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A Data-Driven Analysis of Utility Strikes in Highway Infrastructure Projects Using Natural Language Processing and Rule-Based Classification

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Abstract

Buried service utility strikes cause accidental damages to underground utility lines during excavation works and present an omnipresent challenge in maintaining highway projects. Despite extensive efforts documented in the literature to mitigate these incidents, they remain a priority in highway development. This study examines the causes of these incidents by analysing utility-strike data collated from UK highways projects. Specifically, this study analyses 95 case studies comprising 624 incident entries from 2016 to 2021 to elucidate upon the causes and consequences of utility strikes. Employing natural language processing and a rule-based classifier, seven primary incident categories are identified *viz*.: electrical hazards (f = 296 or 47%), machinery operation (f = 181 or 29%), impact against/struck by (f = 64 or 10%), unknown (f = 20 or 3%), gas hazards (f = 61 or 10%), equipment misuse (f = 1 or 0.16%) and installation errors (f = 1 or 0.16%). Underground communication services emerge as the most affected, followed by low-voltage electric and water services. Injuries that were linked exclusively to lost time stem from electrical shocks, tool contact and impacts. Leveraging these insights, the study proposes the Integrated Utility-Strike Avoidance Framework (IUSAF), that is based upon a Safety-II aligned model which integrates: technological solutions (e.g., geographic information systems (GIS), ground-penetrating radar (GPR) and machine-mounted sensors); regulatory adherence (e.g., HSE guidelines and one-call systems); and human-centric strategies for risk control (e.g., training and behavioural interventions). While offering a robust taxonomy and actionable framework, the research recommends future research *viz*.: enhanced reporting; empirical validation of prevention measures; and exploration of systemic vulnerabilities like fragmented utility records. By implementing the IUSAF and addressing these gaps, stakeholders can significantly reduce utility strikes, enhancing safety, efficiency and service reliability across UK infrastructure projects.

Keywords: safety management; utility strike; incident analysis; rule-based classification

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1. Introduction

Buried service utility strikes incur accidental damage to underground utility lines such as electrical and telecommunication cables, water pipes and gas pipelines during excavation (Metje et al., 2015). These incidents can lead to serious injuries, fatalities and substantial economic costs, with reports estimating around 60,000 strikes annually from 4 million

excavations in the UK alone (ICE, 2017). Previous research works highlighted different strategies to prevent the occurrence and mitigate the impact of utility strikes (Talmaki & Kamat, 2014; Maree et al., 2021; Piratla et al., 2024; Sarvari et al., 2025a). Buried service utility-strike prevention strategies form a crucial role in identifying underground utility lines before excavation works begins (Yadav et al., 2022). Adherence to excavation safety regulations and risk assessment method statements (RAMS) is vital in ensuring that excavation practices are conducted safely and responsibly (Osei-Asibey et al., 2021). Conducting thorough risk assessments can help identify potential hazards and inform proactive measures to mitigate risks associated with utility strikes (Nguyen et al., 2024). Moreover, utility-strike data analysis is instrumental in understanding the trends and causes of incidents, which can inform policy changes and improve safety practices (Bai et al., 2020). Finally, the development of utility-strike prediction models can assist excavators in identifying high-risk areas, enabling them to implement preventive actions before commencing work (J. Li et al., 2025). By integrating such strategies, the industry can significantly reduce the incidence of utility strikes, enhancing safety and minimise economic impacts (Koschmann et al., 2022; Sarvari et al., 2024b). Given this context, leveraging approaches that can predict and mitigate these strikes is increasingly relevant within utility works.

Analysing case studies is a powerful method for better understanding utility strikes because rich historical information and data contained within them allows utility companies to identify patterns that can inform proactive strategies adopted. A primary benefit of case studies is their quintessential role in utility-strike risk assessment, where past incidents are examined to develop effective frameworks for predicting future strikes (Zografopoulos et al., 2021). This study analyses UK utility strikes to identify the key incidents and contributing factors involved. Examining these events highlights patterns and conditions that lead to such occurrences. This analysis is complemented by the exploration of aspects of physical and financial harm to enable the recommendation of targeted interventions. By analysing these fundamental causes, utility companies can implement tailored training programmes and safety protocols that significantly reduce the risk of future incidents.

1.1. Utility Strikes in Highways Projects

Buried utility strikes engender significant financial losses, project delays and safety hazards, making their prevention crucial in highway construction projects (Metje et al., 2015). To mitigate the risk of utility strikes, the significant factors contributing to their occurrence must first be determined (Al-Bayati & Panzer, 2020). Utility strikes during highway projects are often attributed to several interrelated factors that compromise safety and efficiency (Metje et al., 2015; Yadav et al., 2022). A primary contributor is inadequate utility mapping, which refers to the lack of accurate records of existing underground utilities (Apak et al., 2022). This deficiency can lead to unexpected strikes during excavation works, emphasising the need for thorough pre-work surveys to mitigate risks (Koschmann et al., 2022). Effective communication is essential to ensure that all parties are informed about existing utilities and their implications for excavation works (Suleiman, 2022). Another significant factor is the lack of utility coordination, which involves insufficient collaboration between utility providers and excavation or reinstatement teams. A lack of integration can create conflicts and strikes, highlighting the necessity for coordinated planning to minimise disruptions during highway projects (Waugh & Streib, 2006). In addition to inaccurate as-built drawings (Maree et al., 2021), the depth of utility services and techniques used for excavation significantly influence the likelihood of strikes occurring, underscoring the importance of adhering to appropriate methods and safety protocols (Khorrami Shad et al., 2025). Technological advancements in detection (such as ground-penetrating radar (GPR)) are crucial for identifying underground utilities before excavation, thereby reducing the risk

of strikes (Tanoli et al., 2019). Moreover, increased urbanisation leads to a higher density of underground utilities, complicating navigation and avoidance strategies during the works (Labbé, 2016). Recent UK case analysis of dangerous-occurrence and lost-time files likewise shows that worker-related and work-related causes combine, and that prevention has to be staged before, during and after the event (Sarvari et al., 2025a).

The role of workers and associated work-related issues (e.g., worker failure to identify the hazards or worker error in utilising equipment) are pivotal in preventing utility strikes (Sarvari et al., 2024b). Effective workforce management ensures that workers are adequately trained and equipped to handle these risks, which includes understanding safety protocols and emergency response procedures (Sarvari et al., 2024a). Even with proper mapping, the effectiveness of these measures heavily relies on the preparedness of the workforce (Bayramova et al., 2023). Additionally, conducting thorough risk assessments and effective contractor management ensures that all personnel adhere to safety protocols, further minimising the risk of utility strikes (MG et al., 2025). Finally, engaging with stakeholders fosters a collaborative environment where safety issues can be openly discussed and resolved, ultimately contributing to the successful completion of highway projects (Sarvari et al., 2022).

Equipment failures can significantly contribute to utility strikes (Metje et al., 2015). Common types of equipment failures include design flaws (Tanoli et al., 2019), maintenance issues (Yadav et al., 2022) and plant operator errors (Apak et al., 2022). Design flaws create inadequate machinery performance, increasing the likelihood of accidents during excavation activities (J. Li et al., 2025). Maintenance issues (i.e., neglecting routine checks or failing to replace worn-out parts) engender equipment malfunction, which may cause unintended utility strikes (Sarvari et al., 2022). Additionally, operator errors play a crucial role in equipment-related incidents (Koschmann et al., 2022). Moreover, inadequate operator training (Thron et al., 2024) and the lack of proper safety protocols can exacerbate the risk of utility strikes (Metje et al., 2015). When safety measures are not adhered to, the chances of equipment failure increase because operators are not vigilantly monitoring their machinery or the surrounding environment (Edwards et al., 2003). To mitigate these risks, it is vital to conduct thorough equipment failure analyses that identify root causes and develop strategies to prevent future incidents (Nallathambi et al., 2023). These challenges extend to the broader UK context, as explored next.

1.2. Utility Strikes in the UK

Utility strikes in the UK present an omnipresent and intensifying challenge. Recent data highlight that thousands of utility strikes occur each year during excavation activities, resulting in an estimated £1.2 billion in direct and indirect costs (Metje et al., 2015). Historical legal changes, such as the New Roads and Street Works Act of 1993 and subsequent deregulation, have influenced this domain; yet, deficiencies persist in meeting contemporary requirements (Zio & Miqueles, 2024; Sarvari et al., 2025b).

The UK utilities sector constitutes the foundation of national infrastructure but contends with difficulties that exacerbate the dangers of utility strikes. The sector is overseen by organisations such as the Office of Gas and Electricity Markets (Ofgem) and the Health and Safety Executive (HSE) and reconciles service provision with a continuous transition to renewable energy and digital technologies (Bogdanov et al., 2021). Although this transition promotes sustainability via innovative enterprises (Seyfang & Haxeltine, 2012) it imposes challenges on the maintenance of existing and the installation of new underground utilities. Obsolete networks, established decades prior with little documentation, conflict with fast urbanisation and erratic demand, hindering resource distribution and strategic planning (Gilchrist & Allouche, 2005; Edwards & Love, 2016). Practitioners indicate a hazardous

speed in development operations, including road excavations, propelled by cost-reduction pressures, hence increasing strike risks (Edwards & Love, 2016).

The regulatory and operational dynamics exacerbate these challenges. Privatisation and deregulation have promoted competitiveness, requiring effective asset management to ensure operational resilience (Nadel & Herndon, 2014). A significant skills gap in modern digital technologies, essential for utility mapping and maintenance, obstructs safe growth of utility provisions (Sarvari et al., 2022). Utilities face challenges in upgrading infrastructure and preventing strikes without skilled personnel to utilise techniques such as Geographic Information Systems (GIS) or real-time monitoring (Maree et al., 2021). Environmental constraints complicate matters, as stringent sustainability regulations necessitate eco-friendly practices that existing maintenance approaches frequently do not satisfy (Tamosaitiene et al., 2021). Inclement weather, a persistent environmental factor, exposes vulnerabilities in outdated systems by exerting stress on deteriorating infrastructure, exemplified by the formation of potholes and cracks in weathered road surfaces during intense rainfall (Yadav et al., 2022). This degradation underscores the critical need for modernising infrastructure to enhance resilience and ensure operational safety.

Resolving utility strikes necessitates a diverse strategy grounded in thorough data analysis and technological investment. Regulatory frameworks must adapt to facilitate adherence to safety requirements and promote skills development, enabling contractors and utility providers to use innovations such as digital mapping (Koschmann et al., 2022). The Industry 5.0 paradigm (which merges technology with proficient human supervision) provides a prospective avenue, contingent upon the legal system's adaptation to finance infrastructural improvements (Edwards & Love, 2016). Overall, a comprehensive understanding of utility strikes in the UK, encompassing statistics, historical context, causes and regulatory frameworks, can significantly enhance efforts to mitigate their occurrence and impact (Edwards & Love, 2016). This research highlights the necessity of these techniques, utilising practitioner views and historical context to develop practical solutions for a resilient utilities sector (Metje et al., 2015).

