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The impact of heat on London Underground infrastructure in a changing climate

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Introduction

Owned and operated by Transport for London (TfL), the London Underground (LU) is the oldest and one of the busiest urban metro networks in the world, spanning a large proportion of Greater London, United Kingdom (UK). However, the LU now operates in a different capacity and environment than during the Victorian era in which its design and construction commenced. There are physical, financial and planning limitations that constrain TfL's ability to adapt to the current and future climates. Consequently, compared with other metro systems, the LU network may face more, and potentially unique, circumstances leading to service disruption due to both infrastructure constraints and future climate change.

The aim of this paper is to investigate the present and future impacts of temperature on the LU network and its infrastructure. This is achieved by reviewing the present-day and projected future climatological context of London and temperature variance across the LU network. Using a subset of LU assets, the impact of temperature on faults is then quantified using a fault exposure rate approach. These results are then discussed in the context of climate change adaptation for TfL and ways forward are suggested to improve climate resilience across the LU network.

The London Underground: a brief background

The LU network operates above and below ground, and therefore within a range of climatologically different environments. It can be grouped into three different types, herein defined as network types. The surface part comprises 55% of track and runs above ground. The sub-surface, which includes the oldest part of the LU network, comprises 8% of track, using a cut-and-cover construction method to build tunnels beneath the roads above, and to accommodate previously steam-operated trains. The remainder of the LU network is formed of deep-mined 'tube' tunnels, comprising 37% of track. Figure 1 shows where the different network types are located. Most of the surface part runs through the suburbs of outer London, while the sub-surface part is primarily located around the centre of London, mostly north of the River Thames. The deep tube tunnels run through the city centre, most of which pass beneath the Thames, with a short length located to the south.

Many disruptions that cause delays to service can propagate quickly across a transport network, and this includes the effects of weather. The scale of disruption can be severe for a metro network like the LU, due to the frequent train service and high passenger capacity. For example, peak service on the Victoria line is almost one train per minute,[1] so the loss of this service if even for a short amount of time would affect the movement of many passengers travelling along that line. Additionally, rail and metro networks contain critical nodes, such as large interchange stations: a single point of failure on one line that serves an interchange station can lead to further delays on other operating lines and networks (see, for example, Jaroszweski *et al*. (2015) and Ferranti *et al*. (2016)). Infrastructure systems are also interdependent. For example, failures on third-party transport networks can also impact the service on the LU network, and transport systems depend on other infrastructure such as water, power and telecommunications systems to operate (C40 Cities, 2017). Even a small loss in electricity across the national British railway network, for example, can lead to a large proportion of passenger trip disruptions, and the loss of signalling and monitoring assets are most disruptive to other railway operations (Pant *et al*., 2016).

Climatological context

Greater London has a humid temperate oceanic climate, classified as Cfb in the Köppen–Geiger system (Beck *et al*., 2018). According to the latest UK climate projection data (Met Office, 2018c), the climatological baseline (1981–2010) temperature for the Greater London administrative boundary was 11°C, with the warmest monthly mean baseline temperature in July (18°C) and the coldest shared between January and February (5°C). The coldest monthly minimum temperature in the baseline period was −3°C (February 1986), whereas the warmest monthly maximum temperature was 28°C (July 2006). A large area of London, primarily in the city centre, experiences the urban heat island effect (Oke, 1973), where the built environment absorbs the solar irradiance during the day and re-radiates heat from buildings at night, raising the local temperatures. Historically, the nocturnal urban heat island intensity across London was approximately 1–2 degC (Wilby, 2003) and more recently 1–3 degC (Zhou *et al*., 2016; Levermore and Parkinson, 2019).

The tunnel thermal environment differs from the rest of the LU network. Long-term operation of the LU has led to a gradual build-up in tunnel temperatures (Gilbey *et al*., 2011). This is primarily due to train operations, particularly through the heat produced from train braking mechanisms, as well as insufficient ventilation to remove said heat (Mortada *et al*., 2015). In recent years, tunnel temperatures have stabilised year-round at temperatures well above 20°C, with a small seasonal fluctuation in line with seasonal surface temperatures. Certain sections of the tunnels can exceed 30°C on the hottest days of the year (The Evening Standard, 2017; The Independent, 2019). Some studies demonstrated that the fluctuation in tunnel temperatures through the year is, to an extent, a function of surface temperature (for example, Kimura *et al*. (2018) and Jenkins *et al*. (2014)). This means an increased likelihood of more frequent instances of high tunnel temperatures, or higher peak tunnel temperatures, which have implications for both human health and the operation of the LU network.

