnology innovation (e.g. Biomason) on the horizon. Code updates will become more prevalent in order to accelerate the compliance of new

[5] ITA (2019) Tunnel Market Survey, converted to GBP using ExchangeRates.org.uk average exchange rate for 2019 of 0.8733

materials with standard codes and practices. Accelerated age testing is improving our understanding of material durability, and will help to develop future low-cost, low-carbon and high-durability tunnel structures. Recent advances in material resilience open up the use of temporary works as permanent works.

- **Artificial Intelligence (AI)** – AI is emerging across the entire tunnelling project lifecycle. Generative AI, such as foundation models, is increasingly used in design processes, from writing code to researching and writing documents. End-to-end design is already implemented in digital product design and the breadth of coverage of AI in construction is increasing. Driverless tunnelling plants (e.g. TBMs and roadheaders) using AI are operating outside of the UK, including autonomous TBMs and support vehicles. Use of machine learning to predict ground type and behaviour, to optimise TBM drive utilisation and the use of object recognition of tunnel structural defects and tunnel objects to inform predictive maintenance regimes and tunnel asset inventorying. Generative AI using Large Language Models (LLM) is being increasingly used to access structured data. It is recognised that AI, used in combination with other technology, has the potential to disrupt the tunnelling industry and to facilitate incremental innovation across the breadth of the industry. Machine Learning (ML) is a branch of AI increasingly adopted in tunnelling projects at each stage[6].

- **BIM & Design** – Building Information Modelling (BIM) is generally deployed on tunnelling projects with varying degrees of success. There is a reasonable consensus that BIM is not delivering the full potential benefit. Automation of design and construction processes, including when combined with AI, is improving decision making, and has the potential to significantly reduce pre-construction programmes. Advances in cloud BIM technology is overcoming barriers to realising the value of BIM, including in combination with other emerging technologies, such as wearables and VR, to help visualise the BIM model in parallel with on-site as built checking.

- **Prefabrication –** Offsite construction is routinely adopted, particularly for tunnel linings and cut and cover tunnels. Prefabrication offers an opportunity for improved quality and materials innovation in a controlled environment. Prefabrication in the context of a kit-of-parts standardisation of tunnel construction is an emerging theme, with advantages related to efficiency in repeated fabrication, reduced production lead in time, and design automation. This is improving productivity, accelerating construction rates, greater cost certainty and the move to whole design cycle digital optimisation. Precast concrete tunnelling is most likely to benefit from this, as more reliance on Modular Integrated Construction (MiC) and design for manufacture and assembly (DfMA) tunnelling arises. Multitrade integrated Mechanical Electrical and Power (MiMEP) methods on Mechanical Electrical and Power (MEP) and control systems enables whole system modularisation and prefabrication.

Robotic fabrication of HS2 tunnel segment (HS2, 2020)

- **3D printing** – 3D printing is being used across all project stages, from early concept prototyping of fixings and devices, to full-scale tunnel lining printing as the TBM advances. Swissloop Tunnelling's in-built tunnel tube 3D printer concept trials using 3D printed tunnelling linings are ongoing. This reflects a growing trend for offsite 3D printing of structural and non-structural tunnel components.

- **Wearables and mobility –** Wearable technology provides data and communication between construction operatives, with the potential to improve safety and production. Examples include smart watches, geolocated visitor cards and sensors on helmets, and importantly on mobile construction plant and equipment. Wearable technology is emerging in the context of improve health and safety and productivity in the construction industry. For example, wearable carbon monoxide sensors and geospatial technology that tracks the location of workers to aid fire evacuation, and that is linked to the operation of plant.

[6] Refer to a recent summary by Marcher et al. (2021) Capabilities and Challenges Using Machine Learning in Tunnelling. Theory and practice for tunnel engineering 3rd Edition, IntechOpen. Available at: http://dx.doi.org/10.5772/intechopen.97695.

[7] HS2 (2020) Krokodyl robot lifts TBM tunnel segment November 2020. Media Centre report, accessed 29/11/23: https://mediacentre.hs2.org.uk/resources/hs2-vl-19349-s-1205-pep-078-189647-s-001205.

- **VR/AR** – VR/AR technologies are becoming increasingly prevalent in stakeholder engagement, and visualisation of underground infrastructure proposals. This enables realisation of impacts and risks to be assessed in real-world digital landscapes, such as in Environmental Impact Assessments. Use of VR/AR enables designs to be conceptualised in 3D space and underground spaces to be virtually visited in a safe way, enabling operatives to practice and experience underground systems safely first before entry. There is strong links with wearables and digital twins, which could become powerful tools of the future within a metaverse, where virtual social interaction and virtual marketplaces for tunnelling may arise.

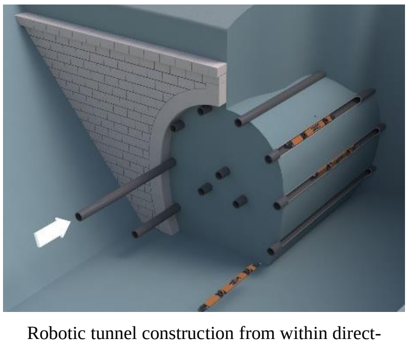
- **Drones** – Drones refer to unmanned aerial or surface vehicles, which are moving from remotely operated towards increasingly autonomous and intelligent. Their use in data acquisition, such as underground inspections, is growing, enabling safer access to confined spaces and high-risk areas, avoiding the need for person entry. The ability to coordinate swarms of drones to undertake complex tasks and combine with emerging technologies like 3D printing of structural elements has the potential to disrupt how structures are constructed and set out. In future, applications emerging include transportation of materials and potentially workers (people or robots).

- **Sensors and IoT** – Advancements in sensor technology and communication devices enhance data acquisition to inform excavation processes, such as TBM driving and predictive maintenance. Increasingly small, robust and versatile sensors will continue to incrementally evolve, providing benefits in the construction and operation phases. Fixed and remote sensor technology to improve real-time monitoring of construction progress, structural health and systems controls is benefitting from advances in active and passive smart sensors, and sensing at all scales from local edge computing devices to relay real-time sensing and compute to satellite image remote sensing to detect tunnel induced ground movements and land classification impacts.

- **Blockchain** – Digital currencies using publicly visible ledgers (blockchain) offers the potential to positively impact construction management. Blockchain has potential to open up new methods for procurement and payment, assurance of materials provenance, and security of design and construction sign-off. Given the specific focus, this technology has not been considered further and reference is made to published literature such as HM Treasury (2015)[8].

- **Digital twins** – Digital models, shadows and twins are growing in sophistication and extent, capturing a growing number of systems associated with a tunnel. As sensor technology evolves and data availability increases, the application of digital twins to tunnels can grow, both applied to tunnels themselves and to the environment in which tunnels are constructed and operated within.

- **Excavation technology** – Significant developments are ongoing in the field of excavation technology. Emerging technology applications are generally incremental in nature, offering improved excavation capabilities such as increased tunnel depth, improved data-driven decision-making including AI, integration of robotics, ground treatment technology, improved materials such as cutting materials and non-circular tunnels. Excavating tunnels from ground level has been demonstrated in limited case studies globally, and remains constrained by land take and impacts of shallow tunnelling on the ground. Disrupting technology such as robotic plasma boring and the use of swarms of robotic excavators are emerging[9], seeking to challenge traditional tunnelling approaches. Herrenknecht, a German tunnel boring machine manufacturer, has developed "Direct Pipe™" microtunneling, which combines machine advance together with pipeline laying behind.



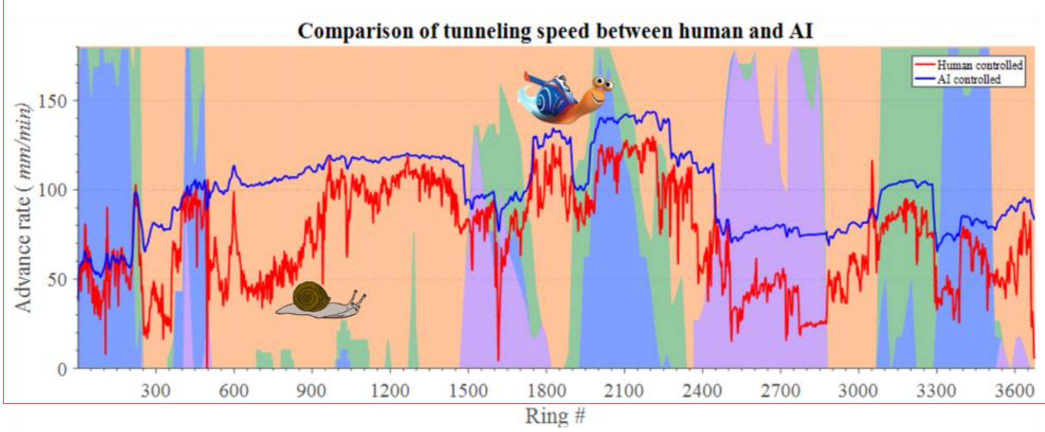
Robotic tunnel construction from within directional drilled holes proposed by Hypertunnel (2022)

- **Investigation and sensing technologies** – Ground investigation technology is developing, including improved reliability and parameters acquisition using remote sensing, and increased confidence in locating buried utilities and obstructions. New geophysical and remote sensing techniques include Muon

[8] HM Treasury (2015) Digital currencies, response to the call for information. March 2015. ISBN 978-1-910337-91-2.

[9] Hypertunnel (2022) within Wired (2022) Swarms of Mini Robots Could Dig the Tunnels of the Future, accessed 13/10/23: https://www.wired.co.uk/article/future-of-digging-tunnels.

technology applications and passive seismic methods. Technology acquiring information remotely is enabling construction processes, operation and maintenance to reduce from site-based human involvement, offering benefits in quality of data, improving H&S, and an opportunity to reduce the size of tunnels if human access is not required. Including data driven autonomous TBM driving.



Comparison human controlled and AI controlled tunnel speeds reported by Colorado School of Mines (2023) [10]

- **Energy** – Energy harvesting technology, including geothermal and thermal tunnels, has proven potential to supplement urban energy networks, when supply and demand can be matched. Renewable energy to power construction plant on tunnelling projects is increasingly looking to electric and hydrogen sources, moving away from conventional diesel supplies.

- **Data storage and processing** – Technology to harvest, store, process and visualise data is well-established and continually evolving. Growing traction in data sharing, together with future improved data capture and technology to harvest archive data and create structured data, offers opportunities to enhance data-driven design and construction. Digital technology, such as edge and quantum computing, offer a step change in processing capability, benefiting pre, during and post construction stage decision making. The increase in cloud computing, compute power and graphical processing unit (GPU) is enabling complex tunnel design and real-time smart sensor data streams to be integrated into design and monitoring. This enables faster and more powerful generative design and multi-parameter optimisation to be carried out on 'big data[11]'.

3.3 UK Position

From research undertaken, the UK-level of adoption of these technologies has been summarised in Appendix A and under the following themes:

- **Investigation and sensing** – Emerging hardware and software technology is improving our ability to investigate the natural and man-made subsurface, such as multi-sensing remote investigation techniques mapping the ground assisted by AI. Sensing technology is facilitating increasingly data-driven construction processes, including TBM operation. Cross-industry collaboration on data sharing initiatives, such as the National Underground Asset Register (NUAR), is enabling more effective information management for buried utilities and understanding of tunnel routing constraints.

- **Design** – Innovation through the supply chain is increasingly enabled by access to public project data. Digital technology, such as parametric design, BIM and AI, is accelerating design and allowing a greater number of solutions to be explored. Innovation competitions and more equitable risk-sharing contracts in some cases promote design innovation, including from tunnelling build contractors, and SMEs. Research funds and collaboration between academia and industry is encouraging the early adoption of technologies onto projects. Lack of standardisation in design is apparent, however, the adoption of low-carbon materials and focus on sustainable outcomes in design is increasing.

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[10] Colorado School of Mines (2023) Comparison of tunnelling speed between human and AI, accessed 12/10/23: https://underground.mines.edu/7m-darpa-contract-3/

[11] Big data: data sets that are too large or complex to be dealt with by traditional data-processing application software

- **Tunnel construction Methodology** – The UK has seen a gradual increase in the adoption of technology at construction stage, though is generally seen as slower to adopt emerging technology than East Asia, such as the use of robotics in tunnelling, tunnelling from ground surface, and AI driven TBMs. Implementing new innovations within active construction comes with a higher risk than at other stages of a project. A commercial landscape that promotes lower commercial risks to adoption, and pain-gain sharing can help in enabling this. A stable pipeline of government backed projects can help ensure continued maturing and adoption of new technology, and reduce the 'brain-drain' of innovators away from the UK market and stalling of technology production at low readiness levels. Innovation examples include the Hypertunnel concept of miniaturised robotic construction and TBM enhancements.

