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TRANSFORMATIVE APPROACHES TO UNDERGROUND INFRASTRUCTURE: ROAD TO NET ZERO AND BEYOND

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Abstract: The urgency to address climate change and achieve net zero targets underscores the critical role of underground infrastructure in considerations of urban resilience and sustainability. This paper leverages insights from the "Road to Net Zero" (RtNZ) initiative in the UK, integrating advanced methodologies such as carbon optioneering tools and autonomous robotics. By addressing the complexities of underground systems, the research presents a cohesive framework for sustainable urban development and infrastructure management.

Drawing on the RtNZ Design Options Framework, the paper explores opportunities to minimize the carbon emissions for four alternative design options for streetworks: trenching, minimum dig techniques, trenchless technologies, and autonomous robotics. Actions in support of carbon reduction form part of a structured pathway to address systemic challenges in subsurface management and highlight the importance of integrating innovative solutions for sustainable infrastructure development.

The integration of data-driven tools, such as the RtNZ Optioneering Tool that accounts for all social, environmental and indirect economic consequences of streetworks, combined with advanced thinking from projects such as Mapping and Assessing the Underworld, offers robust methodologies to quantify impacts, mitigate risks, and optimize design decisions. Pipebots, as a future vision, exemplify transformative solutions to subsurface challenges, combining autonomous capabilities with enhanced ecological stewardship. The overarching threads of sustainability, resilience, and health and safety form part of this 'total value analysis', which takes a whole subsurface perspective.

Keywords: Streetworks, Sustainability, Resilience, Optioneering, Decarbonization.

1. INTRODUCTION

It is neither possible nor desirable to divorce considerations of the urban subsurface from what exists and happens at the surface. Fundamentally, the subsurface serves as an ecosystem service provider, and what occurs below ground must work in harmony with surface activities. The workspace focused on herein is the street corridor, and because they tend to be much more complicated, urban street corridors provide the most serious challenges. Referring to Figure 1, it is clear that the streets accommodate many different types of flow and serve many purposes – in short, streets have enormous value.

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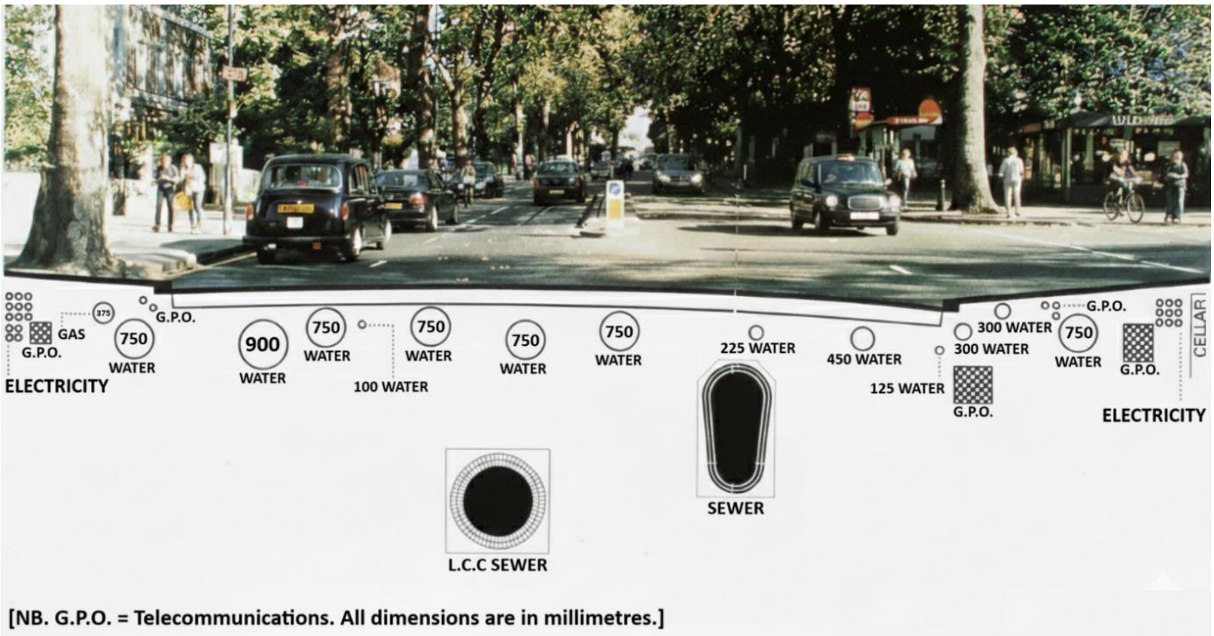