The global climate is changing. The global-mean surface temperature in 2011–2020

[1]Peak Victoria line service operates 36 trains per hour. https://tfl.gov.uk/tube/timetable/victoria/.

RMetS Royal Meteorological Society

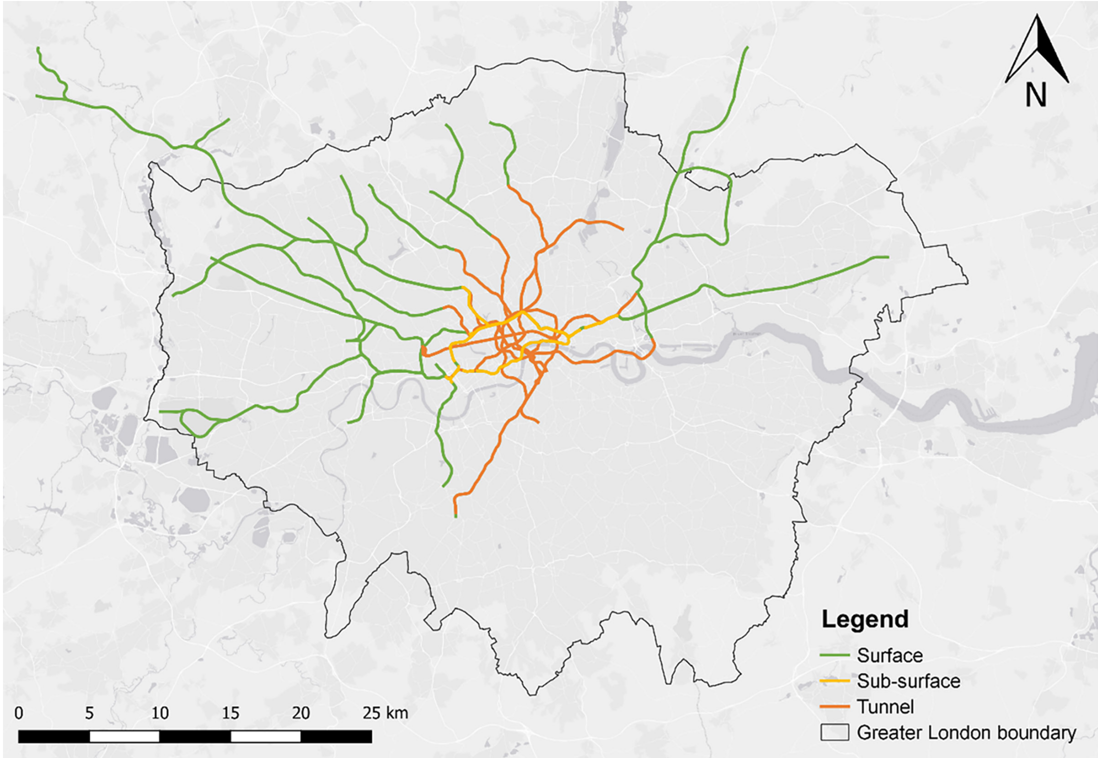

Figure 1. Division of the London Underground network by network type.

Table 1

Key climate index definitions and the 2006–2018 mean annual share of days exceeding the threshold for each index compared to the 1981–2010 baseline.