- **Operation** – Project investments and technology strategies that consider the full life cycle of the asset, from the start of new projects, can benefit from implementing future ready technologies and infrastructure that serve the tunnel system throughout its lifetime. This holistic viewpoint is assisted by innovation contracts, engagement with technologists and academia, and early contractor involvement. Long-term understanding of tunnel systems is aided by gathering relevant data over time, such as structural health monitoring systems. This enables a greater understanding of tunnel lifespans and extension of service life, and the move to predictive asset management, supported by smart sensors, IoT systems, and robust data platforms and in-tunnel communication systems. Innovations which enable energy harvesting from the tunnel itself may be possible in certain situations. Initiatives include thermal energy segments, in-tunnel heat harvesting and wind energy generation from tunnel airflows. The UK has successfully demonstrated trials for energy segments in Crossrail and implemented London Underground heat recovery used to power homes in Islington. Scaling these technologies requires a technology maturation process on live projects supported by matching the magnitude and timing of demand with the energy supply and with construction programmes, and risk-sharing contracts which account for potential increased installation times against the wider benefits provided by new innovations.

- **Planning, powers to construct** – Technology can play a key role in more open, understandable and accessible stakeholder engagement. Virtual town hall events, digital visualisations and realisations can aid engagement with communities. Digital optioneering tools can help to convey benefits and risks and can help improve schemes and democratise decision making. Local governments can aid this by setting requirements for technology-driven engagement to facilitate innovation.

- **Repurposing/reusing tunnels** – The desire for preservation of green space at surface and reuse of existing underground space requires innovations in retrofit, monitoring and resilience of asset life. Legislation towards net zero and alignment with UN Sustainable Development Goal (SDG) targets is likely to see further growth in this area. Ensuring the adequacy of tunnel performance as a system it was not originally intended for may require challenge to existing codes and practices. Relaxation of standards to conform to 'no worse than existing' may be required, as well as innovations in ensuring safe and innovative repurposing e.g. Farnworth tunnel widening and track lowering to accommodate network rail electrification upgrades. Looking ahead to the construction of future tunnels, constructing with repurposing in mind could enable more effective and cheaper future retrofit through adapting client requirements to consider future use cases. Greater reuse of plant and TBMs is increasing, and positive accounting for TBM retrieval sequencing and programme allowance.

- **Shared usage** – Tunnels can serve shared usage function. This is increasingly possible with modular element design and construction, and large diameter bores, enabling greater opportunities for space usage. Limited examples exist within the UK outside of the system that a tunnel has been designed for, i.e. power provided to run trains in a rail tunnel. Shared utility ducts and tunnels are becoming increasingly constructed on new developments, and retrofitting utilities to tunnels has been carried out such as the EletroLink power connections between France and the UK installed within the Channel Tunnel. Prime examples from outside the UK region include Kuala Lumpur's shared usage Stormwater Management And Road Tunnel (SMART Tunnel), and the Fehmarnbelt tunnel, which has a modular immersed tube design to accommodate shared usage between road, rail and utilities connection between Germany and Denmark. These initiatives require strategic foresight and policies that enable cross-region cross-sector thinking to that tunnel systems with long-term functions that can be greater than the sum of its parts.

To stimulate and sustain an ecosystem for technology development and adoption, a strong pipeline of tunnelling projects and planned work is key. This provides confidence in the supply chain to find long term efficiencies through innovation, and to grow the skills and expertise to enable this in the long term. Adoption of innovation into live and active tunnel construction or operational projects can be stimulated by lowering the barriers to adoption, through more equitable contracting mechanisms of risk sharing and innovation reward. PPP and PDB contracts have shown benefit in other regions to enablement of innovation and risk sharing risk-reward allocation. Specific government investments to help support R&D grants, innovation competitions, and SME, research body and early contractor involvement continue to be important mechanisms for incubating innovation, however responsive and timely regulation and policy setting is key to ensuring that innovative practice and technology adoption can be safely and effectively implemented.

3.4 Opportunities

Opportunities for emerging technology to impact the future of tunnelling are significant and cover each of the technology taxonomy groupings identified. Appendix A contains a summary of opportunities for each technology application theme and topic. Table 2 captures a number of the key opportunities identified that are relevant to policy makers.

A consistent theme emerged that the most significant opportunities to impact the future of tunnelling lie outside the theme of excavation technology. Incremental innovation in tunnel excavation technology is expected, punctuated by rapid evolution in specific technologies, in the application of emerging technology to improve tunnel excavation rate and cost. However, in the pre-construction and post-construction stages, emerging technology is anticipated to offer significant benefit. Opportunities to cut programme and upfront expenditure in design, assurance, stakeholder engagement and production of documentation to receive powers to construct have been identified.

Overarching themes, essential to the implementation of these opportunities include:

- Policy setting to directly and/or indirectly set out a pipeline of tunnelling projects in the UK, address industry challenges such as data sharing, and encourage the adoption of technology and investment in the tunnelling industry and the construction industry more widely. Including seeking to remove barriers to the adoption of emerging technology;
- Addressing current and future skills shortages in the industry, through home-grown skills development, providing highly visible career paths and attracting global skills, such as building on previous government initiatives[12];
- Public procurement models that advocate sharing risk and collaboration to foster innovation within the UK supply chain, in line with the Transforming Infrastructure Performance Roadmap to 2030 (TIP Roadmap) and the Construction Playbook;
- Delivery models that enable early contractor involvement, such as Project 13;
- Funding guidance and research, including the key aspects are included in Appendix A;
- Promoting and developing better accessible data and models of ground conditions and existing infrastructure;
- Developing and maintaining a pipeline of tunnelling work; and
- Authoring and funding industry guidance, and championing cross innovation forums and funding for key emerging technology.

[12] Example: BIS (2012) Strengthening UK supply chains: public procurement. Tunnelling: a capability analysis.

Table 2 - Opportunities for the application of technology in tunnelling of particular relevance to policy makers

<table>
<tr><th>Opportunity Theme

Technologies
Prefabrication, 3D printing, Materials, Wearables and mobility, VR/AR, Drones, Robotics, AI, BIM & Design, Sensors and IoT, Blockchain, Excavation technology, Digital twins, Investigation and sensing technologies, Energy, Data storage and processing</th><th>Investigation and sensing</th><th>Design</th><th>Construction methodology</th><th>Operation</th><th>Planning, powers to construct</th><th>Repurposing/ reusing of tunnels</th><th>Shared usage</th></tr>
<tr><td rowspan="2">Standardisation of tunnelling components to create a ‘kit of parts’ approach to construction offers significant benefits:
Parametric design automation delivering a tunnelling scheme and associated deliverables as route optimisation is undertaken. Reduced time solving new engineering problems, instead selecting and applying past solutions, accelerated assurance process. Significantly accelerate programme from project inception to commencing construction.
Reducing construction lead-in time by reusing production facilities such as segment fabrication. Reducing risk by repeating construction processes, increase innovation by providing continuity across supply chains.</td><td></td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td><td>■</td></tr>
<tr><td colspan="7">Technologies: Prefabrication, Materials, Robotics, AI, BIM & Design, Excavation technology</td></tr>
<tr><td rowspan="2">Data-driven design and construction planning – improved access to data to inform design, and improved use of AI and BIM, including improved integration between design, construction and operation. Develop and share a national digital twin, including ground conditions data, shallow utilities in NUAR, existing buildings and below ground structures.</td><td>■</td><td>■</td><td>■</td><td></td><td>■</td><td></td><td></td></tr>
<tr><td colspan="7">Technologies: AI, BIM & Design, Digital twin, Investigation and sensing technologies, Data storage and processing</td></tr>
<tr><td rowspan="2">Excavation technology innovation through accelerating the adoption of emerging technologies, particularly robotics, is expected, at a rate governed by external trends and factors. Incremental innovation of existing technology and potential rapid innovation involving robotic excavation methods.</td><td></td><td></td><td>■</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="7">Technologies: Prefabrication, 3D printing, Robotics, AI, Excavation technology</td></tr>
<tr><td rowspan="2">Construction materials – A key focus on sustainability; optimising concrete for tunnelling operations, including secondary cementitious materials and non-ferrous reinforcement materials. Increase the reuse of materials. Develop understanding of service life through investigating, modelling and analysis to extend the service life of tunnel assets. Implement through project requirements.</td><td>■</td><td>■</td><td>■</td><td>■</td><td></td><td>■</td><td>■</td></tr>
<tr><td colspan="7">Technologies: Materials, BIM & Design, Sensors and IoT, Excavation technology, Investigation and sensing technologies</td></tr>
<tr><td rowspan="2">Energy – utilisation of tunnels to harvest geothermal heat from the ground through tunnel energy segments. Harvesting heat generated from tunnel use, such as rail. Sourcing construction plant fuel from renewable sources, such as hydrogen fuel cells and electric plant.</td><td>■</td><td></td><td></td><td>■</td><td>■</td><td>■</td><td></td></tr>
<tr><td colspan="7">Technologies: Sensors and IoT, Digital twins, Investigation and sensing technologies, Energy</td></tr>
<tr><td rowspan="2">Operational requirements – critically reviewing operational requirements provides an opportunity to refine tunnels. For example, replacing human tunnel operation and maintenance with robotic technology could offer a reduction in space proofing and tunnel diameter.</td><td></td><td>■</td><td></td><td>■</td><td></td><td></td><td></td></tr>
<tr><td colspan="7">Technologies: Drones, Robotics, AI, Sensors and IoT</td></tr>
<tr><td>Shared use – shared use of tunnels offers to reduce competition for subsurface space, reduce CAPEX and OPEX</td><td></td><td></td><td></td><td>■</td><td></td><td></td><td>■</td></tr>
</table>

<table>
<tr><th>Opportunity Theme

Technologies
Prefabrication, 3D printing, Materials, Wearables and mobility, VR/AR, Drones, Robotics, AI, BIM & Design, Sensors and IoT, Blockchain, Excavation technology, Digital twins, Investigation and sensing technologies, Energy, Data storage and processing</th><th>Investigation and sensing</th><th>Design</th><th>Construction methodology</th><th>Operation</th><th>Planning, powers to construct</th><th>Repurposing/ reusing of tunnels</th><th>Shared usage</th></tr>
<tr><td>costs. Multi-utility tunnels in new developments and upgrades where possible. Utilisation of transport and energy tunnels for other uses such as utility infrastructure.</td><td colspan="7">Technologies: Digital twins, BIM & Design, Investigation and sensing technologies</td></tr>
<tr><td rowspan="2">Reusing tunnels and tunnelling equipment – Reuse of tunnels, including by extending their service life, and by utilising abandoned tunnels for similar or new uses. Reuse of tunnelling equipment, including TBMs, on projects.</td><td></td><td></td><td>■</td><td></td><td></td><td>■</td><td>■</td></tr>
<tr><td colspan="7">Technologies: Materials, Drones, Robotics, AI, BIM & Design, Sensors and IoT, Digital twins, Investigation and sensing technologies, Data storage and processing</td></tr>
</table>

3.5 Challenges and Risks

A number of key challenges and risks to the adoption of emerging technology that has the potential to impact the future of tunnelling are summarised in Table 3. Challenges and risks were identified through the interview and survey process outlined in Section 2.2. Refer to Appendix A for challenges related to each technology theme and topic identified.

A number of these challenges are being addressed to some degree by ongoing public and private initiatives, such as the National Infrastructure and Construction Pipeline 2023[13] seeking to inform the industry on the pipeline of construction projects in the UK. This table provides a high-level summary of key recurring challenges identified in the study.

