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Passenger Flow in the Tube

Sponsored by Transport for London/London Underground

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Abstract

With 400 km of rails, 270 stations, and more than 1.3 billion passenger journeys each year, quickly and safely moving passengers through stations and onto trains is an ongoing priority for the London Underground. The goal of this project was to analyze passenger flow and recommend ways to alleviate crowding and congestion. We gathered qualitative and quantitative data, through interviews with London Underground employees, CCTV observation, and analysis of customer satisfaction data. Our findings suggest that the current patterns of passenger flow and congestion are unsatisfactory and unsustainable and we propose a number of recommendation that London Underground and Transport for London might pursue to alleviate the problems in the future.

Acknowledgments

We would like to thank Professor Dominic Golding and Professor Jennifer deWinter for providing clear guidance and continued support to help us completing the project. We offer special thanks to our sponsor, Steve Walling from London Underground, for giving us insight into the complex problems and making human connections for us to complete our project objectives.

Furthermore, we would also want to thank Mike Donnithorne, Custom Service Manager at Euston Station, and Cassius Powell, Custom Service Manager at Liverpool St. Station, for giving us access to the stations and CCTV footage. We also appreciated all interviewed staff members at both Euston Station and Liverpool St. Station for giving us good insight to problem areas at the stations. Last but not least, we want to thank Dr. Taku Fujiyama, professor at UCL, for giving us more information to supplement our background research on passenger flow.

Executive Summary

Use of the Tube has grown over time to provide millions of trips in a single day, leading to congestion issues. At its peak, more than 28 million trips were made in one week. Despite the sheer number of passengers serviced, delays can account for over 25 million lost hours in productivity in a single year. One of the key causes of delays that this paper explores is delays due to congestion and passenger overcrowding.

Poor passenger flow and congestion does not only result in lost hours for travelers, but also results in customer complaints and can contribute to safety issues. Transport for London (TfL) has expressed concern about the congestion in stations before, targeting some of the most travelled stations with renovation projects. Beyond this, passenger congestion on platforms can lead to unsafe circumstances where passenger push too close to incoming trains. Crowded platforms and trains also result in lower passenger satisfaction, a metric that TfL seeks to maximize across all modes of transportation.

This project was designed to conduct a detailed analysis of congested stations and customer satisfaction data to provide us with a basis to suggest potential improvements. We started with an in-depth literature review based not only on the science behind passenger flow, but also international approaches to congestion relief. We created station selection criteria, evaluating eight stations recommended to us by station staff and settling on two primary stations to focus our work on- Euston and Liverpool Street. After identifying our target stations, we conducted employee interviews to gain insight on problem areas in the station and common questions and concerns that passengers had, then performed CCTV analysis on these stations during peak and off-peak times.

After our CCTV observation was complete, we performed research into data collected previously by Transport for London in order to look for a correlation between congestion and passenger satisfaction. Previous passenger surveys did not collect data based on station, but the data for each line was used to analyze their associated stations. We did not find a strong correlation between congestion and overall satisfaction, but did notice that some lines suffered more from congestion than the signage and information issues that were also prevalent.

We found that congestion and passenger flow were poor during peak hours of travel on the London Underground. Level of service measurements in ticket halls were consistently poor, as were the areas around escalators. We found that off-peak hours were much more manageable,

and do not need to be looked at outside of abnormal operation situations. We also found that passengers were unsatisfied in many ways with signage and congestion in the stations. Passengers were frequently confused as to where they need to go and did not know about delays that occurred during their travels. These conclusions led us to make recommendations that the London Underground should take into account while planning their improvements in the future.

We recommend that some measures be taken system-wide on the London Underground to improve service at all stations. We recommend that CCTV systems be upgraded and standardized system wide to facilitate ongoing analyses of passenger flow and congestion. We also recommend that LU take on a large-scale, one time analysis of congestion to develop short-, medium-, and long-term strategies for congestion relief around the system. Changes to the Oyster system to allow for one-station passes for contractors and cleaning staff to be able to enter and exit fare-controlled areas where they work will help staff members be more efficient across the board. In addition, changes to transfers, help points, and implementing more escalators will improve quality of life at all stations.