Climate index	*Definition*	*Mean annual share of days 2006–2018*
Warm nights	Days where daily minimum temperature is above the 90th percentile centred on a five-day window for the baseline period	50.6%
Warm days	Days where daily maximum temperature is above the 90th percentile centred on a five-day window for the baseline period	32.3%
WSDI days	Warm spell duration index: number of days in a year where there are at least six consecutive warm days	13.1%
Summer days	Number of days daily maximum temperature >25°C	6.4%
Hot days	Number of days daily maximum temperature >28°C	2.1%
Heatwave days	At least three consecutive hot days	1.3%
Tropical nights	Number of days daily minimum temperature >20°C	0.1%

Abbreviation: WSDI, warm spell duration index.

was 1.09 degC higher than 1850–1990 (IPCC, 2021) with a slightly higher increase observed in the UK (Kendon *et al*., 2022). In London, heatwaves have also increased in frequency (Slingo *et al*., 2021). To quantify the changing temperature patterns, observations can be compared to annual baseline values. The UK Met Office uses several surface temperature indices (ETCCDI, 2009; Met Office, 2018b, 2022), some of which are shown and defined in Table 1. These are useful to help show whether mean surface temperatures are increasing across the year (i.e. warm nights, warm days, warm spell duration index [WSDI] days) or whether summer temperature extremes are increasing (i.e. summer days, hot days, heatwave days, tropical nights). This study explores changing temperature indices using observations for Greater London, which are available via the UK Met Office Integrated Data Archive System (MIDAS), and based on St. James's Park in Westminster, central London (Met Office, 2019). St. James's Park is considered here to be the best weather station for this purpose because it is the most central weather station geographically in Greater London and therefore central within the overall LU network.

The results in Table 1 are indicative of recent warming in London. For example, over half the study period days (2006–2018) meet the warm night criterion, which would be days above the 90th percentile of minimum daily temperature for the baseline period. Warm night, warm day and WSDI day indices consider temperatures throughout the year and showed that recent increases were greatest in spring and autumn months. On the other hand, summer day, hot day, heatwave day and tropical night indices are indicative of peak summer warming. The average share of summer days, hot days and tropical nights in the baseline period was 2.9%, 0.3% and <0.1%, respectively. Table 1 therefore shows that the study period's share of these days has also increased.

Network Rail and TfL use the 90th percentile data of the medium–high (RCP[2] 6.0) and high (RCP 8.5) emissions scenarios to inform decision-making related to climate change (Network Rail, 2021; TfL, 2021). RCP 6.0 is considered a compromise between likely future emissions reductions and current observed emissions, while RCP 8.5 is a 'worst-case scenario' and representative of climate extremes should emissions reductions not be realised (Dale *et al*., 2018).

[2]Representative Concentration Pathway

Using a subset of climate projection data for the Greater London administrative boundary via the UKCP18 User Interface (Met Office, 2018c), the RCP 6.0 90th percentile describes a mean annual surface temperature warming (relative to the 1981–2010 baseline) of 2.6 degC by the 2050s and of 4.8 degC by the 2080s, whereas the RCP 8.5 90th percentile describes warming of 3.7 degC by the 2050s and of 6.7 degC by the 2080s. These surface temperature increases are consequently likely to affect tunnel temperatures. Using the fundamental methods developed by Kimura *et al*. (2018) with surface temperature observations from St. James's Park, future tunnel temperatures were estimated according to UKCP18 projections via the User Interface. The warmest LU lines at present (Bakerloo and Central) estimated daily maximum tunnel temperatures on both lines to exceed 30°C throughout the year in both scenarios by the 2080s, including some stations experiencing several months frequently exceeding daily maximum tunnel temperatures of 35°C in the RCP 8.5 scenario.

Heat and asset performance

TfL reporting on climate change preparedness shows that all its assets, operations and services carry some degree of weather- and future climate-related risk (TfL, 2021). Figure 2 shows the distribution of these risks across the organisation by type of weather and sector of the business. For the LU, the number of temperature-related risks is the second highest, behind precipitation. Several of the major temperature-related risks to the LU are linked to service delays from staff or passenger heat exposure but are still relevant to asset performance. This is because lost staffing hours due to temperature (as it would be unsafe to work in for extended periods of time) could impact operational decisions and lead to missed maintenance, which in turn could affect asset conditions.

Quantifying the impact of weather events on railway infrastructure and assets can be challenging as it is highly dependent on data quality. Data entries may include subjectivity by the individual who records a fault, including its cause. It is also important to note that maintenance undertaken to address a fault can be either corrective or reactive. Corrective maintenance addresses faults identified through other maintenance activity and repaired outside of routine servicing, whereas reactive maintenance responds to service disruptions while equipment is in operation (TfL, 2022a). Reactive maintenance usually requires more urgent action than corrective, to limit the extent of delays to service that may already have begun to occur.