Table 3 - Challenges and risks to realising the opportunities

Challenges and Risks	**Investigation and sensing**	**Design**	**Construction methodology**	**Operation**	**Planning, powers to construct**	**Repurposing/ reusing of tunnels**	**Shared usage**	***Technologies*** *Prefabrication, 3D printing, Materials, Wearables and mobility, VR/AR, Drones, Robotics, AI, BIM & Design, Sensors and IoT, Blockchain, Excavation technology, Digital twins, Investigation and sensing technologies, Energy, Data storage and processing*
Contractual arrangements inhibiting innovation Contractual arrangements on public projects can create a risk adverse and adversarial environment that is not conducive to innovation, including lack of incentive to share intellectual property (IP). *Opportunities affected:* ***Standardisation***, ***Excavation technology***, ***Sustainable materials, Energy***	✓	✓	✓	✓				Technologies: all
Pipeline of projects Without a pipeline of tunnelling projects, skilled workforce may leave the UK and skills replenishment is constrained. Lack of political certainty, including late changes in project scope can harm innovation and deter investment from contractors, suppliers and investors. *Opportunities affected:* ***Standardisation***, ***Data driven Design and construction planning, Excavation technology***, ***Sustainable materials, Energy, Reusing tunnels and tunnelling equipment***	✓	✓	✓	✓		✓	✓	Technologies: Prefabrication, 3D printing, Materials, Drones, Robotics, AI, BIM & Design, Sensors and IoT, Excavation technology, Digital twins, Investigation and sensing, Energy, Data storage and processing
Assurance processes Prolonged and complex assurance processes on larger tunnelling projects can constrain the agility of designers, constructors and supply chains to implement emerging technology. *Opportunities affected:* ***Standardisation***, ***Data driven Design and construction planning, Excavation technology***, ***Sustainable materials, Energy, Operational requirements, Reusing tunnels and tunnelling equipment***	✓	✓	✓		✓			Technologies: Prefabrication, 3D printing, Materials, Drones, Robotics, AI, BIM & Design, Sensors and IoT, Excavation technology, Investigation and sensing technologies, Energy,
Data availability Lack of access to and availability of data on existing ground conditions and subsurface assets constrains the adoption of data-driven emerging technology.	✓	✓	✓			✓		Technologies: BIM & Design, Excavation technology, Investigation and sensing technologies, Energy

[13] Accessed 15 April 2024 at https://www.gov.uk/government/publications/national-infrastructure-and-construction-pipeline-2023

Challenges and Risks ***Technologies*** *Prefabrication, 3D printing, Materials, Wearables and mobility, VR/AR, Drones, Robotics, AI, BIM & Design, Sensors and IoT, Blockchain, Excavation technology, Digital twins, Investigation and sensing technologies, Energy, Data storage and processing*	**Investigation and sensing**	**Design**	**Construction methodology**	**Operation**	**Planning, powers to construct**	**Repurposing/ reusing of tunnels**	**Shared usage**	
Opportunities affected: ***Standardisation**, **Data driven Design and construction planning, Excavation technology**, **Energy, Reusing tunnels and tunnelling equipment***								
Misplaced focus Industry or project focus on the wrong technology, leading to loss of confidence and distraction from appropriate technology. *Opportunities affected:* ***All***								Technologies: all
Resistance to change Social factors constraining the adoption of technology. Resistance to a move towards data-driven automation may occur if engineers feel their creative input and desire to solve problems is at risk. Robotic and AI can be perceived to pose a risk to jobs, creating a barrier to adoption. *Opportunities affected:* ***All***								Technologies: all
Design over-optimisation Drivers to optimise designs can lead to unique designs, which inhibit wider benefits of standardisation and lead to increased design and assurance programmes, complexity and risk. *Opportunities affected:* ***Standardisation**, **Data driven Design and construction planning, Excavation technology**, **Reusing tunnels and tunnelling equipment, Shared use***								Technologies: Prefabrication, 3D printing, Materials, AI, BIM & Design, Excavation technology
Barriers to shared tunnel use Shared use and reuse of tunnels is limited by safety concerns, differing standards and requirements imposed by different use cases (e.g. a transport tunnel compared to a power tunnel). *Opportunities affected:* ***Reusing tunnels and tunnelling equipment, Shared use***								Technologies: Materials, BIM & Design, Digital twins,
Supply and demand Matching supply with demand. This challenge applies to shared use of tunnels, circular economy including TBMs and excavated material, geothermal and in-tunnel thermal energy. *Opportunities affected:* ***Standardisation**, **Excavation technology**, **Reusing tunnels and tunnelling equipment, Shared use***								Technologies: Prefabrication, 3D printing, Materials, Drones, Robotics, Excavation technology, Energy, Data storage and processing
Policy Complexity and gaps in policy on the ownership of underground space results in challenges allocating responsibility and permission to interfere with the subsurface. *Opportunities affected:* ***Standardisation, Data driven design and construction planning, Excavation technology, Energy**, **Reusing tunnels and tunnelling equipment, Shared use***								Technologies: BIM & Design, Excavation technology, Digital twins, Investigation and sensing technologies, Energy, Data storage and processing

4. Further work

A number of opportunities have been identified to implement emerging technology in this summary report and in the evidence database in Appendix A. Recommendations identified by the study team for next steps include:

- Develop study to undertake thorough literature review of the technologies identified to develop opportunities and government levers to accelerate appropriate emerging technologies.
- Publish study report to engage with the tunnelling industry.
- Extend external engagement to widen the perspective, through interviews, a survey and a steering group.
- Engage with the industry through roundtables and thought pieces to disseminate findings and acquire feedback from the industry to shape next steps.
- Broaden the study to further explore the future contextual environment for tunnelling in the UK including the impacts of Social, (Technological), Economic, Environmental, and Political (STEEP) trends, that will impact e.g., demand and financing. For example, a recent paper from the Institute and Faculty of Actuaries and Exeter University discusses the risks and disconnect between climate science and economic & financial scenario analysis, which could impact over the lifecycle of future infrastructure projects. The effects of climate change over the lifecycle of tunnelling projects will need to be considered when assessing their long-term resilience and value for money.

Appendix A

Evidence database

Theme	Technology Topic	Primary Technology Taxonomy	Secondary Technology Taxonomy	Other Technology Taxonomy	Trends taxonomy	Introduction	Recent Developments	UK Position	Opportunities	Challenges & Risks	References	Potential for industry change	UK Gov levers[1]	UK Gov potential impact
Construction methodology	Robotic tunnel excavation	Robotics	Excavation technology	AI	Technological	- Deployment of robotic technology to mine tunnels through horizontal directional drilling (HDD) or similar advance drilling tubes have been proposed in the UK market.	- Hypertunnel - private firm developing robotic-based tunnelling technology to construct long tunnels using swarms of robots creating support structure excavating out from initial HDD installed tubes or similar. - Robotic TBM operation and maintenance activities are being undertaken outside of the UK,.	- Hypertunnel - commercial agreement with UK contractor Amco Giffen for enhancements, repair, rehabilitation and monitoring of underground spaces across the UK's railways (October, 2023 newsletter)	- Opportunities to utilise robotic tunnelling methods for localised excavations such as crosspassages, extreme heat, and high pressure tunnel maintenance operations, to reduce human intervention in tunnelling environment. - Robotic exoskeleton to increase labour output and draw in people that without this technology could not perform manual handling tasks.	- Challenging to improve on the programme and reliability of TBMs - Allocation of responsibility or liability in the case of accident or failure. - Lack of skilled labour to take forward robotics in UK market at scale. Skills more transferrable, resulting in greater risk of skills leaving the industry. - Hard ground (rock) conditions could still pose difficulty. - Legal position on AI and robotics led decision making less developed than for human decision making. - Lack of mass market to develop technology from a contractor perspective. Steady pipeline of tunnelling work needed to justify larger investment. - Unions and social impact of AI and robotics replacing jobs. Needs to be understood and resolved. - IP, e.g. SBE/SBR/VSM innovations specific to a single supplier		High	- Contractual arrangement to share risk and foster innovation. - Funding for research and innovation in robotics. - Lower barriers for entry for SMEs. - Encourage legal industry to cater for change to data driven decision making using AI.	Medium
Construction methodology	Robotic tunnel processes other than excavation	Robotics	AI		Technological	Use of robotics to perform non-excavation related construction operations, such as segment handling, operation and maintenance.	- Growing trials and deployment of robotics to handle segments in TBM tunnelling - AEC (2023) lists construction typologies as offsite production robots, on-site robots, demolition robots, 3D printing robots, data collectors, autonomous vehicles, robotic assistants. 35 construction robotics firms are listed.	- UK mining project utilised robotic cage welding and segment production on second line - Robotic segment handling on HS2 tunnelling operation - Robotic drilling and fixing operations behind TBM -Use micro robots for embedded operations and maintenance data capturing	- Exoskeleton to improve manual handling. Robotic processes within TBM following segment erection, such as drilling and fixing, installation of tunnel equipment. - Construction plant operation, following mining industry remote vehicles. - Segment production. - Seek opportunities for trial deployment off critical path, e.g. second production line. - Contractual arrangement to share risk and foster innovation.	- Allocation of responsibility or liability in the case of accident or failure. - Lack of skilled labour to take forward robotics in UK market at scale. - Challenging to improve on the programme and reliability of TBMs - Allocation of responsibility or liability in the case of accident or failure. - Skills more transferrable, resulting in greater risk of skills leaving the industry. - Lack of mass market to develop technology from a contractor perspective. Steady pipeline of tunnelling work needed to justify larger investment. - Unions and social impact of AI and robotics replacing jobs. Needs to be understood and resolved. -Tech needs to become cheaper	AEC Business (2023) Construction Robots 2023. https://aec-business.com/construction-robots-2023/ Accessed 12/10/23.	High	- Investment in research. - Pipeline of work and standardisation to increase innovation. - O&M for public projects embrace robotics. - Requirements for tunnelling to encourage innovation in risk sharing environment. - Social impacts of reduced reliance on human intervention needs to be understood and resolved, such as unions preventing job loss, re-training.	High
Construction methodology	Ground conditions - construction verification	Investigation and sensing technologies	Excavation technology	AI	Technological	Sensing technology to better understand ground conditions during tunnelling, reducing programme and risk.	- LiDAR and photogrammetry for quick and accurate mapping and capture of tunnel face conditions. - LiDAR for convergence detection and measurement of ground support effectiveness e.g. assessment of shotcrete thickness compliance and control	Global leader in sensing technology. Behind other geographies implementing in tunnelling environment due to increased risk adverse environment.	- Trial and deploy sensing technology to improve understanding of ground conditions during tunnelling and reduce risk. - Robotic and AI-driven face mapping, allowing reduced risk in microtunnelling	- Technology adoption barriers.	Tani et al., (2023) Development of projection mapping technique for the tunnel face, Report of Taisei Technology Centre, 52(54): 1–6.	High		Low
Construction methodology	Tunnelling rate	Excavation technology				Technologies to enable improved tunnelling productivity rate through automation of mechanized tunnelling activities.	- The Boring Company - competition launched to reduce programme. Limited savings, through reducing TBM size and reducing performance. - Incremental increases in tunnel excavation rate. - Trenchless tunnelling for utilities to accelerate excavation. - Extended to in-tube tunnelling to create larger diameter tunnels for transport systems, to avoid enlargement of tunnels such as at platforms. - Continuous tunnelling technology avoids the need to stop to enable lining segment installation in soft ground - Herrenknecht innovation reported to be 1.6 x faster. - Plasma micro TBM for energy and utilities that accelerate tunnelling in hard rock using plasma torches, such as Earthgrid and Petra.	- Trenchless excavation growing in use, though constrained by the presence of poorly mapped buried services. - Incremental innovation in tunnelling resulting in gradual acceleration of tunnelling. However, key constraints for larger tunnels relates to muck away and site logistics. - Considerable scatter in excavation rates based on project specific and ground conditions - Limited trial use of plasma excavation technology	- Robotic technology to accelerate TBM operations and SCL operations - In-tube tunnelling to omit enlargement, often with SCL, for stations, cross overs etc. - Reduction in cost from reduction in time would lead to increase in demand of tunnels - Alliance model:Encourage collaboration between suppliers, contractors, consultants and client. - Plasma excavation tunnelling technology for small diameter tunnels in hard rock - Re-consider acceptable volume loss criteria for non-sensitive areas to allow faster tunnelling and higher volume loss where acceptable.	- Accelerated tunnel project permission and approval could save more money than faster tunnel excavation - Procurement method selected by contractor affects innovation - Availability of skills to implement innovation	- Jon Wakeling (2023) pers comms. - IPA (2016) Case Study: Benchmarking tunnelling costs and production rates in the UK. Assessed 21/10/23, https://assets.publishing.service.gov.uk/media/5c07dc95ed915d7475317c9b/CCS207_CCS1118018748-001_Benchmarking_tunnelling_costs_and_production_rates_in_the_UK_Web_Accessible.pdf - Herrenknecht (2022) Trade Fair start made to measure: Herrenknecht AG wins Bauma innovation award 2022. Website accessed 23/11/23: https://www.herrenknecht.com/en/newsroom/pressreleasedetail/trade-fair-start-made-to-measure-herrenknecht-ag-wins-bauma-innovation-award-2022/. - New Atlas (2022) Earthgrid aims to re-wire the USA using super-cheap tunnel tech, accessed 12/10/23: https://newatlas.com/energy/eart	Low	- Stable pipeline of projects to foster innovation - Standardisation as an enabler to innovation - Benchmark against international best practice stimulate supply chain, as outlined in the Transforming Infrastructure Performance (TIP) publication.	Medium
Construction methodology	Pre-fabrication	Prefabrication	Excavation technology	BIM & Design		Offsite construction is routinely adopted, particularly for tunnel linings and cut and cover tunnels. Prefabrication offers an opportunity for improved quality and materials innovation in a controlled environment.	Prefabrication in the context of a kit-of-parts standardisation of tunnel construction is an emerging theme, which advantages related to efficiency in repeated fabrication, reduced production lead in time, and design automation. - Standardisation of prefabricated structural elements is routine in other geographies such as Singapore and China, with offering significant benefits to innovation, quality and programme in the design and construction stages.	- Prefabrication of tunnel segments, cut and cover tunnel walls and slabs, and other structural and MEP components are routinely adopted. - Standardisation of prefabricated tunnelling components is not typically adopted. - Standardisation and offsite construction prioritised in healthcare, education, justice and defence public departments (see TIP 2030 roadmap)	- Aids in minimising health and safety risk by reducing site process - Improved quality control - Increase standardisation of prefabricated elements, adopt a 'factory thinking' approach to design where designs select from a catalogue of structural elements	- Uptake of a standardised suite of structural elements risks isolating parts of the supply chain - Reduced flexibility to respond to changes post fabrication -UK govt can aid in transport planning and logistics	- Chen et al., (2023) Survey on the application of prefabrication structure in underground engineering. IOP Conf. Series: Materials Science and Engineering 741 - Yang & Lin (2023) Research and application of prefabrication and assembly construction technology for metro station structures. Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World – Anagnostou, Benardos & Marinos (Eds). - Government (2021) Policy paper: Transforming Infrastructure Performance:	Low	- Pipeline of work and standardisation to increase innovation	Medium