The disadvantages of utility strikes on the UK strategic road network are therefore operational as well as safety-related (Metje et al., 2015). A strike can injure or kill, isolate power or communications, flood a carriageway, delay traffic management and force unplanned diversion of plant and labour (ICE, 2017). Direct repair is only part of the loss (Gilchrist & Allouche, 2005). Indirect effects include prolonged occupation of the highway, compensation risk, damaged client relationships and repeated attendance by the same utility owner (Piratla et al., 2024). These burdens sit inside a distinctive institutional setting: privatised asset ownership, incomplete as-built records, variable contractor competence and cost-driven programmes that compress the time available for locating services (Edwards & Love, 2016). Current controls, including HSE guidance, the New Roads and Street Works Act duties and one-call arrangements, reduce some exposure but do not close the gap created by fragmented records and uneven reporting (Hayes & McDermott, 2018). The present study is confined to National Highways case files from 2016 to 2021 and cannot quantify the full national cost (Metje et al., 2015). It can, however, show where strikes clustered by service type and by cause, and that clustering is the basis for the measures discussed later (Sarvari et al., 2025a).

2. Research Methodology

A mixed philosophical paradigm was adopted which combines both positivism and interpretivism (Edwards et al., 2020; Bortey et al., 2024). The study's scientific and logical basis facilitated the examination of structured data through statistical techniques like frequency analysis (Afshari et al., 2022), whilst the interpretive paradigm enabled the extraction of

meaning from textual accounts within the analysed case studies. This approach has been widely adopted in many contemporary safety studies (Bortey et al., 2024) and hence, its adoption is justified for this present study. Both inductive and deductive reasoning were adopted in analysing the data (Bayramova et al., 2024b). Based on predefined categories of case study data supplied by National Highways, deductive reasoning was used to classify the incidents into predefined thematic categories of 'incident outcomes'. To augment the analysis and obtain a deeper understanding of the data beyond the predefined categories, inductive reasoning was employed to examine the trends and patterns identified in the data.

In total, 95 utility-strike case studies were analysed and consisted of accident reports, mitigation strategies adopted and photographic evidence. Individual case studies consisted of 85 damage reports, 4 dangerous-occurrence reports and 6 lost-time reports. Three categories of incident outcomes were therefore identified based on the case study reports obtained, namely, (i) damage; (ii) dangerous occurrence; and (iii) lost time (Tanoli et al., 2019). '*Damage*' refers to physical harm inflicted on utility lines or surrounding infrastructure, which can result in service disruptions and costly financial losses. This category is critical because it assesses incident severity and informs necessary remedial actions to restore services and mitigate further risks (Yadav et al., 2022). Utility strikes can engender significant damage to underground infrastructure which incurs costly repairs and disrupts essential services (Yadav et al., 2022). Effective utility-strike prevention measures are therefore vital in providing accurate information on the location of underground utilities, thereby reducing the risk of damage during excavation activities (Koschmann et al., 2022). A '*dangerous occurrence*' poses an immediate threat to people, property or the environment and can manifest as gas leaks, electrical shocks and/or explosions, necessitating prompt response measures to prevent further harm (Scott et al., 2019). Identifying and managing such occurrences are vital for ensuring public safety and minimising potential disasters (Paz et al., 2024). Implementing robust risk assessment and management strategies can help identify potential hazards and develop effective mitigation plans (as part of a '*safe system of working'*), ensuring that safety is prioritised during utility excavation works (Sanni-Anibire et al., 2020). Compliance with excavation safety regulations further enhances safety by establishing guidelines that contractors must follow to avoid accidents (Osei-Asibey et al., 2021). '*Lost time*' encompasses the downtime and/or delays caused by utility strikes, which can lead to productivity losses (Zhao & Dungan, 2022), adverse client relations (Chilton et al., 2021) and economic impacts (David & Gonçalves, 2021). The consequence of lost time highlights the importance of minimising disruptions to maintain business continuity and reduce the overall costs associated with utility strikes (Metje et al., 2015).

In addition, incident data from 2016 to 2021, which has 624 rows and 14 columns, were also analysed. Subsequently, content analysis was utilised to conduct an in-depth analysis of the incident's nature. Based on prominent keywords which were identified, a rule-based algorithm (Johansen et al., 2024) was then introduced to categorise the incidents into hazardous causes. A cross-sectional time horizon which focuses on historical data extending over multiple years was adopted and Python programming was employed in the analysis and visualisation of data to effectively communicate insights uncovered. Table 1 explains the variables of the incident data used in the analysis.

Table 1. Description of variables.

No.	Column Name	Description	Data Type
1	Incident Number	Unique identifier for each reported incident.	Integer
2	Client Name	Name of the company involved in the incident.	Categorical
3	Incident Date and Time	The exact date and time the incident occurred.	DateTime
4	Category	Broad classification of the incident (e.g., Damage, Lost Time).	Categorical
5	Type	Specific type of incident (e.g., Dangerous Occurrence, Overhead Lines).	Categorical
6	Incident Details	Description of what happened during the incident.	Text
7	Service Type	Type of utility service being performed when the incident occurred.	Categorical
8	Cause	Hazardous cause assigned based on keyword analysis.	Categorical
9	Cause Explanation	Justification for assigning a particular cause.	Text
10	Injury Type	Type of injury sustained (if applicable).	Categorical
11	Body Part Affected	The body area injured in lost-time incidents.	Categorical
12	Hazard Category	Broad classification of the hazard (e.g., Electrical, Gas, Machinery).	Categorical
13	Outcome	The result of the incident (e.g., Damage, Injury, Lost Time).	Categorical
14	Year	The year in which the incident occurred.	Integer

2.1. Natural Language Processing (NLP)

NLP techniques allow analysts to understand, interpret and reproduce human language (Omar et al., 2025). To derive meaningful insights from the unstructured textual data in the incident details column, NLP techniques were employed to enable efficient textual analysis. Furthermore, to enhance pattern identification and effective keyword extraction, the first step involved data preprocessing. Three different folders each containing the case studies of a specific category was used in the analysis; this contained 85 incident files in the damage category folder, four case files in dangerous-occurrence folder and six case files in the lost-time folder. A python function was employed to extract texts from each pdf file in the folders.

Relevant details in the files based on headings such as incident date, location, etc., were extracted from the texts and saved as data columns while maintaining the folder name as the category for each data entry. A structured dataset was produced with labelled columns and rows of data entries. The final dataset had 95 rows and eight columns. All the text entries were converted to lowercase for easy keyword identification and punctuation marks; special characters and extra spaces were removed to reduce *white noise* in the text. These key text processing steps are essential NLP techniques that are significant in enhancing data quality. The tokenisation technique (Dodić & Regodić, 2024) was also employed to split words in the incident detail column and analyse each word independently. This was crucial in identifying keywords that had close relationships with hazardous causes of incidents.

2.2. Rule-Based Algorithm

A rule-based algorithm is a machine learning method whereby data classifications and decisions are made based on a set of predefined 'if-then' conditions by experts (Islam et al., 2024). The procedure is therefore an expert-specified, first-match classifier rather than a trained supervised model. A supervised classifier was not trained because the cause labels were created by the rules themselves. Training a model on those labels would have reproduced the dictionary rather than provided an independent standard. The 10% dual-coding check is therefore reported as the validation step. In this study, the rule-based algorithm was implemented to automatically classify incidents based on prominent keywords contained within the 'incident details' column. Data preprocessing was performed in Python 3.11 with pandas. All text in the Incident Details column was converted to lowercase, after which punctuation, numeric tokens and surplus whitespace were removed and the remaining string was split on whitespace to permit token-level matching. A predefined set of keywords based on previous studies (cf. Metje et al., 2015; Arora, 2024) was then used to classify

incidents into specific causes. For example, if the incident description contains words such as 'digger', 'machinery' or 'vacuum excavator', the incident is classified under 'machinery operation'. Additionally, keywords such as 'cable' or 'overhead' indicate 'electrical hazard', while 'gas' or 'explosion' suggest a 'gas hazard'. Similarly, 'installation' or 'replacement' is classified as a 'installation error,' 'grab arm' or 'spoil' is categorised as 'equipment misuse,' and 'falling,' 'digging,' 'hit,' or 'damaged' is designated as 'impact against/struck by.' If no relevant keywords are detected, the incident is labelled 'unknown'. The complete dictionary and the frozen matching order used in the analysis were as follows. Electrical hazards was tested first (cable, overhead, voltage, electric, shock, live, lv, hv, streetlight), followed by gas hazards (gas, explosion, leak, pipeline, lp gas, mp gas), machinery operation (digger, excavator, vacuum excavator, plant, machinery, bucket), equipment misuse (grab arm, spoil, attachment, misuse), installation error (installation, replacement, jointing, reinstatement error) and impact against/struck by (falling, digging, hit, damaged, struck, impact). Records that matched none of these terms were labelled unknown. This order was fixed before coding and was not revised after the frequencies had been inspected. This type of classification follows a priority-based approach where the first matching rule determines the assigned cause (Haynes & Onur, 2020). Mathematically, the classification function is expressed as

Let

D be the incident details (description);

C be the cause of incident;

K_i be the set of keywords, where K_1 = Machinery operation, K_2 = Electrical hazard... K_n;

The function $f(D, K_i)$ checks if any keyword in D exists in K_i;

The rule-based logic is then expressed as:

$$C = \begin{cases} \textit{Machinery operation}, \ \textit{if } f(D, K_1) = 1 \\ \textit{Electrical hazard}, \ \textit{if } f(D, K_2) = 1 \\ \textit{Gas hazard}, \ \textit{if } f(D, K_3) = 1 \\ \textit{Installation error}, \ \textit{if } f(D, K_4) = 1 \\ \textit{Equipment misuse}, \ \textit{if } f(D, K_5) = 1 \\ \textit{Impact against/ struck by}, \ \textit{if } f(D, K_6) = 1 \\ \textit{Unknown if otherwise} \end{cases}$$

where

$f(D, K_i) = 1$ if any keyword in K_i appears in D, otherwise 0. The first matching condition is assigned as C. In the published analysis the sets are tested in the same order as the numbered keyword list, beginning with electrical hazards. The first match is retained and later sets are ignored. The notation is therefore a compact statement of that first-match rule, not a separate classifier.

A 10 per cent random subsample of records ($n = 62$) was independently recoded by a second researcher using the same dictionary and the same frozen order. Agreement on the assigned cause was 93.5 per cent (58/62). This check shows that the published protocol can be applied consistently. It is not an independent test of a different coding scheme, and it does not establish the external validity of the seven classes.

The seven categories are a pragmatic coding scheme, not a set of mutually exclusive theoretical classes. Electrical hazards and gas hazards describe the service medium. Machinery operation and impact against/struck by describe the contact mechanism. Equipment misuse and installation errors describe antecedent practice. Unknown records the absence of a usable narrative. An incident can contain more than one of these elements. A single label was assigned because the study required a countable taxonomy for frequency analysis. The first-match order was fixed before coding so that more specific medium terms were tested

before generic contact terms. The published frequencies are therefore assignments under this frozen rule, not estimates of independent causal shares. A different order would reallocate some records, particularly between electrical hazards, machinery operation and impact against/struck by. The 10% dual-coding check tested consistency under the published order. It does not remove that order dependence.