Figure 1. *The urban street corridor – a complex workspace (Image courtesy of Mike Farrimond)*

A starting point for the analysis of the value of street corridors is to consider the urban metabolism - that is, all flows into, through and out of these spaces. A typical urban street scene, such as that represented in Figure 1, will show people moving by active travel (walking, cycling, scootering), people traveling in personal vehicles or via public transport, and goods being transported and delivered by vehicles. Natural flows include animals, birds, insects, and what is carried by the wind (e.g., pollen, seeds, leaves). These streets are also places in which we live and work - they host residential frontages, social spaces, businesses, and nature in the form of street trees. All of this has inherent value that should be recognized, appreciated, protected and where possible enhanced.

The subsurface aspect of the urban metabolism includes the flows transmitted by the buried pipes and cables that carry the essential services and resources required for urban living, while the ground also transmits gases, water, chemicals, and microorganisms (Hojjati et al., 2016). The subsurface must also provide physical support to the buried infrastructure and the overlying transport infrastructure, and it must accommodate the roots of the green infrastructure, particularly trees. The subsurface, therefore, also provides many different forms of value, and this should likewise be appreciated, protected, and where possible enhanced (Rogers et al., 2020).

Moreover, this workspace – the urban street corridor – is dynamic: its surface and subsurface infrastructures change with time. While green infrastructure grows, the non-natural infrastructures (the roads and buried infrastructures) age and deteriorate, requiring maintenance and repair, while there is a seemingly progressive need for the installation of new infrastructure. Alongside this developing landscape is the overarching need for the subsurface engineer to introduce considerations of sustainability and resilience to any intervention, and adopt geoethics principles.

This has many implications for the subsurface engineer. The most obvious is that we should occupy subsurface space responsibly, using only what we need and avoiding unnecessarily compromising the use of this space in the future. More generally, we should ensure that the materials, equipment, and site operations involved in streetworks are chosen to minimize the adverse impact on the environment, society, and the economy. The Road to Net Zero project (LCRIG., 2025; RTNZ Project., 2025), on which this paper is focused, started with a premise of the need to decarbonize construction works, but soon evolved into an evaluation of all potential negative outcomes to be balanced against all the positive outcomes of essential streetworks. This evolution has resulted in the development of an optioneering tool that enables a subsurface engineer to appraise the overall value of an intervention and to minimize the environmental and social harms, which usually translate into economic losses due to their climate and health impacts.

The urban street corridor therefore represents a complex landscape, which in turn needs a systemic approach to engineering in this system-of-systems. This approach to working is usually invoked because of the physical interdependencies between engineered systems – activity associated with one buried pipeline has the potential to impact adjacent buried pipelines and cables, and the overlying road structure (Figure 2). This tacitly assumes that the ground, which supports both the buried and surface infrastructures, is a passive medium. However, if it were to be treated as an infrastructure in its own right, then the engineering process would be far more effective. In essence, this means that we must treat the ground with respect – establish its properties in the undisturbed condition and use engineering judgment to deduce the change of properties according to different types of construction activity. At this point, it becomes immediately evident that open cut excavation will compromise the strength and stiffness of the ground due to lateral stress relief movement (i.e., volume increase), either in the short term or long-term (Torbaghan et al., 2020).