Theme	Technology Topic	Primary Technology Taxonomy	Secondary Technology Taxonomy	Other Technology Taxonomy	Trends taxonomy	Introduction	Recent Developments	UK Position	Opportunities	Challenges & Risks	References	Potential for industry change	UK Gov levers[1]	UK Gov potential impact
Construction methodology	Reducing impacts on 3rd parties	Excavation technology	Materials		Social	Excavation methods that reduce ground movements and therefore impacts on 3rd parties will reduce project cost and programme. Conversely, 3rd party assets with increased flexibility to accommodate ground movements.	- Tunnelling from ground level adopted in other geographies, where impacts on 3rd parties is less critical and therefore does not constrain this technology in the same way. - Placing utilities in service corridors below pavements may help to protect utilities from tunnel induced impacts. - Advancing technology can provide support to the ground more quickly, reducing tunnel volume loss and associated impact on third parties. - Research into improved means of predicting and assessing tunnel excavation inducted damage on buildings ongoing, seeking to reduce conservatism - Employing twin tunnel TBMs has been used in Japan to provide the required sewer cross sectional area whilst avoiding a wider tunnel to navigate around 3rd party	- Utilities and services moving to polyethylene from cast iron/concrete results in more flexible assets, reducing the cost and carbon required to mitigate impacts or strengthen/direct utilities. - Advancing technology can provide support to the ground more quickly, reducing tunnel volume loss and associated impact on third parties.	-Permit greater level of ground movement, reducing the onerous requirements on tunnelling based on volume lost, where appropriate. This can accelerate programme and reduce cost. - Design more resilient assets (utilities and buildings) able to withstand a greater level of ground movement, reducing the constraint on tunnelling related to limiting ground movements - Invest in technology to	- Allowing more ground movement to occur may increase the maintenance burden on 3rd party asset owners.	- HS2 (2017) High Speed Two Phase One Information Paper C3: Ground Settlement, Version 1.5. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/672194/C3_-_Ground_Settlement__v1.pdf - Shmz (2020) H&V Shield Method, World's First Spiral Excavation Using Double Shield at Underground Tunnel, URL: https://www.shimz.co.jp/en/topics/civil/item01/	Medium	- Influence and challenge 3rd party asset owner acceptance criteria	Low
Construction methodology	3D printing to form the tunnel lining behind while drilling	3D printing	Excavation technology		Technological	3D printing the tunnel lining behind as tunnel excavates and progresses	- Trials using 3D printed tunnelling linings are ongoing, e.g. Swissloop Tunnelling -Herrenknecht developed "Direct pipe" that pushes microtunneling machine forward together with the pipeline behind - Hypertunnel propose a 3D printed tunnel lining using robots positioned in the ground using horizontal directional drilling - Spiral tunnel lining being developed in research environment.	- Limited application in the UK tunneling industry. Trials ongoing.	- Opportunities to accelerate construction as it removes pre-fabricated units to be brought in. -The 3D printing concept is designed to overcome the challenges around logistics when it comes to transporting precast concrete linings onto the site and through the tunnel to the heading as it progresses. The design also allows the tunnel to bore continuously without pausing to allow lining segment installation to be undertake - Opportunities in smaller diameter tunnelling and potentially large diameter tunnelling to reduce programme constraint related to segment logistics. Segment logistics can be a critical path activity, moreso than tunnel excavation rate.	- Lengthly owners and review levels. Pyramid structure of reviewers level -Technology challenges including the ability to jack the TBM forward from the lining before strength is gained.	- NCE (2021) 3D printed tunnel lining concept wins Elon Musk tunnel innovation award. Website article: https://www.newcivilengineer.com/latest/3d-printed-tunnel-lining-concept-wins-elon-musk-tunnel-innovation-award-14-09-2021/ accessed 12 October 2023. - Phillips & Delport (2023) 3D printing of tunnels. Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World. Taylor Francis.	Medium	- Stable pipeline of projects to foster innovation - Standardisation as an enabler to innovation	Low
Construction methodology	Robotic fabrication	Excavation technology	Robotics		Technological	Robotic fabrication, including tunnel segment production.	- Robotics used in production factories globally, such as Singapore. - Learning from other industries such as manufacturing industry.	- Examples in UK where robotics used to clean formwork. - Limited examples of robotic fabrication of tunnelling components. HS2 contractors are using robotics to automate segment production tasks	- Improved quality and health and safety - Accelerate production process	- Unique segment fabrication on UK projects restricts robotic fabrication - Risk to production line, risk environment leads to robotics taken offline in UK	HS2 (2023) Production of HS2 tunnel segments begins at new STRABAG facility in Hartlepool. Media Centre report, accessed 29/11/23: https://mediacentre.hs2.org.uk/news/production-of-hs2-tunnel-segments-begins-at-new-strabag-facility-in-hartlepool	Medium	- Investment in research - Pipeline of work and standardisation to increase innovation - Requirements for tunnelling to encourage innovation in risk sharing environment	Medium
Construction methodology	Tunnel (including TBM) monitoring technology	Excavation technology	Investigation and sensing technologies	Digital Twin	Technological	Sensors increasing tunnelling efficiency, facilitating driverless tunnelling (see separate topic) and predictive maintenance of cutter heads.	- Combining TBM sensors, forward geophysical probing, TBM drive parameters for real-time ground prediction. - Interpretation of ground data based on tunnel sensing to verify ground model. - Face mapping digital records to identify changes from expected ground model. - Application of digital twin framework to tunnel during construction.	- Tunnel sensing and monitoring cutting edge - Cambridge Centre for Smart Infrastructure is a leading organisation developing and promoting monitoring technology	- Use of Machine Learning to predict ground type and behaviour based upon multi-sensor data. - Reducing delays due to unplanned maintenance by better prediction of tunnel wear. - Increase scope for data collection using Internet of Things (IoT) approach to collect data from new locations and increased frequency	Low maturity level of ML models for accurate ground prediction.	- Ayawah, P. E., Sebbeh-Newton, S., Azure, J. W., Kaba, A. G., Anani, A., Bansah, S., & Zabidi, H. (2022). A review and case study of Artificial intelligence and Machine learning methods used for ground condition prediction ahead of tunnel boring Machines. Tunnelling and Underground Space Technology, 125, 104497. - Latif, Sharafat, Seo (2023) Digital Twin-Driven Framework for TBM Performance Prediction, Visualization, and Monitoring through Machine Learning. Application of Geographic Information System and Building Information Modelling: Volume II	Medium		Low
Construction methodology	Tenchless drilling: Horizontal directional drilling (HDD), pipe jacking	Excavation technology			Technological	Trenchless drilling is increasing in popularity due to benefits over open excavations.	- Micro tunneling not only for utilities but also to supply micro tunnel infrastructure for mega underground/tunnel infrastructure - Use techniques used for micro tunneling for larger tunnels e.g. Slurry TBMs		- Use of innovative polymer or grout to drill shallower - Electrical powered drilling - Opportunity for digitised constraint tool - Use of micro tunnelling as demo tests for bigger TBMs	- Risk of data storage loss -access to database of underground - Limited to number of demo tests before approving technologies - How to test technology without taking unacceptable level of risk		Medium	- Coordinate mapping buried utilities to enable HDD for new utilities	Medium
Construction methodology	Driverless TBMs using AI	Excavation technology	AI		Technological	AI assisted TBMs using data collected to inform decisions. Use of real-time data in construction, such as monitoring data, face mapping, sensing information, tunnel excavation parameters.	- Driverless TBMs making adjustments based on monitoring data - Examples in Malaysia (MRT) and Japan, Singapore. Required sharing of risk with supplier, contractor and client. Increased productivity resulting from AI assisted TBM steering.	- AI used to plot data and inform human interventions. Not trialled AI driven TBM.	- Increase reliance on data driven decision making, such as face pressure adjustments, based on automated review of sensor data. - Assisting human decision making in the short-term. - Advantages in maintenance of TBMs such as cutter head replacement using robotics. This avoids the need for human intervention in dangerous environments infront of the TBM and can reduce the size of intervention equipment, reducing the size of the tunnel diameter in some cases.	- Fragmentation of the industry and lack of collaboration - Allocation of responsibility or liability in the case of accident or failure -Impacts on workforce -Conflict in allocation of cost of innovation	- NCE (2020) Tunnelling | Malaysia's self driving TBMs. Accessed 28/9/23: https://www.newcivilengineer.com/innovative-thinking/tunnelling-malaysias-self-driving-tbms-18-02-2020/ - Colorado School of Mines (2023) Comparison of tunnelling speed between human and AI, accessed 12/10/23: https://underground.mines.edu/7m-darpa-contract-3/	Medium	- Shared risk approaches to encourage market adoption - Pipeline of work and standardisation to increase innovation	Medium
Construction methodology	Decarbonisation of construction activities	Excavation technology	Energy	-	Environmental	Adoption of decarbonisation technologies and strategies to reduce the carbon footprint of tunnel construction.	- Hydrogen market growing, powering construction sites - Electric powered construction plant	- Hydrogen in construction being trialled on major projects including HS2 - SSE and Siemens are partnering to covert 100MW of onshore wind energy into green hydrogen - UK Hydrogen Strategy (2021) sets out UK approach	- Deliver on UK Hydrogen Strategy, to run construction plant	- Almost no low carbon production of hydrogen in the UK as at 2021, meeting demand a potential challenge	UK Hydrogen Strategy (2021)	Medium	- Refer to UK Hydrogen Strategy - Industry guidance and implement project requirements to encourage adoption of low carbon construction technology	Medium