3. Results

3.1. Results from All Incident Data Between 2016 and 2021

The dataset (comprising 624 incidents) was subjected to detailed analysis. Figure 1 depicts the frequency of utility strikes across various service types within UK highway projects where incidents occurred. The y-axis quantifies the number of incidents, while the x-axis categorises the affected service types, spanning 18 distinct classes identified in the data. Among these, communication underground services were the most frequently impacted, accounting for $f = 241$ (or 36.62%) incidents—a striking figure that underscores their prevalence and/or vulnerability. Low-voltage electric services followed with $f = 111$ (or 17.79%) incidents, trailed by water services with $f = 90$ (or 14.42%) incidents, both reflecting significant exposures to strikes. Low-pressure gas services and electric streetlight services also registered notable impacts, with $f = 66$ (or 10.58%) and $f = 51$ (or 8.17%) incidents respectively, rounding out the top five affected categories. In contrast, the remaining 13 service types exhibited far lower frequencies, with incident counts of $f = 13$ (or 2.08%), $f = 9$ (or 1.44%), $f = 8$ (or 1.28%), $f = 3$ (or 0.48%), $f = 2$ (or 0.32%) and $f = 1$ (or 0.16%), indicating a sharp decline in occurrence. Communication underground services recorded the highest count of strikes in the dataset (241 incidents; 36.62%). This frequency indicates where incidents were concentrated in the present sample rather than a tested measure of inherent vulnerability.

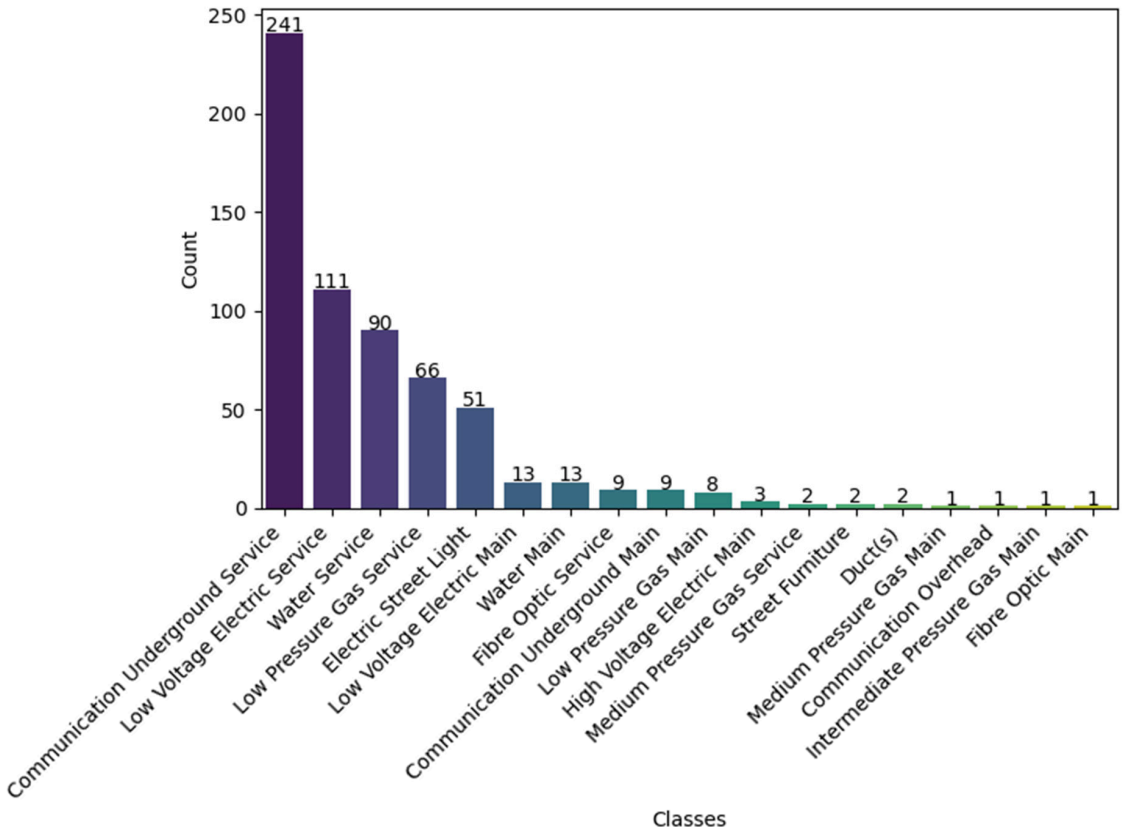


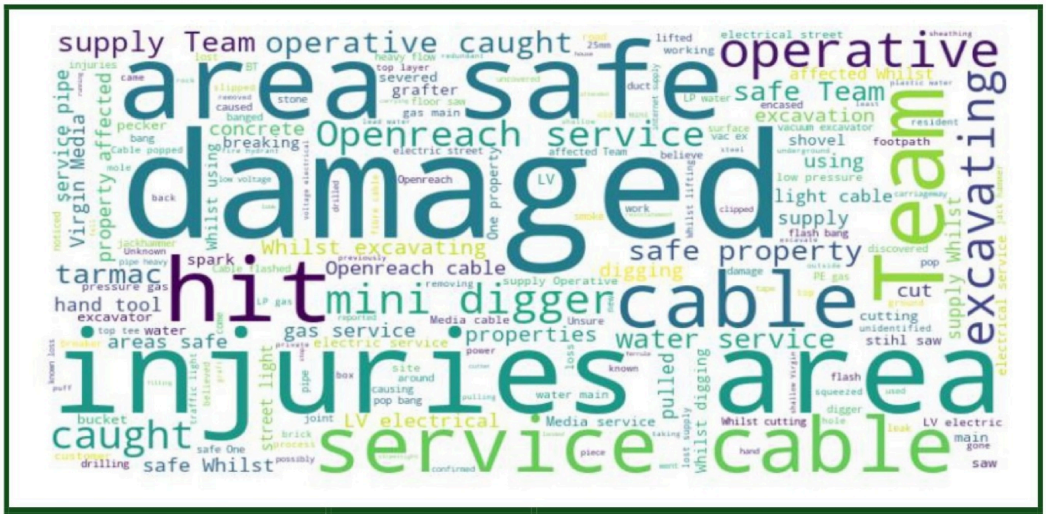
Figure 1. Different types of services.

Injury was recorded only in the lost-time subset. That subset comprises six case files. No injury was recorded among the 85 damage reports or the four dangerous-occurrence reports. With so few injury cases, body-part and injury-type counts cannot be generalised beyond this sample. The data analysis indicates that no injuries from dangerous occurrences were observed. In contrast, injuries were exclusively documented within the 'lost time' category, implying a direct correlation between the injuries sustained and the time lost from work—suggesting that the injuries were the primary driver (or sole reason) for the recorded lost time. Consequently, this finding prompted further investigation to thoroughly examine the nature and circumstances of the injuries sustained. The subsequent analysis pinpointed the specific body areas affected, identifying: (i) hand; (ii) thigh; (iii) ankle; (iv) back; and (v) foot as the most commonly injured parts of the body. Moreover, for each recorded injury, three predominant causes emerged: (i) electrical accidents (specifically shocks) ($f = 2$ or 28.56%); (ii) contact with tools or equipment ($f = 3$ or 42.88%) and (iii) impact against or being struck by objects ($f = 2$ or 28.56%).

Deeper investigation into the injury data illuminated the specific types of injuries sustained, yielding a detailed breakdown: (i) electric shock ($f = 1$ or 14.28%); (ii) laceration ($f = 2$ or 28.56%); (iii) bruising ($f = 1$ or 14.28%); (iv) fracture ($f = 1$ or 14.28%); (v) sprain ($f = 1$ or 14.28%); and (vi) a residual category encompassing other minor injuries ($f = 1$ or 14.28%). These insights not only clarify the injury mechanisms but also underscore the need for targeted preventive measures tailored to each cause and affected body area. To delve deeper into the incident reports documented in the 'Incident Detail' column, a word cloud was generated to spotlight the most frequently occurring keywords within the dataset—refer to Figure 2. Leveraging the most prominent keywords identified, a rule-based algorithm was subsequently applied to classify the incidents into distinct hazardous causes, facilitating a structured understanding of the underlying issues (cable ($f = 152$ or 12.5%): gas ($f = 89$ or 7.3%); damaged ($f = 74$ or 6.1%); overhead ($f = 65$ or 5.3%); digger ($f = 48$ or 3.9%); excavation ($f = 42$ or 3.5%); leak ($f = 40$ or 3.3%); pipeline ($f = 37$ or 3.0%); struck ($f = 34$ or 2.8%); and digging ($f = 32$ or 2.6%)).

The most frequent tokens map onto the seven cause categories as follows. Cable, overhead and electrical feed the electrical-hazard rule. Gas, leak and pipeline feed the gas-hazard rule. Digger and excavation feed the machinery-operation rule. Struck, hit, damaged and digging feed the impact against/struck by rule. Tokens that match none of the dictionary entries are assigned to unknown. Equipment misuse and installation error are rare in the narratives, which is consistent with their counts of one incident each.

At the heart of the word cloud, the term 'hit' emerges as the most striking feature, rendered in large, bold black letters near the centre. Its prominence underscores its role as the defining action in utility strikes, where equipment or operatives inadvertently make contact with underground utilities during excavation activities. This central theme is reinforced by other major keywords, including 'cable,' 'safety' and 'service,' which collectively frame the context of these incidents. 'Cable' recurs frequently, appearing in varying sizes and colours (e.g., green and blue), signalling its prevalence in strike reports. The term 'safe' stands out in green and blue hues, frequently paired with phrases like 'safe service' or 'safe team,' reflecting a strong emphasis on safety protocols aimed at preventing or mitigating strikes. Similarly, 'service' appears prominently in large green and blue fonts, often linked to specific utilities such as 'cable,' 'telecommunication,' 'gas' or 'electric,' pinpointing the types of infrastructure most affected.



Word	Count	Weighted Percentage (%)
cable	152	12.5%
gas	89	7.3%
damaged	74	6.1%
overhead	65	5.3%
digger	48	3.9%
excavation	42	3.5%
leak	40	3.3%
pipeline	37	3.0%
struck	34	2.8%
digging	32	2.6%

Figure 2. Word cloud of incident details.

The word ‘damaged’ displayed in bold red letters highlights that physical harm to buried services is a frequent outcome of utility strikes, with implications for repair costs and service disruptions. Another key term ‘excavation,’ identifies the primary activity during which these incidents occur, encompassing digging for highway construction, maintenance or upgrades. Terms like ‘operative’ and ‘team’ denote the workers or crews involved, emphasising the human element in these events. ‘Area,’ often tied to ‘safe area,’ suggests a focus on the spatial context of strikes, possibly indicating designated zones intended to reduce risk (e.g., excavator exclusion zones). Specific utilities such as ‘gas,’ ‘electric,’ ‘water,’ ‘BT’ (British Telecom) and ‘LV electrical’ (low-voltage electrical) appear in sizable blue and green fonts, delineating the assets most vulnerable to strikes and aligning with the high-incident services noted in prior analyses. Smaller, yet telling, keywords reveal the tools and consequences of these incidents. Terms like ‘digger,’ ‘mini digger,’ ‘shovel,’ ‘jackhammer,’ ‘saw’ and ‘hand tool’ pepper the cloud in less prominent sizes, indicating the tools and machinery commonly used during excavation that contribute to utility strikes. Their subdued presence suggests they are contextual details rather than the focal point. Similarly, ‘injuries,’ ‘property’ and ‘supply’ appear in smaller fonts, hinting at less frequent but critical outcomes (such as worker harm, structural damage, or service interruptions). Readable phrases scattered throughout, such as ‘whilst excavating,’ ‘safe area,’ ‘hit cable’ and ‘damaged service,’ weave these elements into coherent insights to show that utility strikes often occur during excavation despite safety measures implemented and result in tangible damage. Overall, Figure 2 crystallises the pivotal role of safety considerations

(e.g., 'safe,' 'safe area') and the actions of operatives utilising excavators and hand tools. It underscores the recurring damage to critical services (e.g., gas, electric, water) and the ripple effects of injuries or property damage albeit, though these appear secondary to the act of striking itself. This visualisation maps the linguistic landscape of utility-strike reports and lays the groundwork for targeted interventions which could include enhanced safety training to improved utility detection.