We believe that a widespread implementation of dynamic signage is also required to better inform passengers about delays and alternative routes through the station. Currently, the dynamic signage in ticket halls and on platforms is inadequate and does not help passengers find their way to the platform. We believe that most, if not all, static signage should be replaced with programmable signs that can display more relevant information to customers. Beyond this, we would like to see changes in signage to incorporate color-coded lines on the floor to guide passengers, and to move away from the current confusing platform numbering system altogether.

Euston requires many improvements to be able to handle the increased traffic due to projects like Crossrail 2 and High-Speed 2. We believe that Euston should be revamped and renovated to bring disused entrances and tunnels into service in order to provide relief at the cramped ticket hall area and the packed escalators. We hold that increasing the width of major passageways and adding escalators to the current ticket hall will improve the passenger flow enough in the short term to avoid major backups in the station. Moving maps to areas where they are accessible but not in main thoroughfares, eliminating confusing signage, and changing the Northern line into two separate lines for each branch will allow customers to find their way more easily and avoid causing congestion while looking at Tube maps. We would also consider a full station rebuild, moving the glass cubicle in the main ticket hall, and adjusting Network Rail schedules to avoid surges as viable options for improving flow in the station.

Liverpool Street, much like Euston, requires adjustments to avoid becoming a major bottleneck for commuters and tourists. In the event of a shutdown at Ticket Hall B, Ticket Hall C is unable to accommodate the sheer amount of tourists who are trying to purchase tickets to ride the Tube. We believe that adding more ticket machines to Ticket Hall C, the fallback ticket hall, is the best solution to the throngs of passengers who will otherwise line up at the four ticket machines that exist there currently. Expanding each train platform by a meter in depth will allow passengers to wait safely and more comfortably for their trains while abating issues with passengers waiting too close to the tracks. Alternatively, implementing the platform door system from the Jubilee line can also fix the current overcrowding issues. Adding an additional bridge to Ticket Hall A that crosses the tracks can also relieve congestion issues in the station.

Table of Authorship

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1. Introduction	Edward	All
2. Background	Edward	All
2.1	Ian	Robbie, Ian, Aidan
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2.1.2	Ian	All
2.2	Aidan	Ian, Aidan
2.2.1	Aidan	Edward, Ian, Aidan
2.2.2	Aidan	Ian, Aidan
2.2.3	Aidan	Edward, Ian, Aidan
2.2.4	Aidan	Ian, Aidan
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3.1.1	Robbie	All
3.1.2	Aidan	Edward, Ian
3.1.3	Robbie	All
3.1.4	Robbie	Ian, Robbie
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1. Introduction to Congestion in the London Underground

Passenger congestion at underground stations has been one of the major concerns London has faced in recent years. With more people taking the London Underground (LU), also known as the Tube, upwards of a million of people could be congesting the Tube every week. For example, the week ending October 31st, 2015, there were 28.76 million journeys made in the week (McAteer, 2015). In addition, more than 26 million customer hours were lost in 2015/16 (time lost was calculated by customers' waiting time on delayed train for more than two minutes; Blunden et al. 2016). Poor passenger flow not only results in huge loss of productivity but also gives rise to customer complaints and safety issues.

Seeing the severity of the congestion problems, the LU has tried measurements, such as station renovation, increasing train frequency, etc., to mitigate the situation. Hence our project provides further insight into passenger congestion issues at congested stations, Euston and Liverpool St. stations to be exact, as well as helps in LU's efforts to tackle congestion problems. We aim to find out what contributes to congestion the most in Tube stations. We then determined options for ameliorating any problems. All of the stations we focus on contain multiple lines and are used frequently to transfer between lines in order to reach a specific destination. Interchange stations in central London struggle with overcrowding due to the sheer number of passengers—upwards of ridiculous number inserted here—that pass through them every day.

The goal of the project is to conduct a thorough analysis of passenger flows at specific interchange stations in the London Underground and to provide detailed suggestions on how to improve passenger flow. In order to reach the goal, we have three main objectives.

- Conduct a detailed analysis of passenger flows at selected interchange stations to identify major areas and causes of congestion.
- Evaluate passenger opinions about congestion to determine links between public opinion and congestion.
- Recommend approaches to better alleviate passenger congestion.