Theme	Technology Topic	Primary Technology Taxonomy	Secondary Technology Taxonomy	Other Technology Taxonomy	Trends taxonomy	Introduction	Recent Developments	UK Position	Opportunities	Challenges & Risks	References	Potential for industry change	UK Gov levers[1]	UK Gov potential impact
Construction methodology	Non-circular tunnels	Excavation technology			Technological	Non-circular tunnels with more diverse geometries, including non-circular TBMs, mined methods and immersed tube with greater flexibility for varied geometry. This optimises excavation volume and enhances efficiency in space utilisation, i.e. square/rectangular/binocular TBMs. This has sustainability benefits as well as operational advantages.	A growing trend in non-circular TBMs is visible primarily outside of the UK. Examples include: - Singapore pedestrian underpasses with a Rectangular Tunnel Boring Machine (RTBM) at two sites at Havelock and Stevens stations (land Transport Authority, 2017)	- Limited occurrences in the UK	- Early stage tunnel design may preclude non-typical TBM geometry without intervention. Opportunity to incentivise deviating from a standard approach.	- Contractual and commercial challenges due to deviation from current market. - Requires increased knowledge transfer and demonstrator projects of technology to UK from other markets and regions.	- Land Transport Authority (2017) Factsheet: Rectangular tunnel boring machine (RTBM), accessed 27/11/23: https://www.lta.gov.sg/content/ltagov/en/newsroom/2017/11/2/factsheet-rectangular-tunnel-boring-machine-rtbm.html)' - Li.J. (2017) Key Technologies and Applications of the Design and Manufacturing of Non-Circular TBMs. Engineering 3 pp905-914	Medium	Early contractor involvement. Contractual setting conducive to sharing risk, and select supply chain (including designers) capable of delivering this emerging technology.	Medium
Construction methodology	Ground treatment technologies	Excavation technology			Technological	Advances in ground treatment technology are enabling deeper and more complex tunnelling in challenging ground conditions.	Examples include ground freezing, compressed air technology, grouting higher strength polymers. Improvements in HDD enabling ground treatment advancements.	UK is innovating and deploying ground treatment on tunnelling projects, and is connected into the global ground treatment technology development market.	- Ongoing incremental emergence of ground treatment technologies is resulting in pushing the boundaries of feasible tunnel construction.			Medium		Low
Construction methodology	Wearable and mobility	Wearables and mobility			Technological	Wearable technology provides data and communication between construction operatives, with the potential to improve safety and production. Examples include smart watches, geolocated visitor cards and sensors on helmets.	- Wearable technology is emerging in the context of improved health and safety and productivity in the construction industry. For example, wearable carbon monoxide sensors and geospatial technology that tracks the location of workers to aid fire evacuation.	Various R&D projects and site trials have been undertaken in the UK market.	- A future beyond wearables where there is exoskeleton supported technology and robot-human assisted technology	- Health and Safety challenges in ensuring wearables do not detract from workers attention and dexterity on site. Safety case to be fully proven.	Chen et al., (2023) The Impact of Wearable Devices on the Construction Safety of Building Workers: A Systematic Review. Sustainability 2023, 15, 11165.	Low	- Influencing contractors and supply chain to demonstrate H&S improvements	Low
Construction methodology	Tunnelling from ground surface	Excavation technology			Technological	Tunnelling from ground surface has the potential to improve programme by reducing enabling works such as portal construction.	Recent projects have employed TBM tunnelling from ground surface, such as URUP method in Japan (Obayashi, 2023) and Bouygues constructed part of a major road project in France with an exposed TBM. Trials ongoing by Boring Company deploying TBMs from a truck.	Limited to no experience in UK.	- Proven in other regions to offer potential reduction in site enabling prior to tunnelling.	- Risk that programme impact due to remediating ground disturbed/collapsed above shallow tunnelling outweighs early programme benefits. - Lack of space for surface launch in urban areas, which is where tunnels are often required. Impact on land take that is often set early in projects before contractor involvement.	The Boring Company (2023) Website accessed 12 October 2023. Obayashi (2023) URUP TBM launching and receiving at ground level. Website report. Accessed 9 October 2023.	Medium	Opportunities to adopt technology need early contractor involvement and early land take decisions. Early contractor involvement.	Medium
Design	Route optimisation	BIM & Design	Data storage and processing	AI	Technological	Improved access to and use of data and design tools has the potential to continually improve route optimisation and alignment studies.	- Automation of alignments have been developed with increasing sophistication and automation. E.g. at CERN optimising the tunnel alignment and shaft locations	- Start ups offering route optimisation technology - Geospatial tools enabling route optimisation studies based on multi-criteria analysis, without parametric design and wider system impact analysis.	- Develop contextual data to inform analysis. - Parametric design and generative design opportunities which integrate decision informing metrics and impact assessments.	- Lack of data to enable accurate early stage studies - Change in spend profile required to enable up front design effort to set up automation and data-driven parametric approaches.		High	Improved data to inform analysis Promote SMEs and emerging tech firms developing capability in this field.	Medium
Design	Digital twins and representations of existing subsurface to inform design	Digital twins	Sensors and IoT		Technological	Digital models, shadows and twins of the existing surface and subsurface to inform design and construction.	- Digital representations of the subsurface developed in Netherlands, Singapore, Hong Kong. - Excavation and monitoring technology enabling construction of tunnels very close to existing assets, e.g. pile foundations (Bank Station upgrade) and tunnels (Elizabeth Line).	- Dig to share imitative, limited but growing proportion of ground investigation accessible from BGS data stores. - National Underground Asset Register (NUAR) in released in 2023 covering shallow utilities in the UK. Vault providing functionality in Scotland.	- Develop components of a national digital representation, e.g. a digital twin, building on NUAR, Vault and BGS repositories. Harvest existing and future public project data to build up - VR walk throughs - Use of data, map utilities and update GIS - Increase collaboration and efficiency	- Refer to NUAR challenges. - Data ownership, security, trust, intellectual property - Digital technology to host and serve data, time and storage costs. - Extensive hype and offerings in this technology market, leading to distraction and potential loss of confidence.	Government Office for Science, Innovation and Technology and Geospatial Commission (2023) Guidance: National Underground Asset Register (NUAR), https://www.gov.uk/guidance/national-underground-asset-register-nuar, accessed 10/10/23. Centre for Digital Built Britain (2022) National Digital Twin Programme Website, https://www.cdbb.cam.ac.uk/what-we-did/national-digital-twin-programme, accessed 8/10/23.	High	- Deliver key recommendations of the National Infrastructure Commission's 2017 'Data for the Public Good Report'. - Capture, store systematically and provide access to public project data.	High
Design	Generative AI applied to design	AI	Data storage and processing		Technological	Self-generative AI to design tunnels, structural and geotechnical solutions.	Generative AI is increasingly used in design processes, from writing code to researching and writing documents. End to end design is already implemented in digital product design and the breadth of coverage of AI in construction is increasing.		- Generative AI could be used to understand requirements, analyse and design options that meet those requirements, and report on them internally and externally to a project team. - Automation and integration with standardisation could lead to very significant reductions in programme throughout pre-construction stages - Early contractor engagement in design	- Uncertainty and liability can restrict confidence and adoption. - Data needed to follow data-driven design. - Need robust processes to give confidence to user		High	Improved data to inform analysis Promote SMEs and emerging tech firms developing capability in this field.	Medium
Design	Standardisation, e.g. kit-of-parts	BIM & Design	Data storage and processing		Economic	Standardisation of designs to optimise materials usage and design and construction processes, leading to improved cost and programme efficiencies.	- Factory thinking and kit-of-parts adopted in other industries such as data centres. - Standardised tunnel diameter, openings, connections, lining types. - Singapore seeking to construct larger tunnels that encompass station platforms, in order to reduce bespoke elements. Opportunity also to share use.	Behind other geographies who are implementing standardisation within tunnelling, e.g. Singapore.	- potential for significant reduction in design time - potential for significant innovation within a standardised framework, competition increased - increase competitiveness in market for optimisation to obtain those standardisation	- Long term infrastructure planning is lacking and political decisions happen late on in projects , e.g. HS2. Prevents stable market for innovation with payback period beyond a single project - Social impact - designers like to own design rather than choose parts from catalogue - Embodied carbon design refinement can lead to unique solutions, reducing scope for standardisation. Acceptance of reduced optimisation required to implement standardisation		High	- set requirements for standardised tunnels -Make Design requirements not too constrained for designers	High

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Design	Sustainable materials	Materials			Technological	Materials have the potential to reduce carbon, enable new construction approaches, increase asset life through durability and reduce maintenance. Particular focus has been placed on tunnel lining materials, such as cement replacement in concrete. Collaboration between different parties to replace traditional materials with sustainable (including durability) materials.	Low carbon concrete is emerging in effectiveness, a key focus being on supplementary cementitious material - Calcined clay is emerging as a supplementary cementitious material - Accelerated age testing to understand and model durability - Steel fibres concrete - Bio (grown) cement replacements, such as Biomason.	- Growing adoption and trials of emerging materials technology. - Low carbon geopolymer concrete used in London Power Tunnel 2 tunnel lining, using GGBS and geopolymer to replace cement (The Engineer, 2022) delivered as a Project 13 enterprise collaboration - UK seen as a global leader in this field. - Embodied carbon classification scheme for concrete published 2022 to enable benchmarking (Arup & Innovate UK, 2022)	- Key focus is on optimising concrete for tunnelling operations, including segmental linings and SCL. More efficient concrete mixes in pre-cast segment factories. - Standardisation to accelerate uptake of new technology - Extract cement from destructured concrete, such as temporary works concrete. This is an emerging area of research - Technologies using captured carbon and use similar properties to Portland cement - Design for longer life of project to reduce maintenance - Stimulate industry for large scale production that would aid in reducing cost - Reuse of materials, circular economy - Increased durability of waterproofing elements, leading to longer service life and reduced maintenance - Critically assess requirements, such as reduce concrete strength class. - Invest in bio-solutions for cement replacement, including in research and testing, and facilitating the adoption of this	- Lack of confidence for newer tech - Siloed approach between project teams - Concrete becoming more expensive in future - Without clear and achievable targets opportunities are missed. - scalability and durability - Scarcity of resources in future, e.g. GGBS depletion and other cement replacement - Doubts over cement replacement materials over 120years. Accelerated aging technologies for portland cement testing – risk they are not directly applicable to novel technologies - Infrastructure owner not accepting risk of new technology - Increased air time for non-suitable technologies. Resulting in distraction and loss of confidence in similar technology	- Arup & Innovate UK (2022) Embodied Carbon Classification Scheme for Concrete - Biomason (2023) Revolutionizing cement with biotechnology. Accessed 27/11/23: https://biomason.com/. - Project 13 (2023) Website: https://www.project13.info/about-project13/, accessed 10/10/23.	High	- Setting ambitious targets for embodied carbon - Provide research funds - Support and lead avoidance of propagation of non-suitable technology - Govt need to accept as well that it will be more expensive to move away from concrete -incentivise market and not only projects - Funding guidance to lead change such as low carbon concrete classification -Seek international collaboration to harvest ideas. - Collate and curate data on material durability	High
Design	Digital design and assessment - automation and parametric design	BIM & Design	AI		Technological	Design as part of optimisation, cutting programme. Key benefit relates to reducing pre-construction programme and cost, and carbon saving.	- Growing use of automation in design, including data processing, design analysis. Including visualisation platforms and tools. - Incrementally improving analysis technology such as new numerical modelling methods (technology and domain e.g. material point method analysis), edge computing, cloud technology. - Startups offering route optimisation and parametric design tools - parametric automation applied to specific workflows within design packages, and to non-tunnelling assets e.g. road gantry design	- UK global leader in automation in design and visualisation - Constrained by lack of contextual data available to feed into design (e.g. ground conditions) and lack of standardisation as an enabler	- Step change in pre-construction programme, optimisation of alignment early on integrating stakeholder engagement, constraints, ground conditions - increased use of BIM to optimise and automate design process - Improve access to contextual data to inform design - Increase standardisation of design, kit of parts approach to enable automation - Probabilistic design basis, considering uncertainty, enabling more refined designs compared to traditional deterministic analysis.	- Lack of data to inform design - Social impact of reduced 'engineering' reducing appetite of industry to employ this approach - Deliverables required to change to integrate automation, such as new Digital Environment Impact Assessment approach on A417 - Need robust designs for smooth assurance process. - Probabilistic design constrained by application of deterministic design codes.		High	- Project requirements change to facilitate automation , e.g. digital EIA - Collect, store, curate and provide structured data as project requirements and background data - Pipeline of tunnelling projects and project certainty to provide business case for investment in standardisation across design and construction, and automation - Champion and specify standards for data models to standardise data - Champion innovation in design codes and assurance processes, such as use of probabilistic design methods	Medium
Design	Digital technology to harvest existing project information and contextual data.	Data storage and processing	BIM & Design	AI	Technological	Acquiring and incorporating contextual data has been highlighted as a key enabler to improved early decision making.	- Generative AI using Large Language Models (LLM) is being increasingly used to access structured data. - AI assisted OCR to turn archive records into structured data increasingly available. Engineering consultancies are developing in-house (Atkins, Arup etc) and industry offerings (e.g. civils.ai) - Geospatial commission championing utilities data model Open Geospatial Consortium (OGC) MUDDI through National Underground Asset Register (NUAR)	UK position similar to global offering based on limited research. For example, UK based Generative AI consultancy being introduced to HK authorities for borehole archive digitisation.	- Leverage technology by increasing access to digital skills within industry - Seek to serve data (contextual and project requirements) as structured data rather than pdfs to reduce costs - public project data strategy to collate and provide data	- Social concern related to replacement of roles with AI - Repository for data (other than BGS) not available	OGC (2019) Model for Underground Data Definition and Integration (MUDDI) Engineering Report, OGC 17-090r1	Medium	- Project requirements processes utilising structured data - Collate wider scope of project data and contextual data to inform future projects, such as ground models, asset databases - Champion industry data models	Medium
Design	BIM implementation	BIM & Design	Data storage and processing		Technological	BIM technology is well advanced, however, there is a reasonable consensus that BIM is not delivering the full potential benefit	- Increased migration to cloud based technology reduces reliance on users being able to operate desktop tools - Cloud based technology also enables integration with tools and systems on site and globally	The UK is considered to be a global leader in BIM. However, the NBS 2020 National BIM survey shows that uptake is at 62% on public projects at 77% on private projects. Low cost/benefit ratio (BCR) inferred for major UK infrastructure projects in some cases	- Increase the adoption of BIM on public construction projects, client leading implementation. - Utilise BIM throughout project lifecycle, currently different BIM technologies adopted at different stages creates process - Take forward BIM into operation stage, such as digital twins	- Risk of creating more process, increasing costs - Risk that software dependence increases by software giants, reducing future reuse of data in later stages of the project -Codes and compliance concerns	NBS (2020) Summary of findings from the tenth annual BIM survey. Thenbs.com.	Medium	- Refer to UK BIM Framework, including ISO 19650 Guidance	Medium
Design	Nano materials	Materials			Technological	Nano materials have the potential to improve durability and reduce carbon.	Graphene and carbon nanotubes being used in concrete to a greater extent resulting in improvements in mechanical and durability properties and reductions in embodied carbon.			Few examples and potential scaling issues		Medium		Medium
Operation	Energy harvesting: thermal, geothermal	Energy			Political	Tunnels and their enabling structures have the potential to harvest geothermal energy. Success depends on matching supply with demand. Several tunnel uses offer the potential to harvest excess energy, such as rail.	- The Vienna LT22 testing plant was the first geothermally activated sprayed concrete lining tunnel in Austria. '- Katzenberg high-speed rail tunnel in Germany and the Jenbach twin track high-speed rail tunnel in Austria incorporated a 54 m long demonstration section with thermally activated segmental tunnel lining - 11No. thermal tunnel projects in Europe and Asia are summarised by Arup (2022) in South Korea, China, Germany, Austria, Italy, Poland and England. Of which 5 No. achieved thermal activated linings, in Germany, Austria and Italy.	- Attempts to deploy geothermal tunnel energy segments (TES) for the Elizabeth Line (Crossrail) were explored but not installed (Nicholson et al., 2014) - Heat generated by London underground tunnels are being used to power homes and public buildings in Islington, stated as a world first in 2021 RIBA J, 2021)	- Thermal lining, benefit to ground source heat, as proven in Crossrail feasibility studies (Nicholson et al., 2014). - Harvesting heat generated in rail tunnels, such as London Underground (Lagoerio, 2019).	- Matching supply with demand is critical to success. - Risk of delay to tunnel boring programme, which is typically critical path.	"Nicholson et al., (2014) The design of thermal tunnel energy segments for Crossrail. Crossrail Learning Legacy. Arup (2022) Geothermal use of tunnels. Ref ARUP_202204_CER, web address: https://indico.cern.ch/event/1173667/attachments/2465651/4228155/Task%201-%20Thermal%20tunnel%20report_Issue_20220518.pdf. - RIBA J (2021) Bunhill 2 recycles energy in a lacy pink coat, website: https://www.ribaj.com/buildings/macewen-award-2021-shortlist-bunhill-2-energy-centre-city-road-islington-london-cullinan-studio, accessed 5 October 2023. - Lagoeiro et al (2019) Heat from underground energy London (Heat FUEL). The 25th IIR International Congress of Refrigeration, August 24-30, Montréal, Québec, Canada."	High	- Seek to match supply with demand in advance of projects. Broker collaboration across public and private sector. - Incorporate energy harvesting into project requirements. - Study potential supply from public infrastructure and engage private sector. - Use public projects as trial cases to demonstrate technology. Project requirements to include energy harvesting.	High