Figure 2. *Complex interdependencies between physical infrastructures, both old and new*

2. PERSPECTIVES ON AND DESIGN OPTIONS FOR ENGINEERING IN THE SUBSURFACE

There is an extensive array of experience, guidance, rules and responsibilities on which to draw when carrying out streetworks, whether using techniques that have been used for centuries (trenching) or more recent technological innovations (trenchless technologies, robotics and AI). Interestingly, the rules around governance are explicitly and comprehensively described by Haylen and Butcher (2019), and yet there is no mention of the overarching imperatives of sustainability, resilience, decarbonization or consideration of environmental consequences; indeed ‘society’ is mentioned only once in relation to the congestion costs of overrunning works. The messages on governance, therefore, stop short of explaining the purpose of these rules. It was for this reason that the Road to Net Zero project — ironically funded from Lane Rental Funds to prevent unnecessary overruns — was launched to extend such guidance on how to drastically reduce carbon emissions from streetworks, and more generally to promote delivery of environmental and social good.

Given that subsurface construction contributes substantially to the UK’s emissions (e.g., via use of diesel machinery, material production and consumption, and waste transport), a multi-faceted ‘optioneering’ approach has been adopted (Rogers, 2018). This approach entails evaluating a range of alternative design strategies for underground infrastructure interventions, rather than relying on the conventional, default option of open-cut excavation. Four main categories of design options - Trenching, Minimum Dig, Trenchless Technologies, and Robotics and AI - have been identified to cover the breadth of viable interventions. Each represents a different pathway to decarbonization and reduced disruption in the congested urban subsurface, and together they form a toolkit for progressing towards low-carbon streetworks while also accounting for their different sustainability, resilience, and livability outcomes, which are the key criteria in the total value framework (in which all social, environmental, and economic impacts are assessed together; Rogers et al., 2022). By evaluating options against these criteria - something that has been identified as a need for decades (e.g., Burtwell et al., 2006) but never adequately addressed — the optioneering process identifies solutions that minimize total harm and maximize net benefits, moving subsurface infrastructure projects closer to Net Zero carbon while enhancing urban resilience and quality of life (see Figure 3). The following section outlines these options, discussing their technical rationale (key benefits, drawbacks, and assumptions) with references to the RtNZ design framework(Rogers et al., 2023).

Conventional open-cut trenching remains the default for utilities and highways due to its simplicity and decades of institutional expertise, but it is energy- and carbon-intensive, producing high fuel use, waste, and social disruption. Electrification and automation can improve its fuel efficiency and yield a modest benefit-cost ratio (BCR ~1.6–2.8). In contrast, minimum-dig (or ‘keyhole surgery’) techniques precisely target only the point at which activity is required, using for example narrow slots, coring, robotic mini-excavators, and advanced polymer liners. This second approach dramatically reduces excavation volumes, equipment emissions, materials, and traffic impacts, delivering very high net benefits (BCR ~4.1) provided accurate underground mapping and crew upskilling is used. However, the opportunities to use such techniques are relatively few because of the reliance on accurate prior diagnosis of the problem and targeting of the works. Trenchless methods (e.g., horizontal directional drilling (HDD) and microtunneling for new installation, pipe bursting and pipe splitting for size-for-size replacement, and relining of a defective host pipe using cured-in-place liners or thin-walled plastic insertions) avoid continuous surface excavation by installing or renewing pipes via localized entry and exit pits.