Accessing appropriate data and ensuring its integrity is a known challenge for infrastructure operators when attributing the effects of weather on their assets (Fu and Easton, 2016). For TfL, its asset management systems and passenger delay databases include weather-related categories to assign to data entries. Categorisation is typically straightforward to allocate in the event of snow, ice or heavy rainfall that leads to surface flooding, as impacts are clearly visible. On the other hand, temperature is harder to directly link to an asset fault. The result is a potential underreporting of temperature, particularly extreme heat, in faults and ultimately passenger delays across the network (Ferranti *et al*., 2016).

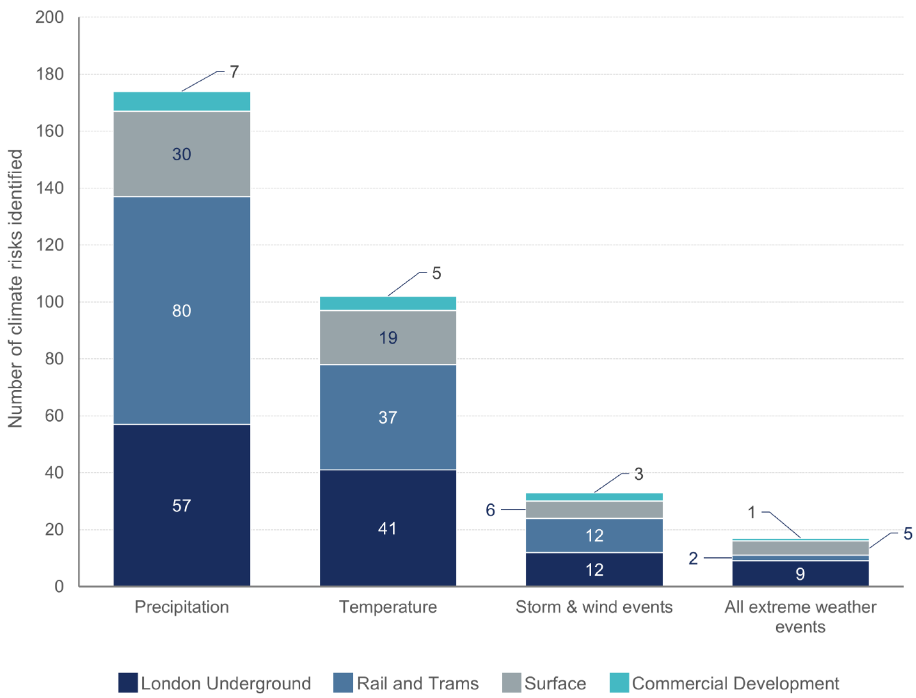

Figure 2. Number of risks per climate hazard for Transport for London (TfL). (Data source: TfL, 2023.)

Additionally, it implies that the impact of heat upon assets and rates of failure are less well understood.

Calculating fault exposure rates is an effective method to address the existing subjectivity in fault and delay data categorisation. This requires combining reliable, daily spatiotemporal weather data (in this case, St. James's Park weather station data), such as daily minimum, mean and maximum temperatures across an area with fault data, then normalising across the study area by the frequency of temperature intervals and number of assets at that location (Fisher, 2020). The resulting outputs are normalised fault exposure values per temperature interval, for example, per 1 degC in daily mean temperature. These are indicative of what temperature ranges resulted in more fault incidents overall. There was also an adjustment to temperatures across the surface part of the LU network to the nearest 100m grid using an urban heat island intensity to capture spatial temperature variance (EEA and Copernicus Climate Change Service, 2020).

Each network type has a slightly different thermal environment, and these require separate analyses to understand the overall effect of temperature on fault exposure rates. Figure 3 shows the total fault exposure rates for each network type for point-related assets[3] across the LU network between 2006 and 2018 inclusive.