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Investigation and sensing	Buried obstructions and utilities	Data storage and processing			Technological	Actively managed databases of current and historic records for the mapping of buried obstructions and utilities. This will aid risk management of underground space throughout the asset lifecyle and impact assessment.	- BT trenchless drilling technique constrained by not knowing where utilities are for fibre duct laying - Utility mapping technology improving, whereas previously mapping was considered to be reasonable on plan with low vertical accuracy.	- National Underground Asset Register (NUAR) launching in 2023 mapping shallow buried utilities in England, Wales, N. Ireland. - Vault used in Scotland to map buried utilities - Recent developments using multi-sensing and AI to improve the accuracy of remote mapping of shallow utilities	- improved mapping of as-built utility locations has the potential to facilitate a greater extent of trenchless drilling for utilities - Improved remote sensing mapping technology.	- Conflicts in ownership of underground space		High	NUAR in progress. Integrate feedback loop to provide as-built data. Extend mapping to capture buildings data.	High
Investigation and sensing	Ground conditions - Remote sensing GI techniques including geophysical investigation	Investigation and sensing technologies			Technological	Remote sensing is used to survey below ground using geophysical methods. New remote sensing ground investigation technology will continue to enhance our understanding of subsurface and improve early project decision making based on better understanding of ground conditions.	- Airbourne geophysical surveying coupled with AI assisted ground modelling (e.g. Emerald Geomodelling) - Passive seismic remote sensing (e.g. Sisprobe) - Muon tomography to detect below ground structures (Thompson et al., 2020)	- Muon tomography used to detect Network Rail tunnels - Airborne geophysics used on infrastructure projects e.g. Nuclear Power stations	Innovation ongoing with supply chain, who are working with infrastructure owners and promotors such as Network Rail.	- Ground truthing required for remote sensing, risk of high uncertainty without adequate calibration - Continuous updates to ground models supplied by remote sensing suppliers when new GI data is available. Challenging when supplier uses proprietary analysis such as ML to interpret ground conditions	- Thompson et al., (2020) Technical paper: Railway tunnel imaging with muon tomography Ground Engineering Technical Paper, 8 January 2020. - CIRIA (2002) Geophysics in engineering investigations C562, Westminster, London.	Medium	- Influence Public projects to be a testbed for new sensing technology.	Low
Investigation and sensing	Ground conditions - GI data sharing	Data storage and processing			Political	Better information at early stages of a project leading to early optimisation and design	- BGS borehole Dig to Share and Construction Playbook mandating borehole data provision for public projects - FAIR principals adopted by public bodies. - Construction Playbook mandating sharing of public ground investigation data	- growing adoption of ground data sharing in the public sector - limited private sector data sharing - ongoing initiatives e.g. Dig to Share (I3P, 2023) with British Geological Survey (BGS) developing this opportunity	- Improved access to data and sharing data for public and private projects. This is a key aim of the Future of the Subsurface project. Refer to the broader outcome of this Go-Science project. Other geographies mandate data sharing. - Store data on ground conditions in a structured format for public projects to share with future project teams. E.g. AGSi for ground models, and IFC for the subsurface.	- Lack of perceived incentive. - Data confidentiality and security. - Central repository for data beyond borehole factual data not available.	- HM Government (2020) The Construction Playbook, Version 1.1. - i3P (2023) Dig to share, website: https://www.i3p.org.uk/en/custom/i3pprojects/view/938#:~:text=The%20Dig%20To%20Share%20project,share%20our%20ground%20investigation%20data., accessed 10/10/23. - Ground Engineering Magazine (2023) Sharing ground models with a new data transfer format, website: https://www.geplus.co.uk/features/sharing-ground-models-with-a-new-data-transfer-format-26-07-2023/, accessed 11/10/23	Medium	- Public project requirements - Planning system, Community Infrastructure Levy, guidance	High
Investigation and sensing	Instrumentation of tunnels and third party assets	Sensors and IoT	Data storage and processing		Political	Impacts on third party assets currently constraints tunnelling projects. Improved measurement of impacts and an improved understanding of acceptable levels of impacts will reduce cost and programme on projects. Instrumentation of tunnels during construction ensures safe construction, evolving the permissible level of construction risk.	Emerging sensing technology offering remote monitoring capability such as InSAR and Computer Visions based on point cloud data. Sensor technology evolving in the built environment. Predictive capability using AI to forecast impacts, e.g. ground movements. Near real-time monitoring technology is incremental improving globally. - Use of drone technology to access challenging locations and providing monitoring and sensing data. - Advancement of sensors on tunnelling plant such as TBMs, providing near real-time data to inform excavation process and predictive maintenance.	Assurance processes require costly monitoring of 3rd party infrastructure. - World leader in monitoring sensor technology, infrastructure operators trialling e.g. Network Rail, National Highways - Near real-time monitoring is improving in the UK at construction and operational phases, including structural health monitoring	- Develop improved risk based and outcome based compensation to affected third party assets - Refine monitoring scope using remote sensing to reduce monitoring costs	- Satisfactory demonstration to third party asset owners required. - Full understanding and agreement of risk based and outcome based compensation challenging to agree.	- Giardina, Milillo, DeJong, Perissin, Milillo (2017) Evaluation of InSAR monitoring data for post-tunnelling settlement damage assessment. Structural Control and Health Monitoring No. 26. - Devriendt, Corbo, Kemp, Bologna and Bourton (2015) Data analytics to support monitoring for underground construction projects. Geotechnical Engineering for Infrastructure and Development ICE November 23. CIRIA (2020) Structural health monitoring in civil engineering. C788. - Chio et al., (2023) An overview of drone applications in the construction industry. Drones 2023, 7, 515.	Medium	- Influence third party asset owners requirements - Contracts to encourage innovation in sensing technology, lead collaboration with academia	Medium
Operation	Change O&M to reduce tunnel geometry	Investigation and sensing technologies	Robotics		Technological	Omitting the need for human intervention by replacing O&M tasks with robotic technology can lead to a significant reduction in tunnel diameter where this governs space proofing. Halving the tunnel diameter can lead to proportional cost reduction (HS2, 2016).	- Robotic tunnel inspections carried out in several tunnels across transport, science, energy industries, growing confidence in robotic inspections - Existing small diameter tunnels utilise similar technology, such as sewer tunnels.	- UK is a global leader in autonomous inspection of tunnels, and exporting skills to other geographies. - Robotic O&M is less well advanced, with technology such as 'Spot the Dog' being trialled on construction sites and in tunnels	- Reduction of cost and time by reducing tunnel diameter - Robotics inclusion to clean formwork -Improved quality and H&S removing operatives from confined spaces / hazardous environments - Improved use of smart sensors smart pumps, to reduce the need for manual inspections, with feedback systems	- Social aspects of reducing reliance on persons and moving to robotic technology - Desire to inspect assets physically remains	HS2 (2016) High Speed Two A guide to tunnelling costs. Website: https://assets.publishing.service.gov.uk/media/5a819fe740f0b623026984f5/HS2_Guide_to_Tunnelling_Costs.pdf, accessed 10/10/23.	High	- Review project and O&M requirements to facilitate change in operational use, leading to potential relaxation of requirements	High
Operation	Digital twin and representations of tunnel to increase service life	Digital twins			Technological	Digital models, shadows and twins of tunnels facilitate an improved record and understanding of the condition and performance of the asset, resulting in improved maintenance and an increased service life.	Increased desire for whole life digital twins covering operations and maintenance aspects e.g. tunnel maintenance, integration with embedded sensors, MEP systems controls			- Use case challenging to agree, in order to set a deliverable scope, given the wide-ranging scope and aspirations that a team may have for a digital twin. - Lack of feedback loop (data coverage and frequency) from real asset to digital representation. - Challenges migrating data from design models to operational model digital twin. Contractual, and technical (e.g. data model, scale of data, interoperability).		Medium	- Public infrastructure bodies to drive change. - Project requirements include digital twin model and sensing technology, with process for feedback during operation.	High