3.2. Causes of Incidents in UK Utility Strikes

Seven different causes were identified in the data analysis (refer to Table 2) *viz.*: (i) electrical hazards'; (ii) 'machinery operation'; (iii) 'impact against/struck by'; (iv) 'unknown'; (v) 'gas hazards'; (vi) 'equipment misuse'; and (vii) 'installation errors'. Electrical hazards account for the largest share of causes of incidents ($f = 296$ out of 624 or ~47%). Following it, machinery operation accounts for the second-largest share ($f = 181$ out of 624, or ~29%). Impact against/struck by ($f = 64$ out of 624) and gas hazards account ($f = 61$ out of 624) for ~10% of the causes of incidents. The remaining causes (equipment misuse and installation error) account for the smallest shares ($f = 1$ out of 624 or ~0.16%). The remaining 20 incidents (3%) were recorded as unknown.

Table 2. Causes of incidents in utility strikes.

#	Cause of Incident	Number (%)	Examples	Common Risk/Contribute Factors	Reference
1	Electrical Hazards	296 (47)	1. A contractor accidentally strikes a live cable while using a mechanical excavator due to outdated GIS records. 2. A worker receives an electric shock when attempting to manually dig near an unidentified power line. 3. Poor communication between the utility provider and contractors leads to misidentified cable locations, resulting in multiple strikes.	Inadequate mapping, GIS errors, improper isolation, lack of real-time detection tools, failure to update utility records, inconsistent data sharing between contractors and utility owners, poor training and insufficient adherence to safety protocols.	(Batra & Ioannides, 2001; Bates, 2009; Koschmann et al., 2022; Patel et al., 2022)
2	Machinery Operation	181 (29)	1. An excavator operator fails to use a GPR before digging, leading to a water main rupture. 2. A backhoe unintentionally severs a fibre optic line due to inadequate machine control and a lack of supervision. 3. A mechanical trenching machine damages a low-pressure gas pipeline because of incorrect excavation depth settings.	Improper handling of excavation equipment, operator error, poor supervision, equipment failure, lack of safety protocols, insufficient maintenance of heavy machinery, poor visibility, improper and rushed excavation planning and failure to use advanced detection systems.	(Suruda & Smith, 1992; Metje et al., 2015; Al-Bayati et al., 2022)
3	Impact Against/ Struck By	64 (10)	1. A worker using a shovel inadvertently punctures a buried gas pipe due to improper excavation practices. 2. A mini-digger operator fails to identify underground warning markers, resulting in a strike on a telecom cable. 3. Hand tools, such as jackhammers, are improperly used near underground utilities, leading to damage and service disruption.	Failure to enforce safe work zones, lack of PPE, inadequate signage, failure to follow non-destructive excavation techniques, poor visibility, crowded excavation sites, lack of worker awareness, improper use of hand tools in excavation sites and poor site planning.	(Metje et al., 2015; Koschmann et al., 2022; Al-Bayati et al., 2022; J. Li et al., 2025)

Table 2. *Cont.*

#	Cause of Incident	Number (%)	Examples	Common Risk/Contribute Factors	Reference
4	Unknown	20 (3)	1. A project site experiences a utility strike, but the exact cause remains unknown due to missing incident reports. 2. Poor record-keeping leads to uncertainty over whether a water main break was caused by excavation or pre-existing damage. 3. An underground electrical strike is classified as 'unknown' because no detection tools were used before digging.	Data gaps, missing reports, inconsistent incident reporting, poor incident documentation, lack of standardised reporting protocols, failure to identify underlying causes and insufficient investigation into utility strikes.	(Stillman & Darveniza, 1989; Bates, 2009; Hodder & Mustchin, 2024)
5	Gas Hazards	61 (10)	1. A gas pipeline explosion occurs after an excavator punctures a high-pressure gas line due to inaccurate utility markings. 2. A contractor mistakes a disused gas main for an inactive pipeline and unintentionally causes a hazardous leak. 3. Workers fail to follow non-destructive excavation methods, leading to a rupture in a natural gas supply line.	Inaccurate pipeline records, improper excavation, outdated maps, inadequate pressure monitoring, failure to implement protective measures such as non-destructive digging and incorrect utility location markings (misidentified utility lines).	(Madden, 2017; Metje et al., 2015)
6	Equipment Misuse	1 (0.16)	1. A worker misuses a pneumatic drill near a utility trench, leading to unintended cable damage. 2. An untrained employee operates a vacuum excavator improperly, causing an underground water pipe to crack. 3. A hydraulic breaker is used near an underground telecom duct, resulting in service interruption.	Tool mismanagement, inadequate training, incorrect tool use, improper tool selection, failure to adhere to operating procedures, improper handling of excavation machinery and failing to use appropriate techniques and tools in sensitive excavation zones.	(Suruda & Smith, 1992; Jackson, 2020; Al-Bayati et al., 2022;)
7	Installation Errors	1 (0.16)	1. A newly installed electrical conduit is placed too shallow, making it vulnerable to future excavation damage. 2. Inaccurate installation records lead to an underground sewer pipe being mistakenly identified as a gas line. 3. A major road project experiences repeated utility strikes due to errors in utility depth alignment and mapping discrepancies.	Incorrect utility installation, mapping errors, inaccurate as-built records, improper depth alignment, failure to follow engineering standards, inadequate quality control during installation projects, poor workmanship and inconsistencies in utility mapping.	(Madden, 2017; Barrett et al., 2010; Koschmann et al., 2022; Zhang & Lin, 2025)

To visualise the relationship between service types and the hazardous causes of incidents prone to these services, a heatmap (refer to Figure 3) was generated to understand the connection between these two variables (service type and causes). It was observed that communication underground services are prone to electrical hazards ($f = 181$ or 29%) the most. Low-pressure gas services are prone to gas hazards ($f = 41$ or 6.57%) and machinery-operation hazards ($f = 25$ or 4%). Water services are also prone to impact against/struck by hazards ($f = 39$ or 6.25%) where the incident involves an impact from an object.

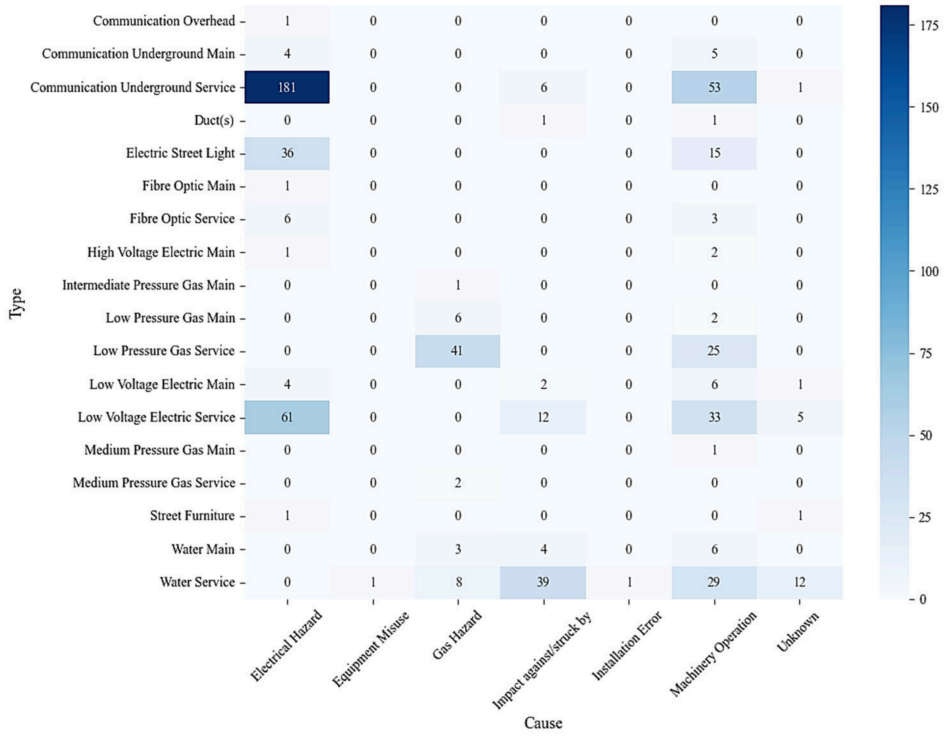


Figure 3. Heatmap of service type vs. causes.

Figure 3 shows that the most frequent co-occurrences are communication underground service with electrical hazards, low-voltage electric service with electrical hazards, and communication underground service with machinery operation. These are the largest cell counts in the sample. They are descriptive patterns only and are not presented as statistically tested associations. Similarly, 'low-voltage electric service' paired with 'electrical hazards' reflects the inherent risk of working near live circuits, even at lower voltages, where arcing or unintended contact can occur (Bindi et al., 2023). Linkage between 'communication underground service' and 'machinery operation' suggests that excavation or mechanical interference frequently disrupts these buried lines, possibly due to their shallow placement or inadequate marking.

Other high-risk combinations identified in Figure 3 include: 'low-pressure gas service' and 'gas service', 'water service' and 'impact against/struck by', 'electric streetlight' and 'electrical hazards', 'low-voltage electric service' and 'machinery operation' and 'water service' and 'machinery operation'. The 'low-pressure gas service' and 'gas service' pairing likely indicates incidents where gas lines are mistaken for one another or where a strike on one triggers a broader gas-related hazard, such as leaks or ignition risks. 'Water service' combined with 'impact against/struck by' points to physical damage from tools or equipment, potentially fracturing pipes during excavation or trenching. 'Electric streetlight' and 'electrical hazards' aligns with the exposure of street lighting circuits to damage during maintenance or nearby works, while 'low-voltage electric service' and 'water service' tied to 'machinery operation' underscore the vulnerability of these utilities to mechanical mishandling, such as over-digging or misalignment of equipment. Additionally, Figure 3 highlights high-risk combinations with lower frequency but notable concern: 'low-pressure gas service' and 'machinery operation', 'electric streetlight' and 'machinery operation', 'low-voltage electric service' and 'impact against/struck by', 'low-voltage electric main' and 'machinery operation' and 'low-pressure gas main' and 'gas service'. These less frequent pairings still warrant attention. For instance, 'low-pressure gas service' and 'machinery operation' might reflect occasional but severe incidents where gas lines are ruptured by

heavy equipment, while 'low-voltage electric main' and 'machinery operation' could involve deeper infrastructure damaged during piling or drilling. The recurrence of 'machinery operation' across these combinations suggests a broader mechanical risk factor that transcends specific service types.