The surface part of the LU network is most exposed to the weather, and the combination of high temperatures and solar radiation can lead to several known asset failures, including track buckling. Most of the surface part of the LU network is around the suburbs of outer London, which are less densely built up than the city centre. Therefore, while surface assets may be less impacted by the urban heat island effect, the openness leads to greater exposure to solar radiation. Corrective fault exposure rates on the surface for the assets shown in Figure 3 were relatively consistent at all temperatures, though increased at the highest observed maximum daily temperatures in the study period. For surface assets, this can be linked to increased monitoring activity to prevent heat-related failures. In the tunnels, the two large increases in the fault exposure rates were associated with several different data entries. However, only two entries underpin the highest corrective tunnel fault exposure rate peak. Reactive fault exposure rates were the highest at the lowest observed

[3]Points are movable sections of track that allow trains to move to another line or route. For further information, see https://www.networkrail.co.uk/running-the-railway/looking-after-the-railway/delays-explained/signals-and-points-failure/.

RMetS
Royal Meteorological Society

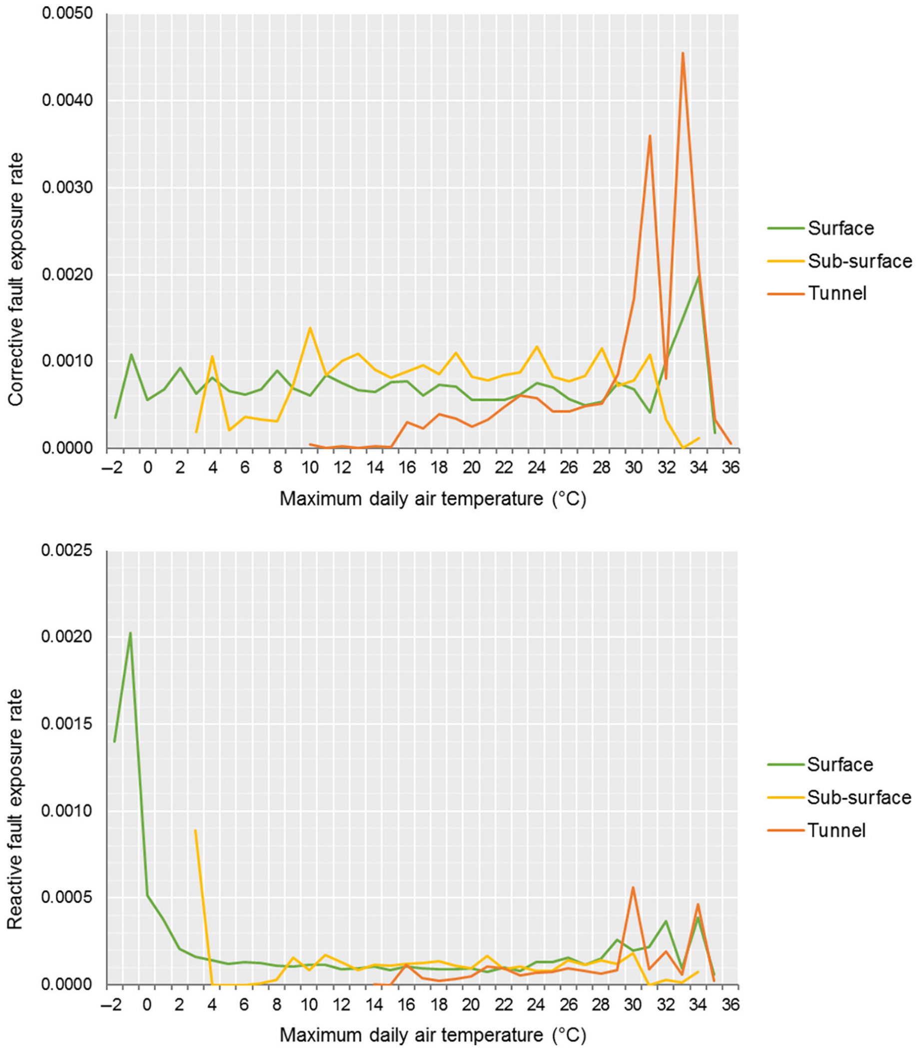

Figure 3. Fault exposure rates for corrective (top) and reactive (bottom) data entries across the London Underground asset management database for point-related assets, by network type, 2006–2018. Note different y-axis scales.

maximum daily temperatures (below 0°C), but these were infrequent instances across the study period compared with high temperatures. Overall, surface fault exposure rates were otherwise low but began increasing slightly from a maximum daily temperature of 24°C.