Theme	Technology Topic	Primary Technology Taxonomy	Secondary Technology Taxonomy	Other Technology Taxonomy	Trends taxonomy	Introduction	Recent Developments	UK Position	Opportunities	Challenges & Risks	References	Potential for industry change	UK Gov levers[(1)]	UK Gov potential impact
Operation	Extending the lifespan of tunnels	Investigation and sensing technologies	Robotics	AI	Technological	Emerging technology used to Investigate existing infrastructure can provide a better understanding of the ability of the asset to continue to perform in a current or new function. Every year, a total of £8 billion is spent on repair and maintenance in Infrastructure in the UK; with inspections alone costing up to £100 million.	- Small buggy mounted mobile mapping scan and video survey (e.g. New Civil Engineer, 2022) - Computer vision used to understand the condition of existing tunnels through remote sensing. - Robotic tunnel asset management inspections. - Hardware and software using AI to capture better quality and coverage of data on assets, reducing the need for manual interventions. - Mono-rail in Singapore cable tunnels to facilitate remote inspection	- Growing adoption of use of robotics for survey - UK is a global leader in asset inspection and condition surveys of tunnel assets. - Example UK Power Networks tunnels inspected using robotic technology with sensing capability (UKPN, 2023) - Tunnels being replaced with new tunnels. E.g. Thames cable tunnel stated to be at the end of useful service life after 50yrs and to be replaced with new tunnels (Ground Engineering, 2023) - CIRIA (2009) guide collaboration between asset maintainers provides guidance (technology advanced since publication). - CIRIA are about to publish an update to this report	- Old and/or confined infrastructure spaces that pose a risk to health and safety can be accessed using robotics for surveys. - Improved sensing allows a better understanding of asset condition and can lead to prolonged service life.	- Social impact of reduced reliance on humans. Translation of uncertainty into quantifiable metric, what level of error is acceptable? - Access challenging. - Assurance processes for new and existing assets may not reflect emerging technology.	- CIRIA (2009) Tunnels: inspection, assessment and maintenance. C671 - Panella (2023) Automating inspection of tunnels with photogrammetry and deep learning, PhD thesis, University College London, submitted 7 February 2023. - Panella et al., (2020) Cost benefit analysis of rail tunnel inspection for photogrammetry and laser scanning. XLIII-B2-2020:1137–1144. - UK Power Networks (2023) Robotic 'dog' halves time power workers spend in confined spaces. Website article accessed 23/11/23: https://www.ukpowernetworks.co.uk/news/robot-dog. - New Civil Engineer (2022) World first remote-controlled tunnel inspecting robot deployed on high-speed rail project, website: https://www.newcivilengineer.com/latest/world-first-remote-controlled-tunnel-inspecting-robot-deployed-on-high-speed-rail-project-11-04-2022/, accessed 10 October 2023. - Ground Engineering (2023) Consultation begins for Kent-	Medium	- Collaboration with supply chain to test and develop new technology on existing tunnels to demonstrate prolonged use. - Review definition of end of service life due to corrosion.	Medium
Planning, powers to construct	Stakeholder engagement	BIM & Design			Political	Powers to construct linked to stakeholder engagement and support. Technology a key enabler to preventing this becoming a barrier.	- Digital EIAs - Digital stakeholder engagement - VR/AR to visualise scheme for stakeholders. - Singapore Land Authority 50yr masterplan updated every few years, including subsurface use.	- Digital EIAs being undertaken on major schemes e.g. A417 - Digital stakeholder engagement platforms emerging, including use of AR/VR, e.g. HS2 SoundLab - Complex rights of stakeholders and lack of means to efficiently identify and liaise with stakeholders creates a barrier.	- Improve stakeholder engagement through digital technology and visualisation, AR, VR. - Use of opensource software reduce reliance on a supplier.	- Barriers to technology adoption of new technology sit outside of project team. - Unique aspects of projects that are not foreseen can become a barrier to automated processes. - Reliance on proprietary software may limit the progression of the technology solution through the project lifecycle, or result in reliance on a supplier.		Medium	- Set requirements for technology driven stakeholder engagement, facilitate innovation	Medium
Repurposing/ reusing of tunnels	Reusing TBMs and equipment	Excavation technology			Technological	Increased standardisation and collaboration across the tunnelling industry opens up the opportunity for increased reuse of TBMs.	- Boring company have acquired second-hand TBMs to reduce costs and lead in times for tunnelling. - Reuse of micotunnelling TBMs for utilities is undertaken. - Reuse of TBMs gradually occurring, e.g. in Singapore and India. Modifications to TBMs are possible to adapt them to different ground conditions. - Over-specification of TBMs by designers. - International guidelines (ITA-ATIES, 2015) have been developed to standardise the process of reusing a TBM on another project.	- Careful consideration of TBM use within projects considered as part of TBM strategy. - reuse of TBMs on subsequent projects not common	Standardise tunnel diameter and construction type to facilitate opportunity to reuse TBMs.	- Removal of TBMs is costly and increases programme, and may require larger tunnel portal facilities to remove TBMs rather than bury them. - Guaranteeing quality of TBM rebuilding can be challenging. - Risk-related to coupling multiple construction project programmes. - Lack of maintenance during TBM boring reduces the scope for reuse.	- ITA-ATIES (2015) ITAtech Guidelines on rebuilds of machinery for mechanized tunnel excavation. ITAtech report No5 V2. - TBM News (2018) Weighing the options: Is industry bias toward new machines limiting?, article published 5/5/18.	High	- Pipeline of work and standardisation to increase innovation and opportunities to reuse TBMs - Project requirements to encourage reuse, including allowing for additional TBM retrieval cost/programme impacts. E.g. critically reviewing specifications to avoid over-specification, and asking in bids for details of TBMs to be reused.	High
Repurposing/ reusing of tunnels	Reusing existing tunnels	Investigation and sensing technologies	Digital twins		Technological	Reusing or extending the use of tunnels for new uses or changing requirements. This may require modifying the tunnels, such as enlarging tunnels to fit new rolling stock, or repairing old tunnels to bring them back into use.	- Farming - London deep shelters - Communications - BT using military tunnels - Mine workings pedestrian tunnels - Polyhalite mines - neutrino facilities - Carbon capture and storage - Enlarging transport tunnels to change the use. - Singapore seeking to construct larger diameter tunnels that encompass station platforms, in order to reduce bespoke elements. Opportunity also to share use due to great extend of free space. - WilkinsonEyre and London Tunnels Ltd. experiential tunnel refurbishment of WWII bomb shelter.	- Given the age of UK tunnel infrastructure, the UK is a leader in the reuse and prolonging of tunnel assets - Military tunnels in London have been reused for various uses such as farming, culture experience, communications - Rail tunnels have been enlarged to receive larger rolling stock, including brick arch tunnels, cast iron tube tunnels - Carbon capture and storage - Mine workings repurposed as pedestrian tunnels - Mine workings re-purposed as underground pumped storage reservoirs (Colas et al., 2023) - polyhaelite mines - neutrino facilities	- Technology to widen or deepen tunnels whilst still in use. This may be for adjusting the performance required (e.g. larger train rolling stock) or to form connections to existing tunnels (e.g. Northern Line extension junction in Battersea, London). - Enlargement of tunnels using formwork whilst tunnels are still in use, e.g. transport tunnels - Replacing mechanical, electrical and power (MEP) equipment to reduce space take - Re-purposing old rail tunnels as cycle route e.g. Ireland and Bristol - Design tunnels with future use in mind, such as ducts for future utilities, large diameter to increase space proofing - Review design life of structures, is 120 years still appropriate?	- Change in regulations - How to rebuild tunnels that are not repairable - Onerous requirements for certification and liability - Lack of information on existing tunnels	Colas et al., (2023) overview of converting abandoned coal mines to underground pumped storage systems: Focus on the underground reservoir. Journal of Energy Storage, 73. WilkinsonEyre reveals £220m plan to restore London's secret wartime tunnels https://www.architectsjournal.co.uk/news/wilkinsoneyre-reveals-220m-plan-to-restore-londons-secret-wartime-tunnels	Medium	- UK govt set an example to the market by re-using existing tunnels - Encourage industry to adopt risk-based criteria such as 'no worse than existing' rather than conform to new standards, to enable reuse - Extend emerging planning policy to encourage reuse, e.g. requiring demonstration of the need for a new asset - Change requirements to design with future use in mind	High

Theme	Technology Topic	Primary Technology Taxonomy	Secondary Technology Taxonomy	Other Technology Taxonomy	Trends taxonomy	Introduction	Recent Developments	UK Position	Opportunities	Challenges & Risks	References	Potential for industry change	UK Gov levers[1]	UK Gov potential impact
Shared usage	Multiple occupancy	BIM & Design			Political	Sharing tunnels use offers the potential to more efficiently use the subsurface. Shared use extends beyond a single project system. This includes shared use from the outset of a tunnelling project and retrofitted during operation.	- Multi-utility tunnels/ service ducts used below pavements globally e.g. USA, Australia. - Malaysia SMART tunnel, Fehmarnbelt, Saudi government projects - seeking to use transport tunnels for multiple uses including utilities infrastructure. - Singapore government building large diameter tunnels for mix uses. Below deck space typically not utilised, however, opportunity to do so if shared use barriers overcome (such as power and water pipes and cables sharing a tunnel space with means of separation).	- Multi-utility tunnels proposed in several forums, limited adoption due to historic utility infrastructure. - Limited adoption of shared use of large diameter tunnels, such as road and rail. - Greater London Authority (GLA) Infrastructure Mapping Application (IMA) to share infrastructure planning. - Merseyside tunnel proposed to house shared use.	- Utilise tunnel unused space for power and water - Technology to share infrastructure planning, such as the Greater London Authority (GLA) Infrastructure Mapping Application (IMA)	- Risk, programme, litigation - Access for maintenance a challenge if space is shared - Concerns about co-locating certain assets such as power and water - Security risk - outside of control of a single entity and different uses pose different risks to users. - Clients focussed on their own remit - External delays, e.g. political will, become outside of a sponsor's influence in shared use scenario - Strong discourse between transport, power and water authority - Misalignment of requirements between different sponsors. - Ambiguities in laws and regulations may hinder the implementation of shared tunnel usage and require policy interventions.	Hunt et al., (2012) Sustainable utility placement via multi-utility tunnels. Tunnelling and Underground Space Technology, Vol 39, pp15-26.	High	- Coordinate infrastructure systems and networks to align needs and seek to share tunnels - Research barriers to shared use of space and develop solutions to overcome barriers - Strategies and policies to create an enabling environment for shared tunnel usage - Influence project requirements. - Offer warrantee or guarantee to given confidence in multiple sponsors relying on other sponsors. - Consider delivering tunnels as public projects for private use - Reduce uncertainty in market, sudden cancellations or changes in projects, and delays, result in loss of confidence and reduced likelihood of shared usage. - Influence industry guidance and processes to seek to remove barriers to shard usage based on security and safety concerns	High