Moreover, the rows with multiple dark spots (i.e., communication underground service, electric streetlight, low-pressure gas service, low-voltage electric service and water service) in Figure 3 show where incident counts are concentrated by service type. For example, 'water service' is linked to all causes of incidents except 'electrical hazards', which indicates that this service type has systemic issues across causes. This broad susceptibility could arise from the widespread presence of water pipes in highways projects, their varying depths (Sahle & Aregawi, 2021) and the physical fragility of older infrastructure (Cavalieri et al., 2012), making them prone to impacts, machinery damage and gas-related confusion (e.g., mistaken for gas lines). Similarly, 'low-voltage electric service' is another critical example, linked to 'electrical hazards', 'impact against/struck by', 'machinery operation' and 'unknown' causes. This pattern indicates that low-voltage systems, often implemented in dense urban networks, encounter various hazards, including the impact from tools, electrocution from live wires, mechanical failures and unidentified factors potentially. Furthermore, 'communication underground service' and 'low-pressure gas service' are highlighted by two dark spots, indicative of their inherent systemic issues, namely shallow burial depths and frequent co-location with other utilities. Furthermore, columns that appear dark across several rows indicate that specific incident types (e.g., those caused by machinery) frequently affect many different service types, revealing common risk patterns. For instance, 'machinery operation' affects most of the services, appearing as a high-intensity column with dark cells spanning 'communication underground service', 'low-voltage electric service', 'water service', 'low-pressure gas service', 'electric streetlight' and 'low-voltage electric main'. This pervasive influence suggests that operator error, inadequate equipment controls, or lack of real-time utility detection during mechanical work are systemic issues. It suggests a need for enhanced training, stricter oversight and possibly the adoption of technologies like machine-mounted utility locators to mitigate risks across the board. Similarly, 'electrical hazards' shows strong intensity with electrically oriented services ('low-voltage electric service', 'electric streetlight', 'communication underground service'), indicating that live circuits remain a persistent danger, necessitating improved isolation procedures or better worker awareness of electrical proximity.

Expanding on these observations, the heatmap also implies interplay between causes. For instance, 'machinery operation' and 'impact against/struck by' frequently affect similar utility services (e.g., low-voltage electric service and water service). It indicates that addressing one cause could reduce others. Likewise, 'unknown' causes linked to 'low-voltage electric service' might reflect gaps in incident reporting or detection, a problem that could exacerbate other risks if left unaddressed. This co-occurrence of categories underscores the complexity of utility strikes and the need for a holistic approach to prevention.

Cumulatively, these insights offer actionable guidance for UK highways project stakeholders. High-risk pairings like 'communication underground service' and 'electrical hazards' call for better utility mapping and clear physical or procedural barriers to prevent interference between utility types, while the dominance of 'machinery operation' across services demands improved operator training and equipment safeguards. Service-specific vulnerabilities, such as those in 'water service' and 'low-voltage electric service', highlight the urgency of tailored risk assessments and mitigation strategies for these utilities. Patterns driven by specific causes in utility strikes reveal the urgent need for targeted systemic solutions to mitigate risks effectively. For instance, enhanced survey accuracy for 'inaccurate records', procedural enforcement for 'unsafe practices' and technology upgrades for 'ma-

chinery operation' can ensure that precise causes of incidents in utility strikes can be covered effectively. These results not only pinpoint the most hazardous intersections of service types and incident causes but also reveals broader trends in UK utility strikes. By focusing on the most critical areas of the heatmap and addressing the fundamental patterns, industry leaders may prioritise measures such as pre-work geophysical surveys and real-time monitoring to mitigate events, enhance safety and improve project efficiency. This heatmap serves as a critical tool for evidence-based decision-making in utility-strike prevention. The analysis is descriptive. Frequencies, percentages and the heatmap summarise the observed distribution and do not constitute inferential tests of association. This heatmap serves as a critical tool for evidence-based decision-making in utility-strike prevention. The analysis is descriptive. Frequencies, percentages and the heatmap summarise the observed distribution and do not constitute inferential tests of association. For interpretation, a cell is treated as a high-count pairing when it is among the largest observed frequencies in Figure 3, namely communication underground services with electrical hazards ($f = 181$), low-pressure gas services with gas hazards ($f = 40$), and water services with impact against/struck by ($f = 39$). No chi-square or residual test is reported. The pairings are descriptive only.

4. Discussion

Utility strikes threaten critical infrastructure utility services and each disruption bears unique implications for public safety, economic stability and societal function (ICE, 2017). Although the consequences differ by service type, their causes frequently converge on systemic and operational deficiencies (Kovvali & Macey, 2023). Analysis of UK utility-strike case studies delineates seven incident categories *viz*.: electrical hazards; machinery operation; impact against/struck by; unknown; gas hazards; equipment misuse; and installation errors. This taxonomy not only elucidates the underlying causes of these incidents but also reveals their interdependence, offering a robust framework for crafting prevention strategies that tackle both immediate risks and entrenched vulnerabilities.

The findings point to three high-level pillars that later structure IUSAF: information accuracy and accessibility; human-centric design and training; and systemic integration and oversight. Information accuracy responds to the concentration of electrical-hazard records on communication and low-voltage services. Human-centric design and training respond to machinery operation and impact incidents. Systemic integration and oversight respond to incomplete narratives and the unknown category. Expert ranking of 33 strike causes on UK highway projects places failure to follow a safe system of work, poor familiarity with site controls and inadequate buried-service drawings above isolated worker error (Sarvari & Edwards, 2026). That ordering is consistent with the present counts, in which electrical hazards and machinery operation dominate the recorded narratives.

Electrical hazards constitute a prominent category in utility strikes, frequently arising from unintended contact with live electrical cables, which can lead to severe injuries or fatalities (Bortey et al., 2025). These incidents stem from an interplay of factors, including inadequate utility mapping (Arun et al., 2021), insufficient safety equipment (Bourassa et al., 2016) and human error (Sarvari et al., 2024a). Research underscores their prevalence; for instance, Koschmann et al. (2022) found that errors in GIS often produce inaccurate location data thus, heightening electrical risks. Similarly, Yadav et al. (2022) emphasised that tools like GPR and precise utility mapping are vital to mitigate these hazards. Addressing electrical risks demands accurate utility maps communicated clearly to contractors, alongside strict adherence to safe practices (such as non-destructive digging and comprehensive worker training) to substantially lower incident rates. Electrical hazards are extensively documented across industries as causes of incidents. Bates (2009) highlights their propensity for severe injuries or fatalities, stressing risk management, while Batra

and Ioannides (2001) note a global decline in fatal electrical accidents in energy sectors, reflecting improved practices. The case studies emphasise that electrical hazards align with the literature, reinforcing the urgency of robust safety measures (such as precise utility mapping) to mitigate these pervasive risks. Mitigation requires accessible, accurate utility maps for contractors, reinforced by non-destructive digging, real-time detection tools and comprehensive training. The UK HSE reports frequent electrical strikes during rushed urban excavations, endorsing pre-work verification like the 'Safe Dig' initiative (Jackson, 2020). Bates (2009) supports this view and highlights the high risk of serious injury associated with such incidents, advocating for stronger risk-management practices, while Batra and Ioannides (2001) observe a global decline in fatal incidents, reflecting improved isolation protocols. The present study's results align with HSE data identifying electrical hazards as a primary injury source, suggesting that proactive maintenance (e.g., inspecting cable insulation) could further curb degradation-related risks often neglected under project deadlines. This convergence underscores the need for integrated safety systems to address both human and infrastructural factors (Mitsova, 2021).

Machinery operation ranks as another critical category, typically linked to improper use of equipment during excavation or construction (Koschmann et al., 2022). Heavy machinery, such as mechanical excavators, often strikes underground utilities, endangering workers and damaging infrastructure (Metje et al., 2015). In 2022, an excavator severed a power line on the M25 motorway in the UK and exemplifies the £1.5 billion annual cost of such delays. Utility locators and GPR systems can pinpoint buried assets and reduce risks (Yadav et al., 2022), while regular machinery maintenance and enhanced operator training are essential to curb accidents (Yadav et al., 2022; Al-Bayati et al., 2022). These measures could mitigate the costly delays and safety threats posed by machinery-related strikes. In other similar research, Lowder (1993) details a welding machine incident causing severe injury due to improper operation, underscoring safety protocol failures. Suruda and Smith (1992) link portable power tools to a significant share of construction-related electrocutions, implicating equipment design and operator error. The case studies' focus on machinery operation echoes these findings, highlighting human error and equipment factors as key drivers, necessitating enhanced training and supervision and design improvements such as machine-mounted sensors. Such measures have cut strikes by 20% in Scandinavian trials (Batlle & Pérez-Arriaga, 2008) and align with the HSE's call for smarter practices (Edwards et al., 2020), indicating that technological and procedural upgrades could yield significant safety and economic gains.

Impact against/struck by encompasses collisions between workers, equipment and/or tools and utilities, yielding injuries, fatalities or damage. Misuse of equipment and/or tools (particularly hand tools and excavators) dominates this category, often striking utility lines or pipes (Metje et al., 2015; Koschmann et al., 2022). Non-destructive digging techniques offer a proven countermeasure, minimising accidental contact (Yadav et al., 2022). Training workers on proper tool handling can significantly reduce these risks, addressing a key driver of physical harm and service disruption (Al-Bayati et al., 2022). Though not explicitly categorised, Bourassa et al. (2016) connect equipment failures to industrial accidents, including strikes by machinery or objects. Wijeratne et al. (2014) identifies physical hazards as a major threat to distribution workers during maintenance. By isolating this category, the case studies expose a literature gap, calling for targeted research into physical impact incidents in utility contexts beyond generalised equipment failure discussions. Training must emphasise situational awareness (e.g., utility marker recognition), while wearable sensors (cf. Tavanti et al., 2024) could provide proximity alerts. The category's prominence suggests a UK-specific issue, possibly due to dense utility networks, necessitating targeted research and guidelines beyond generic safety protocols.

Gas hazards present a severe category, typically involving damage to gas lines during excavation, which can trigger leaks, explosions or fires with devastating consequences (Chen et al., 2024). Metje et al. (2015) highlight cases where gas strikes led to fatalities and property loss, emphasising the stakes involved. Prevention hinges on accurately mapping gas lines, communicated effectively to contractors, alongside non-destructive digging and safety gear (Koschmann et al., 2022). Regulatory tools like one-call services exemplify how pre-work utility verification can avert such disasters (Hayes & McDermott, 2018). Gas hazards are well-recognised in utility operations. Madden (2017) examines risks in explosive atmospheres, advocating preventive measures, while Wijeratne et al. (2014) flags gas-related dangers during maintenance. Consistent with the literature, the case studies affirm gas hazards as a priority, emphasising proper equipment installation and maintenance to avert catastrophic leaks or explosions. Real-time gas detectors (mandatory in some EU nations) and stricter HSE Gas Safety Regulation enforcement could enhance prevention (Osei-Asibey et al., 2021; Acheampong & Kemp, 2022), while co-location risks (i.e., gas near electrical lines) suggest integrated multi-utility mapping. This gap in current standards highlights a need for holistic risk assessment to prevent cascading failures.

