1 Introduction

1.1 Aim

The aim of this investigation was to understand the general trends in temperatures on the London Underground network using recorded data, and to provide the current understanding of what factors contribute to heat gain within the London Underground deep tube environment. The report also concentrates on the effect of solar heat gains on trains and provide an understanding of the estimated contribution it may have to tunnel temperatures in the network.

1.2 Recorded Temperature Trends

1.2.1 Seasonal Variations

TfL has actively monitored temperatures on the deep tube network. Temperature sensors ('tiny-tag') have been placed on all deep tube line platforms. Data from 2013-2020 is available to the public at:

https://data.london.gov.uk/dataset/london-underground-average-monthly-temperatures

A plot of this data along with average monthly ambient air (dry bulb) temperatures for the year can be found below. The peak values for each category and year have been plotted for simplicity.

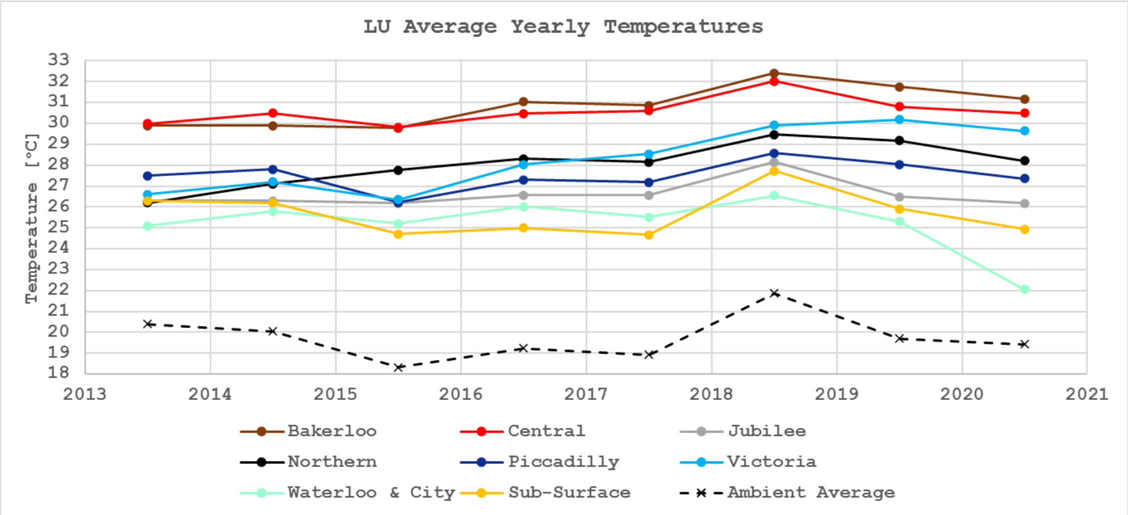

Figure 1: LU Peak Average Yearly Temperatures between 2013 and 2020

It can be seen from Figure 1 that the Bakerloo line and the Central line have the highest air temperatures (dry bulb) on the network. The Victoria line in recent years has been on an up-ward trend approaching the temperatures found on the Central Line and Bakerloo Line. The same can be seen for the Northern line but to a lesser extent. The Piccadilly, Jubilee and Waterloo & City lines show little up-ward trend. The Sub-Surface line, although not a deep tube line is also displayed for comparison

In 2018 all lines showed an upward trend which can be seen to align with the average ambient air temperatures for that year being higher. This demonstrates that the ambient air temperature plays a significant role in tunnel air temperatures.

The network temperatures oscillate with seasonal changes. This can be clearly seen in the figure below showing the full average monthly line temperatures between 2013 and 2020:

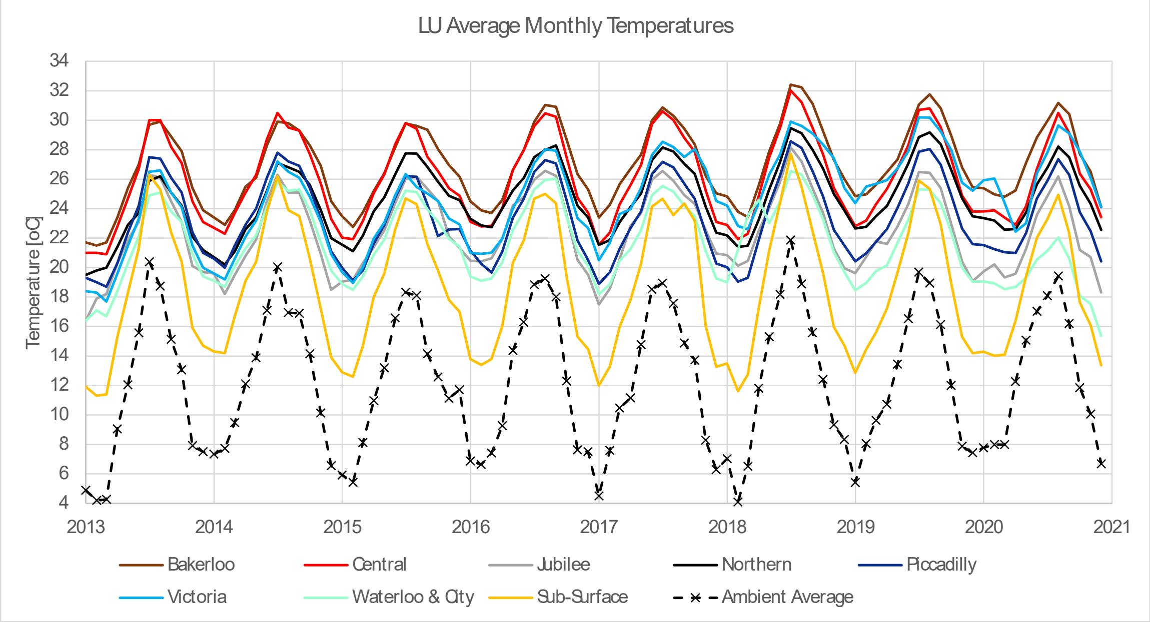

Figure 2: LU Average Monthly Temperatures between 2013 and 2020

Some observations can be found from Figure 2, when comparing the line tunnel air temperatures with the ambient air temperatures. First, the Sub-Surface railway follows the ambient line trends closely, which is to be expected given that most of underground sections are wide open cut-and-cover tunnels close to the surface. However, all lines illustrate how changes in ambient air conditions throughout the year directly influences the tunnel temperatures seen throughout the year.

The Victoria line operates completely underground with the depot above ground at Northumberland Park. The Victoria line tunnel temperatures demonstrate the same trends as for other lines which operate for significant distances overground. Whilst trains are stabled above ground, the high services levels maintained throughout the day significantly limits each trains exposure to external conditions and solar gains. Many trains are stabled in covered sections of the depot. The trains also enter the line via the train wash, which cools the trains surfaces prior to entering the tunnels. Given that Victoria line temperatures are similar to those experienced on lines that operate significant lengths above ground, the data suggests that ambient air temperatures and train heat output are two key drivers of tunnel air temperatures experienced across the Victoria line and across the network.

The Waterloo & City line, which is completely underground (both depot and running lines) also shows similar trends to other deep-tube lines, however in 2019-2020 where the service was stopped due to COVID-19 pandemic, the temperature drops significantly and tends towards the Sub-Surface railway temperature values. As with the Victoria line, this suggests that ambient air temperatures and train heat output are two key drivers of tunnel air temperatures experienced across the network.

To summarise, the data presented shows that seasonal variations in tunnel air temperatures are highly correlated to seasonal variations in ambient air temperatures; with the delta between tunnel and ambient air temperature at any point in time being the consequence of train operations and other heat sources. The Victoria and Waterloo &

City lines demonstrate how lines wholly operated underground are similarly affected by the air exchanged between tunnel and ambient air, as for lines that operate both under & overground. This air exchange is provided by the piston effects of trains and mechanical ventilation systems. With higher ambient air temperatures there is a lower delta temperature and therefore the ability to lose heat through air exchange is much reduced.

1.2.2 Ventilation Assets

Along the London Underground in deep tube tunnels there are ventilation assets which help the flow of air within the system. There are two main ventilation assets that help with temperature controls: Station & Mid-Tunnel Ventilation Shaft (MTVS) Fans and Draught Relief (DR) shafts. The former forces air into or out of the tunnels depending on the direction of the fan whilst the latter relies upon the piston pressure effect of the trains pushing and pulling air though the shafts as they are passed.

In terms of ventilation assets per deep tube station the Bakerloo line has the fewest of all the deep tube lines whilst the Jubilee line has the most. For the Jubilee line, this is mainly due to the Jubilee Line Extension, which was completed in 1999.

The Central line and Victoria line which also exhibit high temperatures have more ventilation assets per deep tube station than the Northern and Piccadilly lines which exhibit lower line average temperatures. This indicates that ambient air temperatures are not the only factor that influence tunnel temperatures and that other factors must be contributing to the tunnel temperatures experienced on lines such as the Central and Victoria.

1.2.3 Train Performance

The trains operating the deep tube environment give off heat in the tunnels via various mechanisms. Trains receive electricity via the 3rd and 4th rail which power electrical motors that allow the train to accelerate. There are some losses due to motor efficiency and mechanical efficiency where energy is lost as heat, however most of this energy is stored in the train as Kinetic Energy. When the train needs to decelerate or stop, this Kinetic Energy needs to be removed and this can either be returned to the 3rd and 4th rail as electricity (regenerative braking) or lost as heat through the trains onboard braking systems).

During deceleration, trains perform rheostatic braking whilst travelling at a sufficiently high speed. The motor poles are reversed, and the motor effectively acts as a generator. The generator passes current through the resistor grids on the train where the energy is then dissipated as heat. At low speeds (typically below 16kph), friction braking is applied to decelerate the train to standstill. The break blocks physically slow the train wheels, the friction between the brake block and the wheel also generates heat.

Trains on the Central, Victoria, Northern and Jubilee lines are enabled with regenerative braking. For these lines, some of the energy is transferred back to the 3rd and 4th rail during braking. This reduces the quantity of energy that needs to be lost as heat through the resistor grids. Trains operating on the Bakerloo, Piccadilly lines do not have this functionality. This is another factor that supports the Bakerloo line being as warm as the Central line even though it operates at a lower service level.

As trains pass through the air within the tunnels, they must overcome aerodynamic drag and skin friction effects, which contribute to the trains energy which is lost as heat.

Other ancillary equipment on the train will also have contributions to energy consumption, such as lighting, ventilation fans and (in more recent train stocks) air conditioning systems.