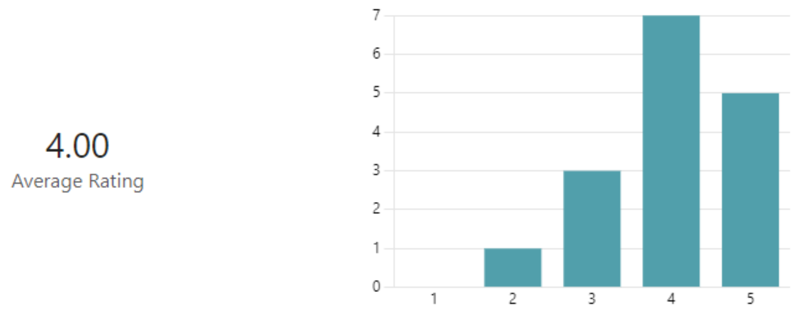
Appendix B

Survey results

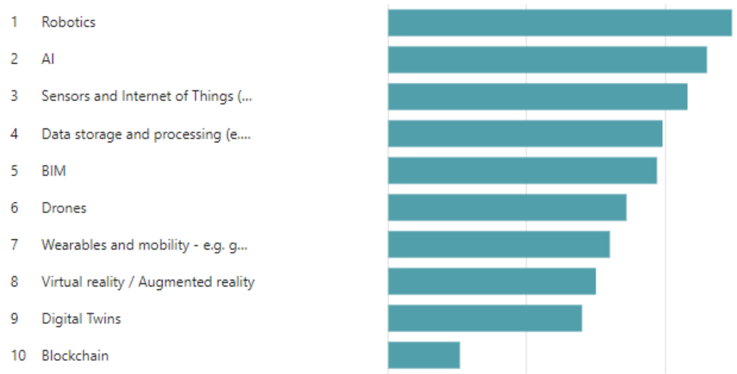
Internal Survey

1. Looking ahead 5-20yrs, what is the potential for technology to transform how tunnelling is carried out?

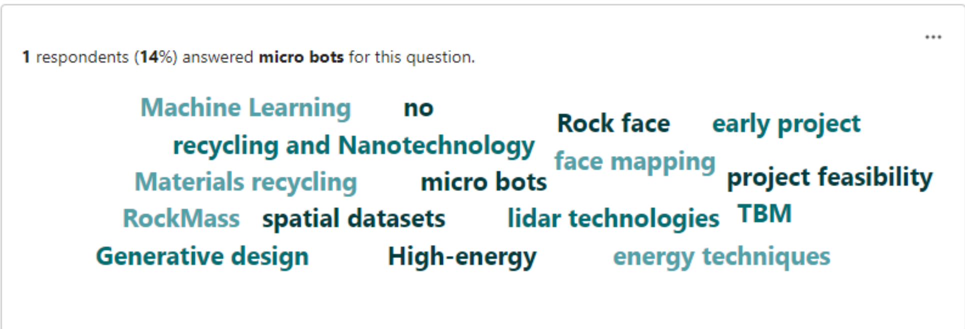
   1 = very limited potential
   3 = a reasonable potential
   5 = huge potential



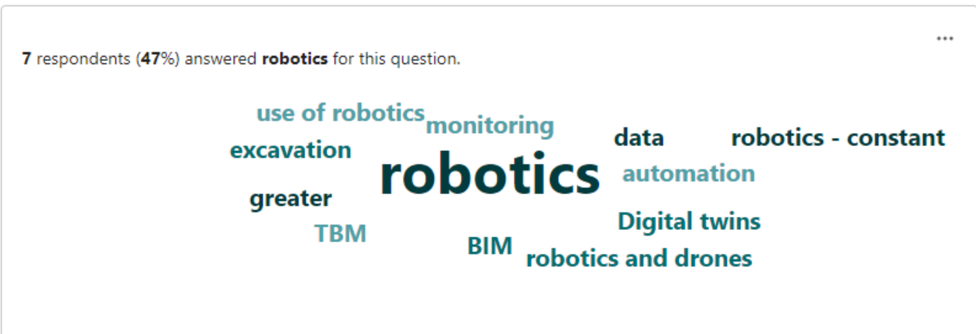
2. Please rank these digital technologies in the order of importance of impact to the tunnelling industry over the next 5-20yrs (Ranking 1 being the most important to 10 being the least)



3. Are there any other digital technologies that you think are missing?



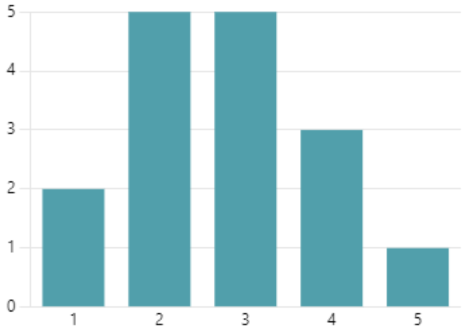
4. What digital technology do you think has the most potential to change the future of tunnelling, and why?



5. How much do you think tunnel excavation technology can reduce tunnelling cost and programme in future, thinking 5-20yrs?

   1 = not a lot (<10%)
   2 = some potential (10-50%)
   3 = a reasonable amount (50-100%)
   4 = a significant amount (100-200%)
   5 = a game changing amount (>200%)

2.75
Average Rating



6. How much do you think tunnel excavation technology can reduce tunnelling cost and programme in future, thinking 20-50yrs?

   1 = not a lot (<10%)
   2 = some potential (10-50%)
   3 = a reasonable amount (50-100%)
   4 = a significant amount (100-200%)
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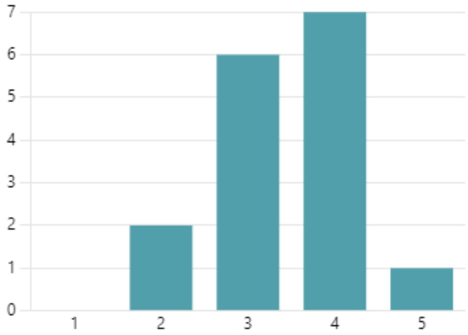
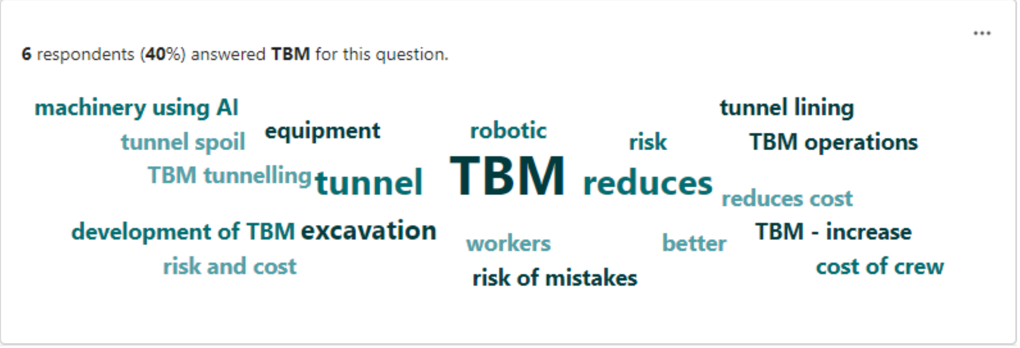
3.44
Average Rating

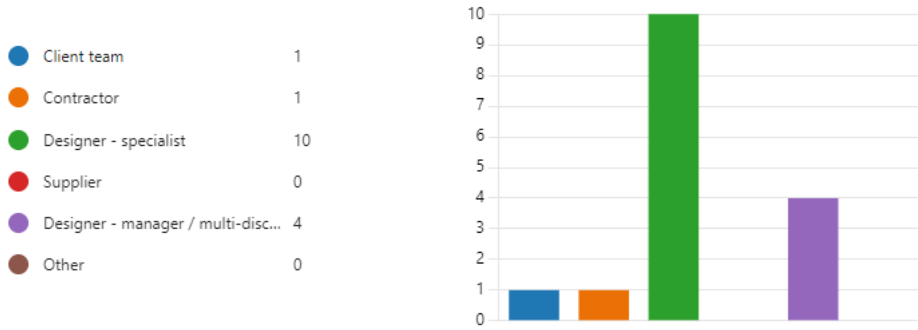


7. What tunnel excavation technology do you think has the most potential to change the future of tunnelling, and why?

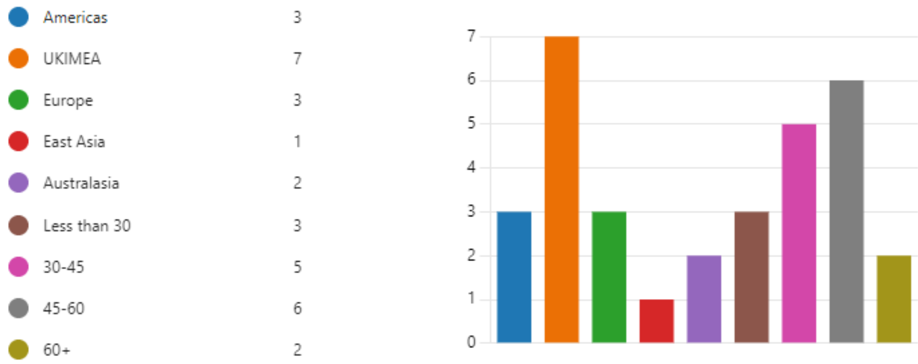


8. What is the greatest barrier to the adoption of emerging technology in the tunnelling industry?

9. What is your role best categorised as?

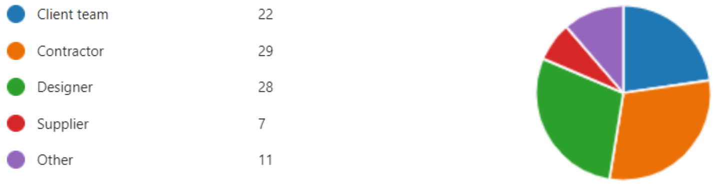


10. Which region are you based in and age group you belong to?



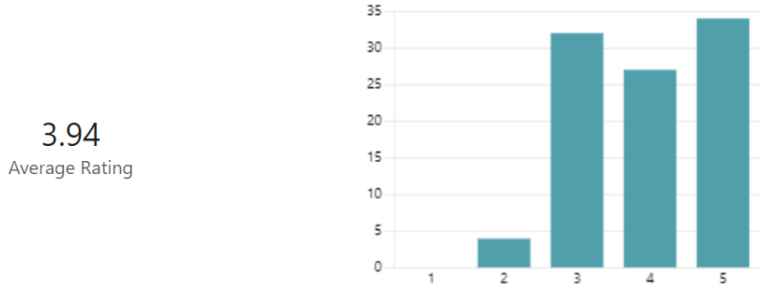
External Survey

1. What is your role best categorised as?



2. Looking ahead 5-20yrs, what is the potential for technology to transform how tunnelling is carried out?

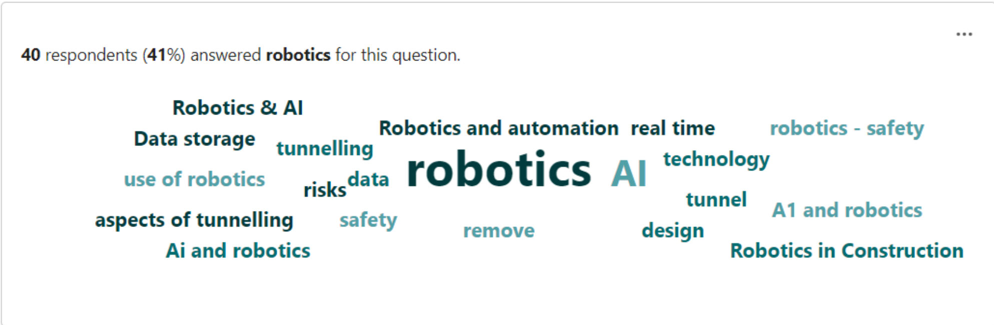
   1 = very limited potential
   3 = a reasonable potential
   5 = huge potential



3. Please rank these digital technologies in the order of importance of impact to the tunnelling industry over the next 5-20yrs (Ranking 1 being the most important to 10 being the least)

4. Are there any other digital technologies that you think are missing?

5. What digital technology do you think has the most potential to change the future of tunnelling, and why?



6. How much do you think tunnel excavation technology can reduce tunnelling cost and programme in future, thinking 5-20yrs?

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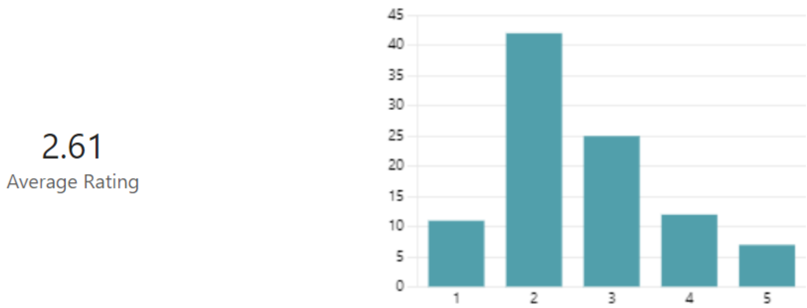

7. How much do you think tunnel excavation technology can reduce tunnelling cost and programme in future, thinking 20-50yrs?

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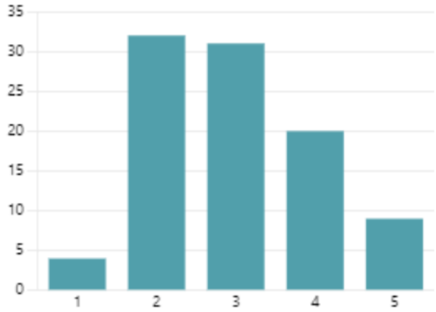
2.98
Average Rating



8. What tunnel excavation technology do you think has the most potential to change the future of tunnelling, and why?

97
Responses

Latest Responses

"Slipform tunnelling, because it is more likely to be able to be completely auto...

"See above"

"automation"