Equipment misuse, which reflects improper tool or machinery handling during excavation, damages utilities. This category overlaps with machinery operation but focuses on operator error or neglect rather than equipment type. Proper training, routine scheduled equipment maintenance and adherence to safety protocols are critical to reducing these incidents (Edwards et al., 1998; Yadav et al., 2022). Complementing these efforts with utility locators and GPR can further minimise accidental strikes, addressing a preventable yet persistent risk (Al-Bayati et al., 2022). Equipment misuse is a recurrent theme in the extant literature. For example, Jackson (2020) recounts an electrician's injury from mishandling high-voltage gear, spotlighting human error. Suruda and Smith (1992) tie portable tool misuse to electrocutions, often due to inadequate safety adherence. This current research reinforces these previous findings, advocating for rigorous training and protocol enforcement to curb preventable misuse incidents. Annual competency certifications and digital tool-use logs could ensure adherence, addressing cultural drivers like haste or lax oversight evident in the case studies. This blend of behavioural and technical interventions offers a nuanced approach to a persistent challenge.

Installation errors arise from mistakes during utility placement, such as inaccurate GIS data or incomplete maps, which later increase strike risks during excavation (S. Li, 2014). Koschmann et al. (2022) note that flawed location data compounds this issue, while advanced technologies like GPR can enhance mapping accuracy (Yadav et al., 2022). Ensuring up-to-date utility records and enforcing strict installation standards are essential to break this cycle of error propagation, reducing future vulnerabilities (Al-Bayati et al., 2022). Installation errors significantly contribute to electrical incidents. Madden (2017) stresses compliance with installation standards, while Barrett et al. (2010) tie poor installations to electrical incidents. This evidence is consistent with the focus of this research on installation errors, highlighting the need for meticulous inspections and adherence to standards to prevent future risks. Blockchain-based registries could secure records and post-installation audits might catch errors early. The case studies demonstrate that utility maps are often disjointed and unclear due to management and oversight by multiple corporate entities. This highlights the need for a centralised national database to unify utility data as a long-term solution to ongoing legacy challenges.

The **unknown** category captures incidents with unclear causes, often due to incomplete data or inconsistent reporting (Bates, 2009). Hodder and Mustchin (2024) argue that non-standardised reporting obscures incident analysis, relegating events to this ambiguous group. Improving data collection through standardised formats and robust management

systems can clarify these cases, enabling better prevention (Osei-Asibey et al., 2021). The literature rarely addresses 'unknown' incidents directly. Stillman and Darveniza (1989) explore unpredictable power system failures, while Bates (2009) critiques deficient reporting systems that obscure causes. Stillman and Darveniza (1989) link adverse weather to power system failures, suggesting an environmental dimension overlooked in the case studies. This highlights a serious data quality crisis. Real-time logging apps (Wu et al., 2022) and weather-risk assessments could refine analysis (Zhang & Lin, 2025) addressing both procedural and environmental gaps overlooked in current frameworks.

5. Integrated Utility-Strike Avoidance Framework (IUSAF)

Figure 4 depicts a theoretical IUSAF that integrates technological, regulatory and human-centric measures, informed by the case study findings, to reduce the frequency and severity of utility strikes. The framework is distinguished from generic utility-strike guidance by the way its components are mapped onto the seven cause categories and the service types that dominated the present dataset. Electrical hazards and communication and low-voltage services inform the emphasis on mapping accuracy, isolation and machine-mounted detection. Machinery operation and impact incidents inform the emphasis on operator competency and non-destructive excavation. The unknown category informs the emphasis on fuller incident reporting. IUSAF is therefore a synthesis organised around these empirical concentrations. It has not been trialled as an intervention and no claim is made that it will remove utility strikes. Effective prevention requires coordination between accurate mapping (Yadav et al., 2022), strict pre-excavation protocols (Khorrami Shad et al., 2025), advanced on-site technology (Newman et al., 2021), competent people (Yadav et al., 2022), safe excavation techniques (Al-Bayati et al., 2022), diligent post-installation practices (Koschmann et al., 2022) and continuous learning from incidents (Bayramova et al., 2024a). The framework pertains to proactive safety procedures and practices, referred to in the literature as Safety II (Sarvari et al., 2024b). Each component is detailed in the following sections.

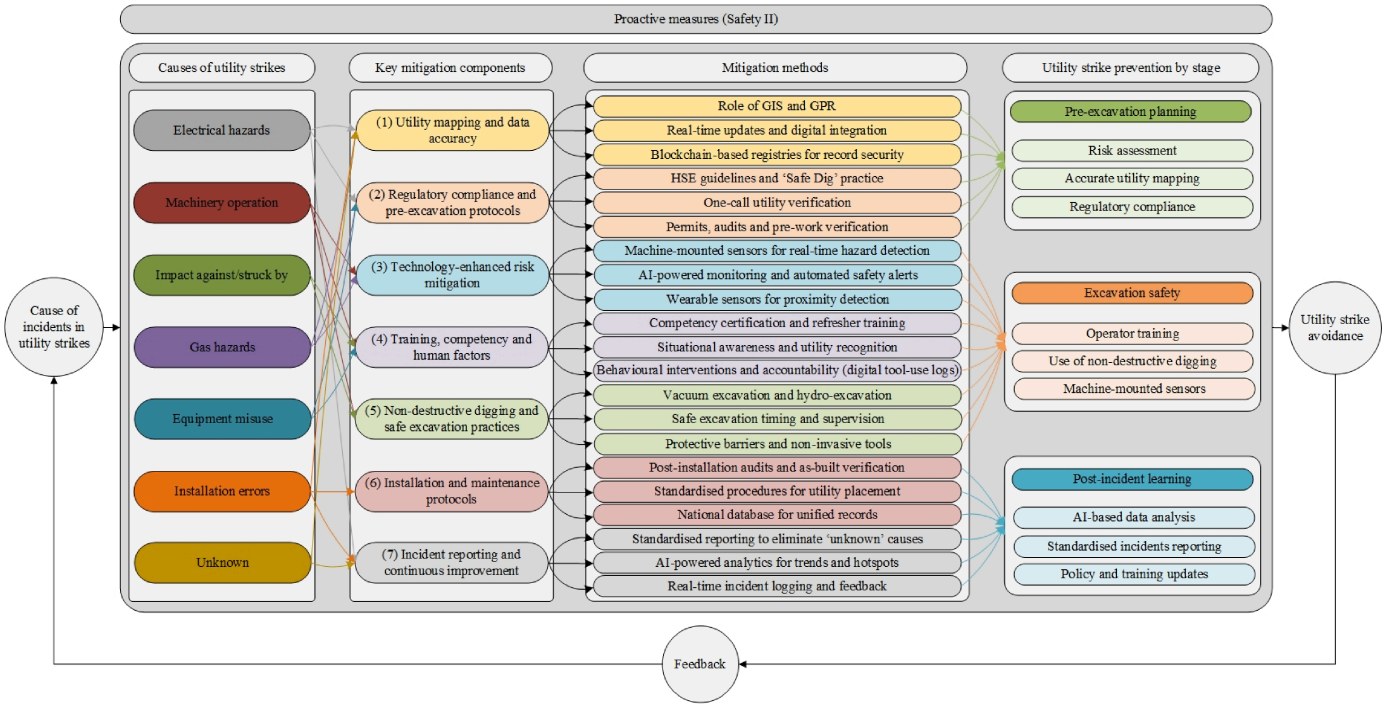


Figure 4. Integrated utility-strike avoidance framework (IUSAF).

5.1. Utility Mapping and Data Accuracy

Role of GIS and GPR: Accurate underground utility maps form the foundation of strike avoidance. Projects should employ GIS to compile all known utility records and use GPR and electromagnetic locators to detect unknown or inaccurately mapped services (S. Li, 2014). This ensures a high-confidence 3D map of buried pipes and cables. Early and precise mapping allows designers to eliminate clashes by rerouting works away from utilities wherever possible, removing the hazard altogether at the planning stage (Osman & El-Diraby, 2007).

Real-time updates and digital integration: Utility data must be kept current (Maree et al., 2021). A centralised digital map (ideally cloud-based) should be updated in real time as utilities are exposed, moved, installed or removed (Luo et al., 2015). This means surveyors and crews update the GIS immediately when on-site findings differ from records (Ames et al., 2020). Real-time integration with construction Building Information Modelling (BIM) models is also encouraged, so that as-built utility data feeds into the project's 3D models for use by site engineers and machine control systems (Rashidi et al., 2026). By having a living digital twin of underground utilities, crews can trust that what they see on their tablets or machine guidance systems (Rashidi et al., 2026).

Blockchain-based registries for record security: To further improve data confidence and sharing, blockchain technology has been proposed for utility record management (Ameyaw et al., 2023). Asset owners often hesitate to share underground data due to security and liability concerns (Hansen & Pang, 2023). A blockchain-based registry creates an immutable ledger of utility information that multiple parties can trust (Javaherikhah et al., 2025). Once a utility's location or attribute is recorded on the blockchain, it cannot be altered unnoticed, ensuring integrity of records. This secure, distributed approach could unify utility maps across multiple companies (Alnahari, 2023). Although still an emerging concept, such technology could give clients, contractors and utility owners greater confidence in the accuracy of shared plans, knowing they are viewing the single source of truth for underground assets (Alnahari, 2023). Immutable records also aid investigations and lessons learned after projects (Mourtzis et al., 2019).

5.2. Regulatory Compliance and Pre-Excavation Protocols

HSE guidelines and 'Safe Dig' practice: Regulatory compliance sets the minimum standard that all projects must meet before breaking ground (Fine, 2017). Project clients and principal contractors should identify underground service risks and take steps to avoid them (Koschmann et al., 2022). This means no excavation should start until all reasonable checks for buried services are completed and a safe dig plan is in place (Tanoli et al., 2019).

One-call utility verification: Before any excavation, workers must verify and mark the location of all utilities on site (Al-Bayati & Panzer, 2020). This method is sometimes referred to as a 'one-call' system and is considered as a mandatory standard of practice in many countries (Hayes & McDermott, 2018). This aligns with the HSE guidance that all underground services must be identified and communicated to those breaking out ground to expose utilities (Hayes & McDermott, 2018).

Permits, audits and pre-work verification: After utilities are identified, a formal permit-to-excavate (or permit-to-work for ground penetration) protocol should be enforced (Biber & Ruhl, 2014). A permit system acts as a checklist to verify that all preventative steps have been implemented before digging. On UK highway projects, permits must be raised and authorised by competent persons—for example, a Permit Raiser collects all utility information and a Permit Authoriser checks it and approves the excavation with specific controls (Yadav et al., 2022).

5.3. Technology-Enhanced Risk Mitigation

Machine-mounted sensors for real-time hazard detection: Advanced sensing technology on excavation equipment can drastically reduce strikes by providing live warnings (He et al., 2023). Such machine-mounted proximity sensors essentially convert the excavator into a giant cable locator, continuously scanning the dig area and alerting the operator before a strike occurs (Gallwey, 2021). Other innovations include hydraulic excavators with built-in auto-stop features tied to geofencing—if the machine's GPS indicates it is within a forbidden zone, the machine can slow or lockout further movement, forcing the operator to reassess the potential hazards of utility strikes (Ames et al., 2020).