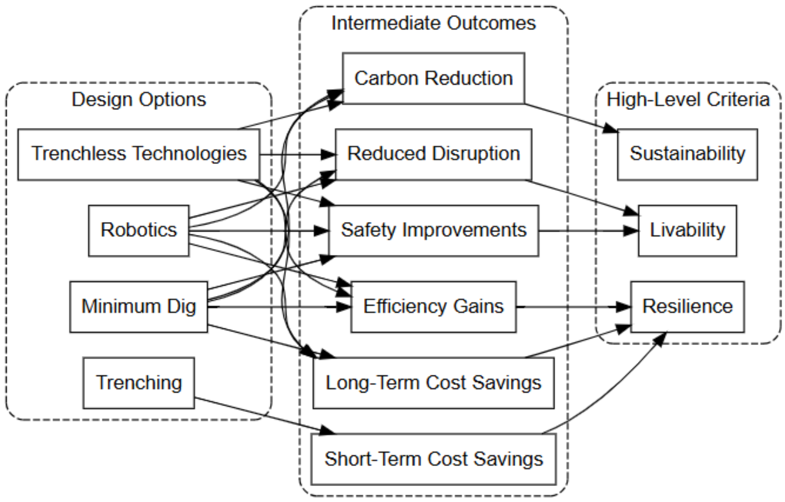

Figure 3. *Conceptual progression from each design option to a holistic* ***total value analysis*** *optioneering model*.

Typical scenarios show a reduction in carbon emissions by up to ~68%, and greatly reduced spoil haulage and surface reinstatement. Although they require more specialized planning, potentially higher upfront costs for equipment purchase and additional care in ground-condition assessment, the drastically reduced surface (notably traffic; Goodwin, 2005) disruption can result in greatly lowered carbon, other environmental and social costs. Finally, advanced robotics spanning autonomous excavators, drones, sensor-equipped crawlers, and AI-driven 'digital workers' offers a cross-cutting enabler that enhances precision, safety, and efficiency across all approaches. In view of the fact that this technology is emerging, this currently requires significant capital investment, digital skills, regulatory adaptation, and mature integration to realize its transformative potential.

The four generic design options therefore present a spectrum of trade-offs between technological disruptiveness, ease of implementation, and multidimensional value. Table 1 summarizes several key metrics across the options. Robotics and AI stand somewhat apart as an enabling layer: they can amplify the benefits of the other methods (e.g., by automating precision tasks), although on their own they both require further development to realize their full impact. The most appropriate path forward, therefore, is one that invests in innovation adoption (to unlock the high-value options) while managing risks with interim improvements—ultimately steering the sector onto a net-zero trajectory with broad societal gain.

Table 1. *Key comparative metrics across alternative design options.*
(*Carbon Reduction values are indicative, based on hypothetical case analyses of site works alone. Disruption Level refers to relative level of surface and community disruption caused by the works. Adoption Readiness reflects current maturity and industry uptake.*)

Option	Carbon Reduction Potential of Site Works	Disruption Level	Adoption Readiness
Trenching	**Moderate:** incremental improvements yield ~20-40% emission cuts by using electrified plant and vehicles	**High:** requires full excavation (partial or full road closures, high waste volumes)	**High:** fully mature technique (widely practiced)
Minimum Dig	**High:** considerable reductions by avoiding large excavations	**Low:** minimal surface opening; targeted intervention only	**Medium:** proven in niche uses, but slow uptake so far
Trenchless Technology	**High:** up to ~68% less CO_2 than open-cut in selected scenarios of different technologies	**Low:** only entry/exit pits needed; surface largely undisturbed	**High:** wide range of established methods exist
Robotics and AI	**Very High to Medium:** includes indirect gains via efficiency and automation	**None to Medium:** depends on application (can eliminate or reduce time on site)	**Low:** emerging technology (pilot stage development)