The sub-surface LU network type is the smallest by track length but includes some of the oldest infrastructure. From a weather perspective, this network type is somewhat covered and so is sheltered from the highest temperatures but still exposed enough to show similar trends to the surface part. Figure 3 shows relatively consistent corrective and reactive fault exposure rates across the sub-surface part of the LU network. The high reactive rate at the lowest maximum daily temperature (approximately 3°C) was an outlier observation, as the following temperature intervals report rates of 0, and aligned to the days around the lowest observed daily maximum surface temperatures.

The tunnel part of the LU network includes some of the oldest deep-mined tunnels in the world, having begun construction in the late nineteenth century. As a result, there are a range of complex thermal issues due to the legacy design and consequent limitations on retrofitting the infrastructure for cooling. The narrow-mined tunnels primarily run through clay and acted as a heat sink over several decades, which has gradually reduced in efficacy. Heat has now stabilised in the tunnels, with a very low diurnal temperature change and a small seasonal fluctuation. Observed temperatures in the tunnels can be high, leading to increased passenger thermal discomfort (Jenkins *et al.*, 2014) and potentially an increased risk of illness such as heatstroke. In Figure 3, corrective fault exposure rates accelerated at intervals where maximum daily temperatures exceeded approximately 28°C, while the reactive rates were comparatively lower to corrective yet did increase at intervals higher than 30°C. Despite increased corrective maintenance, there were still instances of increased reactive fault exposure rates when some of the highest daily maximum tunnel temperatures were observed.

Heat risk management and climate change adaptation

The fault exposure rates presented in this paper indicate increased asset failure rates at the highest temperatures across all network types, but particularly in tunnels. TfL already undertakes corrective maintenance when surface temperatures are high; however, there remains a small but noticeable increase in reactive fault exposure rates on the surface and tunnel parts of the network. This indicates that the LU network is likely to require further adaptation of its infrastructure to climate change to help protect customers, staff and assets.

Additionally, the fault exposure rates highlight a substantial difference in response to extreme cold in comparison with extreme heat that merits further investigation in terms of adaptation through monitoring and response. Although extreme cold is representative of fewer days than extreme heat events, there were no increases in corrective fault exposure rates at lower temperatures, but an increased reactive rate. This suggests that current corrective maintenance may not detect cold-related faults prior to network operation during an extreme cold event. It may be indicative of the differing weather characteristics and operational capacity underpinning failures in cold weather. For instance, asset failures in cold temperatures may combine with ice and snow, which can also be more localised and unpredictable as weather hazards. Instances of extreme cold in a warming world are likely to reduce, though may still occur, and it must be recognised that their albeit infrequent occurrence severely disrupts operations (such as during the 'Beast from the East' in early 2018 (Met Office, 2018a)).

Indeed, TfL does and continues to research and undertake several heat management countermeasures in preparation for extreme heat across the LU network. Countermeasures shared in public are primarily hard measures via advancements in technology and engineering. Examples include air-conditioned rolling stock across the sub-surface lines; cooling units and ventilation upgrades across the Victoria line (Botelle *et al.*, 2010); research on groundwater cooling methods (Ampofo *et al.*, 2011) and waste heat extraction (Davies *et al.*, 2019). There was even a competition in 2003 launched by the former Mayor of London to design solutions to cool the tunnel network, although no practical, workable solutions were successful (BBC, 2005). Currently, there are plans to introduce air-conditioned trains for the first time in the deep tube tunnels on the Piccadilly line from 2025 (TfL, 2018, 2022b), and a trial of cooling panels at a disused deep tube tunnel at Holborn station (TIES Living Lab, 2022).

The fault exposure rates indicate that, without further interventions, the operation of the LU network will likely face future heat-related challenges owing to future climate change. This would be primarily due to an increasing frequency of hot days or heatwaves, which may include their occurrences earlier and later in the year. Future observed temperatures may also include observations higher than those reported in Figure 3, so the level of impact these instances may have on faults cannot yet be quantified. Mitigating these future high temperature risks may require adaptation countermeasures such as conducting preventative maintenance at lower observed temperatures than at present, or earlier in the year in the lead-up to the summer months.