AI-powered monitoring and automated safety alerts: Artificial intelligence (AI) and computer vision are being leveraged to monitor excavation work and flag dangers that humans might miss (Oguntoye et al., 2023). AI video analytics (using convolutional neural networks) are also emerging; cameras on site can live-monitor excavations and use machine learning to recognise unsafe practices (Drage & Frabetti, 2024). Another AI application is predictive analytics on past strike data. Algorithms can identify patterns (e.g., strikes are more likely at end of shifts) and proactively alert managers to intervene (Drage & Frabetti, 2024).

Wearable sensors for proximity detection: Human workers on site can also be protected by wearable tech that prevents close calls between personnel, plant and utilities (Patel et al., 2022). This concept can be extended to underground hazards, e.g., a utility line could be outfitted with a localised Radio Frequency Identification (RFID) beacon during exposure and workers' wearables would alert if they approached the live line (Tavanti et al., 2024). Wearables thus heighten situational awareness by cutting through site noise with a direct warning (i.e., noise, lights and/or vibration) to those at risk (Patel et al., 2022). Besides preventing machinery strikes on workers, the data from these proximity systems is logged (Patel et al., 2022). Site managers can review 'proximity breach' events via a dashboard, helping identify if certain teams (or individuals) frequently encroach on no-go utility zones. Indeed, these recorded proximity data can be analysed to identify patterns of unsafe behaviour and inform targeted safety interventions.

5.4. Training, Competency and Human Factors

Competency certification and refresher training: Human error and lack of skills are underlying factors in many utility strikes, so continuous training is paramount (Sarvari et al., 2024a). This ensures everyone understands the dangers of utility strikes and knows how to interpret utility plans and use locators properly (Koschmann et al., 2022). By having a formally certified and regularly re-evaluated workforce, the likelihood of procedural mistakes drops significantly (Pasha et al., 2024).

Situational awareness and utility recognition: Even with maps and tools, workers on the ground need keen situational awareness to notice risks and hazards and respond appropriately (Yadav et al., 2022). The model emphasises training in utility marker recognition and on-site clues. Fostering a vigilant mindset (sometimes termed a 'stop and think' culture) is critical (Gillespie et al., 2022). This ties into human factors such as minimising time pressures and encouraging questioning attitudes, so that no one feels they must 'dig blind' to stay on schedule. An organisation that creates psychological safety (MG et al., 2025) enables workers to challenge bad behaviours and reinforce good ones without risk or fear of reprisal (Lee, 2021). By improving awareness and caution on the ground, many strikes can be averted (Sarvari et al., 2024a).

Behavioural interventions and accountability (digital tool-use logs): Human nature can lead to shortcuts, especially under schedule pressure (Liu et al., 2021). To counter this, the model includes behavioural safety interventions essentially, systems that track and enforce the desired behaviours (Bisbey et al., 2021). A prime example is the use of data-logging

cable locators (Mologni et al., 2021). Another behavioural tool is digital checklists or apps that workers must complete before digging. Integrating human factors engineering by using logs, checklists and feedback helps close the gap between having the 'right process on paper' and 'doing it right in practice' (Botti et al., 2022).

5.5. Non-Destructive Digging and Safe Excavation Practices

Vacuum excavation and hydro-excavation: Traditional mechanical digging near utilities carries a high strike risk, so the model prioritises non-destructive digging methods whenever feasible (Janjua, 2014). Unlike a metal excavator bucket, a vacuum excavation hose is unlikely to break a cable; at most it might slightly nick a utility. Many case studies (especially in congested city street works) show vacuum excavation reduce the frequency and severity of utility strikes to zero when used properly (Al-Bayati et al., 2022).

Safe excavation timing and supervision: Even with the right methods, when and how excavation is performed can influence strike likelihood. The model incorporates strict supervision during any excavation near utilities, especially at critical times (Koschmann et al., 2022). Additionally, scheduling of excavation work can be a mitigation: for instance, doing the most hazardous digging at times of lower site activity (to minimise distractions and pressure) (Janjua, 2014). Off-peak working (e.g., night work on live highways) often means less rush but it introduces other risks (fatigue, poor visibility). With vigilant supervision and carefully chosen timing, the chance of errors leading to a strike is greatly reduced (Yadav et al., 2022).

Protective barriers and non-invasive tools: The model promotes using physical and procedural barriers to protect known utilities during excavation (Pinkiewicz et al., 2024). Once a utility is located, it should be positively identified and safeguarded before proceeding (Al-Bayati et al., 2022). This can include placing barrier tape, temporary coverings or enclosures around the exposed asset (Yadav et al., 2022). By using shovels and spades with insulated handles and blades, workers are more protected from electrocution and are less likely to cut a cable compared to using sharp metal tools. Finally, procedural tools like a 'use of tool of choice' protocol can help ensure that workers select the safest and most appropriate equipment when working near exposed utilities, thereby reducing the risk of accidental damage or injury (Bali et al., 2021).

5.6. Installation and Maintenance Protocols

Post-installation audits and as-built verification: Avoiding strikes is not only about existing utilities but also ensuring that new or diverted utilities are left in a safe state for the future (Koschmann et al., 2022). The model includes formal post-installation checks whenever utilities are installed, moved or exposed during a project. This involves surveying the final position and depth of the utility and comparing it to the plan (Metje et al., 2015). Additionally, every utility intervention in the project goes through a 'QA/QC' (Quality Assurance/Quality Control) process just like any construction element, to verify it will not become the source of a future strike due to poor documentation or installation error (Forbes & Ahmed, 2020).

Standardised procedures for utility placement: Consistency in how utilities are laid out within highway corridors can greatly aid in avoiding strikes (Apak et al., 2022). The model endorses adhering to national standards and codes of practice for utility positioning (Apak et al., 2022). Another procedural element is ensuring spatial separation and orderly trenching when multiple utilities are installed together. Clustering utilities haphazardly can make one dig threaten several lines at once; hence, it is better to follow a structured arrangement (Dechamps, 2024). Overall, standardised installation practices today prevent strikes tomorrow by making utilities easier to locate, identify and avoid (Metje et al., 2015).

National database for unified records: Akin to other countries, a longstanding issue in the UK has been fragmented utility record. Indeed, each company holds its own plans, in various formats and accuracies (Metje et al., 2015). The theoretical model underscores the creation and use of a national utility database that unifies this information for easy access by excavators. Standards essentially establish a common language and format for utility records so they can interoperate between different GIS and databases. In essence, a unified record system greatly complements site-level efforts in strike avoidance (Meis et al., 2023).

5.7. Incident Reporting and Continuous Improvement

Standardised reporting to eliminate 'unknown' causes: There is much to learn from a utility strike, not least how to avoid such incidents in the future (Sarvari et al., 2024b). A major impediment to industry learning has been inconsistent incident reporting; if the cause or circumstances of a strike are not recorded clearly, it is hard to prevent a repeat. The model therefore requires the use of standardised reporting formats for any utility strikes or near-misses (Tamascelli et al., 2022). By reducing 'unknown' classifications, the cause(s) of strike can be better determined. Essentially, standardised reporting turns every strike into a data point for learning, rather than a lost anecdote.

AI-powered analytics for trends and hotspots: With a rich dataset of standardised reports, the model leverages modern data analytics (including AI) to glean insights and predict risks (Bayramova et al., 2024b). Machine learning algorithms can be used to identify correlations (time of day, type of utility, method used, crew experience, etc.) with higher strike rates (Bortey et al., 2024). Armed with this intelligence, stakeholders can take proactive measures: focusing training where needed most, improving records in certain zones, or enhancing monitoring for specific activities. AI can also help predict the likelihood of a strike on a given planned excavation. By inputting factors like utility density, contractor history and soil conditions, AI could generate a risk score and recommended controls (Bortey et al., 2024). Essentially, analytics turn raw data into actionable knowledge, creating a feedback loop for continuous improvement (Sarvari et al., 2024b).

Real-time incident logging and feedback: To support timely reporting and learning, the framework employs real-time logging of incidents via digital applications. By having a real-time log, trends can be monitored almost live (Botti et al., 2022). Integrating the logging system with notification workflows means utility owners are informed instantly of any damage to their asset, improving emergency response. Furthermore, the existence of a continuous improvement cycle (i.e., report, analyse, improve and implement in a loop) is important (Sarvari et al., 2024b). By learning from every mistake (and near-mistake) and rapidly updating training, guidelines and technology in response, the industry can continuously drive down utility-strike rates (Sarvari et al., 2024b).

The seven components above form an integrated model for utility-strike avoidance. Each element is essential and must act in unison. Crucially, they interconnect *viz*.: accurate mapping (component 1) underpins effective permits (component 2); advanced tech (component 3) supports workers and training (component 4) in the field; safe excavation methods (component 5) rely on good data (component 1) and competent crews (component 4); proper installation practices (component 6) feedback into better maps (component 1) and fewer future incidents (component 7); and reporting and analytics (component 7) highlights where mapping or training needs to improve (closing the loop). By addressing the issue from all angles (i.e., technological, regulatory and human) the model aligns with best practices to reduce the frequency and severity of utility strikes on highway projects. Adopting this comprehensive IUSAF will help project teams 'dig safe' every time, protecting lives and infrastructure while keeping projects on track. To adopt this model, project teams must incorporate all seven components into their planning and execution workflows,

ensuring that each element is not treated in isolation but as part of a cohesive strategy. This includes embedding accurate utility mapping into early design stages, enforcing robust permitting processes, deploying advanced technologies on site, delivering targeted training to field crews, applying safe excavation methods, adhering to proper installation standards and maintaining continuous reporting and analytics. By integrating these interrelated components into everyday operations, teams establish a feedback-orientated system that perpetually enhances safety performance. This dynamic framework enables project managers to make informed, proactive decisions, respond to emerging risks in real time and foster a culture of accountability and continuous improvement that ultimately mitigates the danger of utility strikes across all phases of the project lifecycle. Indeed, the adoption of the IUSAF provides a robust, holistic pathway to reduce the frequency and severity of utility strikes. By leveraging IUSAF, stakeholders can safeguard critical infrastructure and enhance public safety.

Implementation Sequence and Safety-II Alignment

Near-term actions can be taken with existing duties and plant. They include tighter permit-to-dig checks, confirmation of marked services before excavation, operator refresher training focused on electrical and machinery incidents, and trial use of machine-mounted proximity sensors on high-count routes. Longer-term actions require institutional change. They include a shared national utility record, more consistent as-built capture after reinstatement, and only then any registry technology used to secure those records.

Safety-II is operationalised here as a distinction between work-as-imagined and work-as-done. Work-as-imagined is the planned sequence of maps, permits and isolation. Work-as-done is the sequence observed in the narratives: incomplete records, compressed programmes and contact with live or unmarked services. Barriers to putting Safety-II into everyday excavation practice include fragmented procedures and weak learning loops after incidents (Sarvari et al., 2025c). Those barriers explain why IUSAF remains an organising frame until its components are tested on site. IUSAF treats the seven cause categories as traces of that gap. Mapping and isolation close the information gap. Training and non-destructive excavation close the practice gap. Reporting closes the learning gap. The framework remains untrialled. It organises existing controls around the counts in this sample rather than promising that strikes will cease.