3. ACCOUNTING FOR THE CONSEQUENCES OF STREETWORKS

All actions have consequences; the consequences of actions occurring in the urban street corridor extend to all societal and environmental dimensions (Hayes et al., 2012), and therefore also economic consequences – the street corridors house our 'economic infrastructures' and potentially disrupt our 'social infrastructures'. The choice of streetworks design options is therefore a considerable responsibility. Key components of the assessment of these consequences include: (1) Social impact metrics including traffic congestion delays for vehicles and pedestrians (e.g., converted to lost time costs), noise and dust pollution affecting nearby residents, and any public safety risks; (2) Environmental impact metrics including greenhouse gas (GHG) emissions from construction machinery, air quality degradation, waste generation, and damage to green infrastructure (such as harm to street trees or biodiversity); and (3) Indirect economic impacts including business revenue losses due to reduced footfall during road closures, vehicle operating costs from detours, accelerated road wear from works, and other knock-on effects on the local economy. By capturing these factors, an optioneering tool, such as that being created in the RtNZ project, embodies recommendations from recent research: the total impact of utility projects can only be assessed by evaluating all direct and indirect costs alongside social and environmental externalities (Hojjati et al., 2018).

In practice, the optioneering system prompts engineers to input key details of a proposed streetworks operation (such as location, duration, equipment and site operations, affected traffic volumes and facilities and communities affected). These inputs are then processed through a comprehensive consequences calculator that quantifies the reach and magnitude of impacts under each scenario (i.e., design option and context). For example, the tool might estimate the GHG emissions of open-cut trenching versus a trenchless method in terms of the direct works, while simultaneously computing the cumulative expected traffic delays and disruption to local business and integrating them into a monetized cost in each case. Any impacts that cannot be easily quantified (for instance, temporary loss of community amenity or cultural disturbance) are noted qualitatively in the form of an associated narrative so that they are not ignored in the decision-making process. Integrating such multi-dimensional analysis early in the planning stage, engineers can undertake truly holistic design evaluation of subsurface projects. Each candidate solution for utility maintenance or installation is therefore judged not only on engineering feasibility and upfront cost, but also on how well it minimizes total harm and maximizes net benefits across stakeholders and the environment. This broad evaluative perspective would mark a significant shift in subsurface engineering philosophy, from a narrow focus on the asset being buried in the ground, to a system-wide consideration of how the work on that asset reverberates through the urban ecosystem.

4. REQUIRED OUTPUTS AND OUTCOMES

The RtNZ optioneering tool is designed to inform and enhance decision-making, not to supplant human judgment. It serves as a sophisticated decision support mechanism that compiles complex data into actionable insights for engineers, project managers, and policymakers. In using the tool, decision-makers are presented with outputs that transparently compare the anticipated consequences of different design choices, thereby enabling evidence-based decisions. It is important to note, however, that the tool itself remains agnostic; it does not "choose" the best option on behalf of the user. Instead, it illuminates the trade-offs inherent in each option, allowing stakeholders to weigh priorities (such as budget constraints versus environmental goals) in light of quantitative evidence – only the decision-maker can fully appreciate the context. This aligns with best practices in infrastructure management, where computational models and multicriteria analyses support the expert's decision rather than making it autonomously. The ultimate selections still rely on professional judgment, regulatory context, and stakeholder values, but the tool's comprehensive output ensures those decisions are far better informed than before. In essence, the optioneering tool functions as a catalyst for better decision-making, one that provides a common platform of facts and projections that all parties can discuss, thus depoliticizing debates and focusing attention on holistic outcomes.

The expected outputs of the optioneering tool include quantitative summaries, comparative graphics, and detailed breakdowns for each evaluated scenario. For each candidate solution (e.g., a conventional open-cut repair versus a trenchless repair), the tool can output a suite of metrics: estimated project carbon emissions (in CO_2-equivalent), total duration of road disruption and associated delay cost to commuters, number of people or businesses directly impacted, projected accident risk or safety incidents, noise levels, excavated material waste volume, and so on. Many of these results are monetized or scored against benchmarks – for example, hours of traffic delay might be converted into monetary cost using standard values of travel time – and carbon emissions might be translated into an equivalent social cost of carbon. By presenting results in common units (e.g. currency or score indices), the tool facilitates an apples-to-apples comparison of alternatives on a single dashboard. In addition, the tool can flag any threshold exceedances or regulatory compliance issues (for example, if an option would produce noise above allowable levels at night, or if expected road disruption exceeds what permit conditions allow). The outputs are typically delivered both in tabular form (detailed reports) and as visualizations that condense the information, such as bar charts stacking impact categories (Figure 4), radar charts of sustainability criteria, or map-based illustrations of the spatial extent of disruption for each option. These user-friendly outputs empower project planners to identify the dominant impacts of each option at a glance, and to pinpoint where design modifications could yield improvements (e.g., if one option's carbon footprint is high, perhaps alternative machinery or materials could be considered).