To make effective climate adaptation decisions for the future, data quality is imperative. The LU asset management databases were not originally designed for environmental analysis and so there are inconsistencies when converting entries into fault exposure rates. Additionally, temperature data were joined to fault data entries according to the date the fault was raised, but corrective maintenance entries specifically were often closed many weeks or months afterwards. It is therefore unclear when exactly maintenance took place, which could affect the associated temperature observation. Without the knowledge of the LU staff who enter these data and the engineers who undertake the maintenance work, it is difficult to retrospectively correct data.

Data from other stakeholders are also essential to support the decision-making process. Fault exposure rates provide a useful metric on the resilience of the LU network to weather, but it depends on the availability of other data, such as weather exposure frequencies, to calculate them. Converting fault exposure rates into future fault estimations due to climate change would require projected temperature exposure frequency data. These data are not directly available from the Met Office, though could be calculated from existing data. Combining fault exposure rates with projected temperature exposure frequencies provides revised temperature thresholds, which could impact design standards and the planning of operational and physical interventions. Therefore, working with stakeholders to design and provide the most appropriate projection data is crucial to improve the capacities of decision-makers.

Infrastructure networks are only as resilient as the systems they depend on, so cross-sector collaboration is critical to address infrastructure interdependencies and cascading risks. The UK's Infrastructure Operators Adaptation Forum (IOAF) is the only known national cross-sector forum for sharing best practice on reducing infrastructure vulnerabilities to climate change (House of Commons and House of Lords, 2022). TfL is a member of the IOAF, so can utilise the forum to facilitate further external stakeholder engagement.

TfL's recently published adaptation strategy also begins to address other pan-organisational processes that would also increase its adaptive capacity to climate change that directly acknowledge these factors mentioned above to improve adaptation decision-making. It represents progress in more cohesively integrating actions across the whole organisation from the short term to the long term. Proposed actions include training on carbon literacy, strengthening engagement with inter- and intra-organisational stakeholders and improving information and data management (TfL, 2023).

Looking ahead

Using existing data, the LU network shows signs of vulnerability to temperature extremes, but better data quality would help improve fault exposure rate analyses. The multi-stakeholder exchange of knowledge has proven effective in developing climate-resilient policies (Ndebele-Murisa *et al.*, 2020). For TfL, improved data quality could be facilitated by improving the data collection systems, facilitated by increased internal stakeholder engagement between those who complete fault data entries with the environmental analysts and decision-makers within TfL. Additionally, external stakeholder involvement from weather and climate data providers would support the development of fault exposure rates and appropriate forms of climate projection data. It is nevertheless important to note that this paper only presents analysis pertaining to one group of assets, so the validation of the method presented in this paper would be beneficial for other asset types to confirm the extent of fault exposure rates to temperature.

Like any infrastructure owner or critical service provider, TfL would benefit from adapting to climate change as part of an iterative process that enables the continual improvement of infrastructure resilience in cycles. An iterative approach to climate change adaptation underpins guidance for transport practitioners around the world, for example, Quinn *et al.* (2017) and Greenham *et al.* (2022), and supports integrating and aligning adaptation into 'business as usual' activity (Quinn *et al.*, 2018). TfL address this in its adaptation plan (TfL, 2023), which outlines the high-level actions it is taking to embed adaptation to high priority climate risks into business practices. As a result, with each cycle of business planning, while the climate may incrementally change, so would the capacities of TfL's decision-makers to develop targeted climate change adaptation actions across the LU network.

Conclusion

As the climate changes, TfL, like many other network operators, face increased climate risks. This paper demonstrates that there are currently greater fault exposure rates at temperature extremes, which vary greatly by network type. Future climate change is also likely to further exacerbate temperature risk with an impact on faults across the LU network and TfL has responded to these risks to date with a range of hard countermeasures. TfL's adaptation plan is welcome and relevant progress in integrating practices across the organisation more cohesively. As TfL improves its data management and engagement with stakeholders, the capacity to monitor and evaluate progress in climate change adaptation should increase. As a result, the LU network has the potential to become more climate-resilient in future.

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