5.8. Research Limitations and Future Research Directions

The analysis of UK utility-strike case studies provides a structured taxonomy of incident causes and offers valuable insights into their causes and prevention strategies. However, several limitations undermine the findings' robustness and applicability. The research relies on case studies spanning five years, raising concerns about the sample's generalisability. A narrow sample may not capture the full spectrum of utility-strike incidents across the UK, potentially missing rare or underreported events. Additionally, the 'unknown' category, accounting for 20 incidents (3%), reveals gaps in data collection and reporting. Incomplete or inconsistent records obscure causes, hindering the development of precise prevention strategies for a substantial share of strikes (Hodder & Mustchin, 2024). Although the study compares findings with international research (such as Koschmann et al. (2022) from Australia), differences in regulatory frameworks, infrastructure and operational practices limit their relevance to the UK. The UK's dense urban utility networks and privatised management pose distinct challenges not fully addressed by global data, requiring a sharper UK focus. Furthermore, while advocating for prevention measures like non-destructive digging and training, the research lacks robust empirical evidence of their effectiveness across varied UK contexts. It cites prior studies without detailing their scope or practical

impact, weakening the basis for prioritising interventions. The analysis also flags UK-specific issues, such as urban density driving 'impact against or struck by' incidents but fails to explore these thoroughly. Without deeper investigation or comparisons to explain category prevalence, the framework's relevance to local conditions remains limited. To overcome these shortcomings and advance understanding, future research should follow the directions outlined in Figure 5.

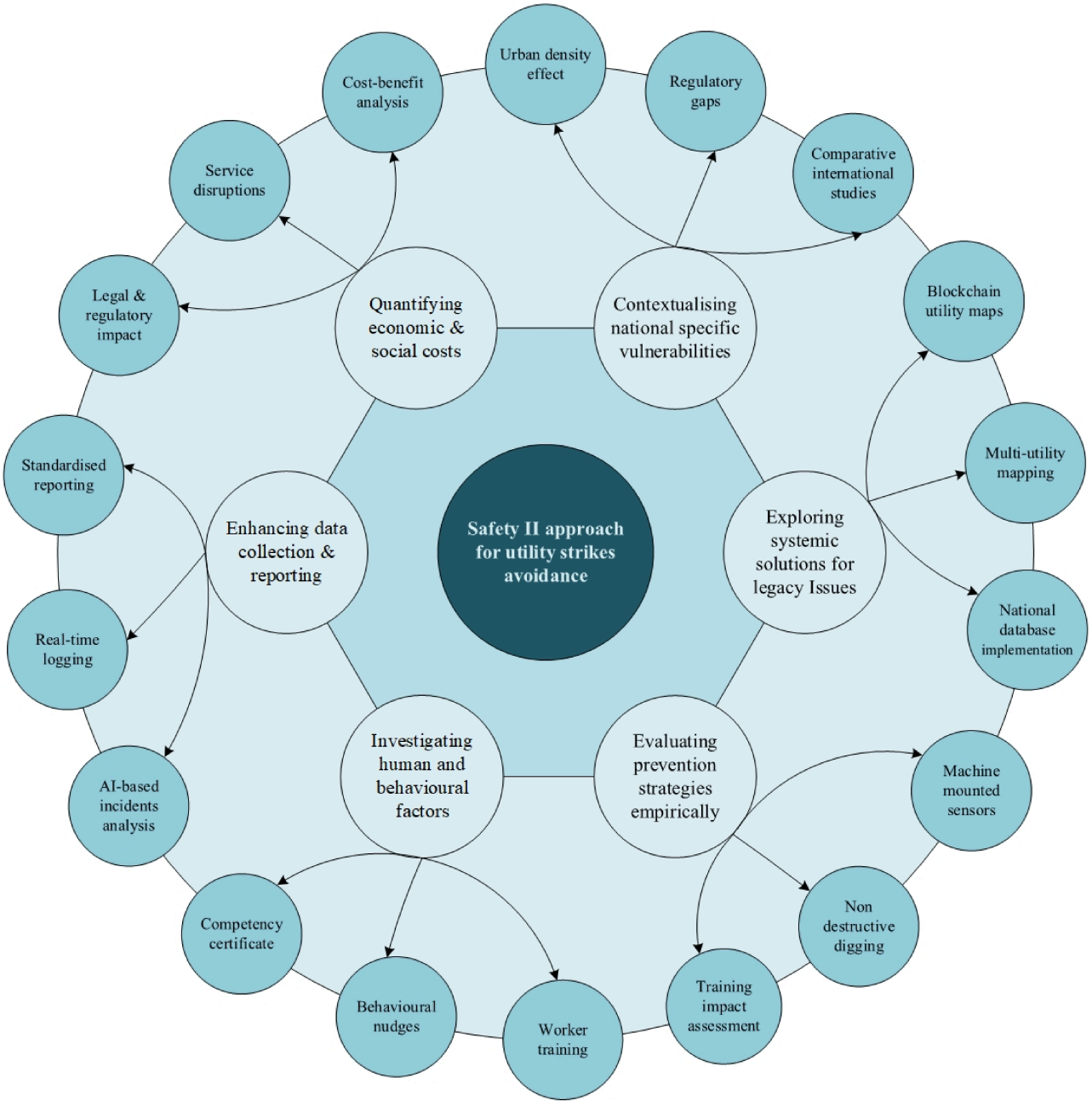


Figure 5. Future research areas for safety utility-strike avoidance.

Four further limitations follow from the source and design of the evidence. First, the records were supplied by National Highways and therefore reflect reporting practices within that organisational setting. Incidents that were not written up, or that were written up with incomplete narratives, may be under-represented and may inflate the unknown category. Second, the study is observational. The taxonomy and the heatmap describe what was recorded between 2016 and 2021. The cause totals should be read as outputs of a

priority-based coding scheme whose classes can overlap in the underlying events. They do not estimate causal effects. IUSAF therefore remains a theoretical organising frame until its components are evaluated in practice on National Highways projects. They do not estimate causal effects and they do not evaluate whether any element of IUSAF would have prevented the incidents observed. Third, the files contain no consistent monetary fields, so direct and indirect economic loss could not be quantified. Fourth, UK institutional conditions, including privatised utility ownership, fragmented as-built records, HSE and New Roads and Street Works Act duties, and the one-call and permit-to-dig arrangements used on the strategic road network, shaping both the occurrence of strikes and the quality of the reports. Findings should not be generalised, without further testing, to local-authority roads, to other countries, or to sectors with different asset-record regimes. The incident window ends in 2021 because that is the latest complete extract supplied by National Highways for this study. Later years were not available to the authors. Replication with records from 2022 to 2025 is identified as a priority for future work. The dataset contains an incident year field, but the published analysis does not test change in category share over time. A year-disaggregated table is reserved for a subsequent paper once the annual extracts have been prepared.

To overcome these shortcomings and advance understanding, future research should follow the directions outlined in Figure 5.

Enhancing data collection and reporting: The high number of 'unknown' incidents highlights the urgent need for better data quality. Research should prioritise the creation of standardised reporting frameworks and the adoption of technologies, such as real-time incident logging applications, to minimise unclear causes. These improvements would provide clearer insights into incident origins, supporting the development of precise prevention strategies.

Investigating human and behavioural factors: Categories like 'equipment misuse' and 'machinery operation' point to human error, workplace culture (such as rushed tasks) and weak supervision as major influences. Future studies should employ qualitative approaches, including worker interviews and surveys, to examine these behavioural drivers. Evaluating interventions like competency certifications or subtle prompts could foster safer working practices.

Evaluating prevention strategies empirically: Thorough evaluation of prevention measures is essential. Comparative or longitudinal studies could assess the effectiveness of tools such as machine-mounted sensors alongside non-destructive digging methods and training initiatives. Adding cost–benefit analyses would pinpoint the most efficient solutions, informing policy and resource decisions.

Quantifying economic and social costs: A detailed analysis of direct costs, such as repairs and indirect costs, including service disruptions and legal claims, sorted by incident type, would sharpen prioritisation efforts. Research should also explore wider societal effects, such as impacts on public health and the environment, to reveal the full scope of utility strikes' consequences.

Exploring systemic solutions for legacy issues: Fragmented utility maps, inherited from privatised systems, increase risks like 'installation errors.' Future studies could explore the feasibility of a national utility database, potentially secured with blockchain, to maintain unified records. This approach, combined with integrated multi-utility mapping, could address co-location hazards, such as gas lines near electrical cables, providing a sustainable solution to systemic vulnerabilities.

Contextualising national-specific vulnerabilities: The prevalence of incidents like 'impact against/struck by' suggests that factors specific to the UK, such as urban density, regulatory shortcomings, or workforce habits, may amplify risks. Comparative research with other

countries could distinguish these elements, providing a basis for customised guidelines and policies to address local challenges effectively.

6. Conclusions

Across 624 incidents, electrical hazards accounted for 296 cases (47%), machinery operation for 181 (29%), impact against/struck by for 64 (10%), gas hazards for 61 (10%), unknown causes for 20 (3%), and equipment misuse and installation errors for one case each (0.16%). Communication underground services recorded the highest service count (241). The analysis of 95 case studies, encompassing 624 incident entries from 2016 to 2021, reveals that communication underground services, low-voltage electric services and water services are the most frequently affected. Seven distinct incident categories including electrical hazards, machinery operation, impact against/struck by, unknown, gas hazards, equipment misuse and installation errors provide a structured taxonomy that not only elucidates the root causes but also shows how these categories co-occur in the sample. Formal tests of interdependence were not undertaken and the patterns should be read as exploratory.

The research underscores that utility strikes stem from systemic deficiencies, including inadequate utility mapping, poor communication, equipment failures and human error. To address these challenges, the proposed Integrated IUSAF offers a comprehensive strategy based on the Safety-II approach, integrating three interdependent pillars: (1) Information Accuracy and Accessibility; (2) Human-Centric Design and Training; and (3) Systemic Integration and Oversight. IUSAF advocates for precise utility mapping using technologies like GPR and GIS, real-time data sharing via centralised digital platforms, advanced on-site detection tools such as machine-mounted sensors, rigorous workforce training, standardised excavation safety protocols and continuous learning through AI-powered incident analytics. By aligning technological advancements with regulatory compliance and human factors, the IUSAF aims to mitigate risks proactively, reducing the frequency and severity of utility strikes.

The current research provides a foundational taxonomy for understanding utility-strike causes in the UK; however, its limitations in data completeness, contextual specificity and empirical evaluation highlight the need for further inquiry. By addressing these gaps and pursuing the proposed research directions, future studies can strengthen prevention frameworks, improve safety outcomes and reduce the economic and societal toll of utility strikes.

In conclusion, utility strikes remain a pressing concern with profound implications for safety, cost and service reliability. Committing to the integrated measures (i.e., IUSAF), alongside ongoing research to refine prevention efforts, will pave the way for a future where utility strikes are a rarity, ensuring the resilience and continuity of essential services.

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