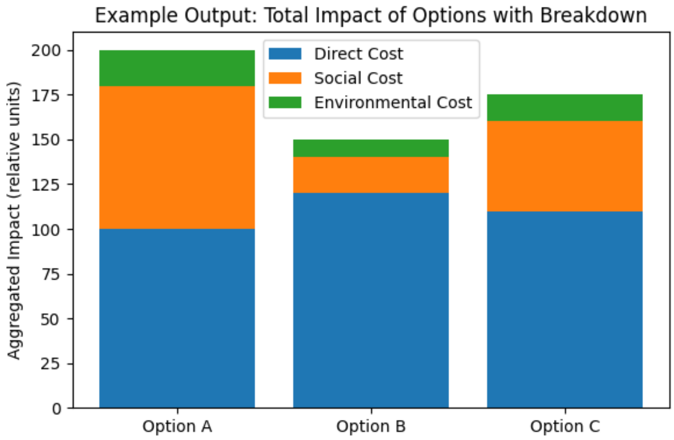

Figure 4. *Conceptual output from optioneering tool.*
(Conceptual output from an 'all consequences' optioneering analysis, comparing three design alternatives for a hypothetical streetworks project. Each bar represents an option's aggregated impact (lower is better), subdivided into direct construction cost (blue segment), indirect social costs such as traffic delay and inconvenience (orange segment), and environmental costs such as carbon footprint (green segment). In this illustrative example, Option B has a higher direct expense than Option A but far lower social and environmental costs, resulting in the lowest total impact when all consequences are accounted for. Such output visuals enable stakeholders to immediately grasp the trade-offs and net benefits of more sustainable engineering choices.)

5. CONCLUSIONS

That we live in a complex world, made up of a system-of-systems, is universally understood, and this complexity is exemplified in urban street corridors that support civilized life. Not only are they the places in which we live and work, but we rely on them to support the urban metabolism - if they operate efficiently and effectively, then all urban systems have the potential to function as intended. Disrupting these systems to install a new buried utility pipeline, or repair or upgrade an existing pipeline, therefore has potentially serious consequences. It is essential to identify and characterize such consequences so that any proposed streetworks activity can be evaluated in terms of net value. This means balancing the value realized (for example, providing new or protected utility service provision, many of which are essential and make the works unavoidable) against the value compromised to those who live, work, and pass through the affected area. Such an evaluation must consider all forms of movement through the urban street corridor, direct impacts on the local context, and more indirect impacts on the wider environment.

The RtNZ project is addressing this issue of national (and global) importance by developing an optioneering tool that makes transparent the full consequences of adopting different design options for streetworks, and then iterating them - choosing different equipment that might achieve the same result (e.g., electrically powered excavators to replace those using diesel engines), different site routines, alternative materials to use in the works, different material sources (with an eye on transport distances, hence emissions), different transport regimes for staff moving to and from site, the rapidity and timing of the works, the GHG emissions in the street corridor and its impact on traffic management, and so on. While the original motivation for the research described in this paper, as the project title implies, was to make transparent the carbon consequences of alternative approaches to streetworks, it rapidly became evident that the broader scope now adopted in this work is critical if those commissioning and carrying out streetworks are "to do the right thing." This is to look after the interests of the end user of all the services offered by urban street corridors, and ultimately that is every one of us. One final point here, of course, is that these findings are not limited to urban areas but are relevant wherever buried infrastructure and surface infrastructure coincide.

6. ACKNOWLEDGEMENTS

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