In order to get into the discussion about main objectives, we provide the background on passenger congestion and the nature of its effect in Chapter 2. We then discuss our key objectives in our path to achieving this goal in Chapter 3, starting with an assessment of the state of the art in passenger management. Through interviews with experts and an expansion of our literature review, we have identified the process by which passenger flow in the London

Underground is controlled and influenced. For example, in Section 3.1, we measure passenger flow at specific interchange stations through CCTV observation, direct platform observation, and station concourse observation. We then analyze survey data from previous Transport for London surveys in Section 3.2. Finally, in Section 3.3, we discuss how we vetted our solutions and refined them through our work with Transport for London employees.

Section 4 encompasses the analysis and findings that we have determined from our work in Section 3. First, we discuss our findings from all the elements of our research combined. We then combine all of our methods into one complete analysis of the problems involving passenger flow in our primary stations in Section 5. Finally, we propose recommendations to address these problems in Section 6. Each suggestion has a succinct explanation of its purpose and how it will benefit the station.

2. Background on Congestion and the London Underground

This section describes the Tube and passenger flow to give context for the rest for the report. The Tube is a public railway transit system that serves Greater London and its nearby counties. Opened in 1863, the Tube is the oldest railway system in the world. It began with one line and only six stations, from Paddington Station to Farringdon Station ("London Underground," n.d.). During 150 years of operation, the Tube has expanded across the city to be able to meet the demand of the city, and now runs eleven different lines traveling on 402 kilometers of rail, servicing 270 stations across London ("Facts and Figures," n.d.) (See Figure 1).

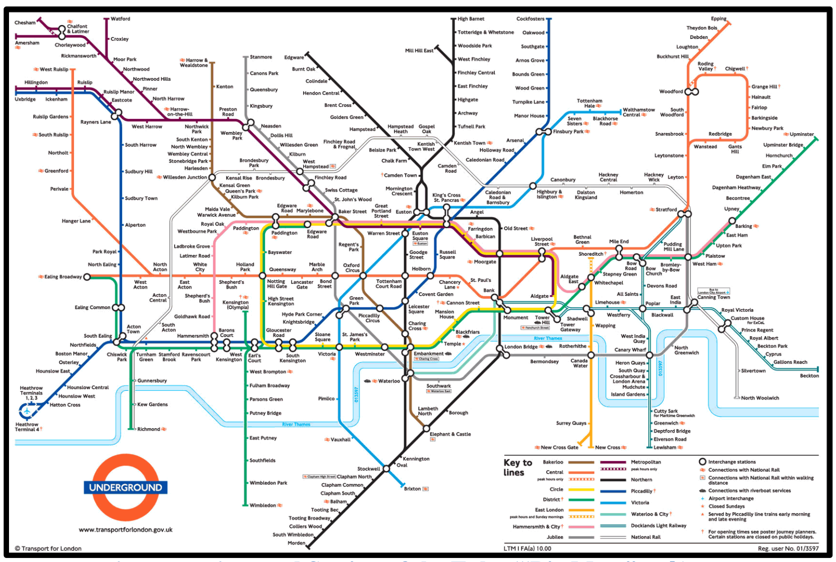


Figure 1: Lines and Station of the Tube ("Big Map," n.d.)

London continued to grow as the Tube developed. Today, London has become a large metropolis, boasting a population of 8.7 million and attracting 35.1 million international tourists who travel to tourist attractions through the Tube (Coldwell, 2016). Each person in London makes, on average, 921 trips over the course of a year, and 86% of those trips are in a vehicle (primarily cars and vans). Recently, Londoners have been changing their commuting habits, shifting away from private vehicles to public transportation. Compared to transportation mode in 2002, the distance traveled by car has decreased by 649 miles. As can be seen in Figure 2 below, the use of rail, including both surface rail and the Tube, has increased in distance by 158 miles, and 7 trips (Sullivan, J., Kershaw, K., and Cummings, J., 2016). In 2015, the week leading up to

October 31st, broke London's record for numbers of trips made in a week: 28.76 million trips (McAteer, 2015). In 2015/16, approximately 1.35 billion passenger journeys were made by the Tube ("Facts and Figures," n.d.). With so many passengers, most of the stations in the Tube suffered excessive passenger volume and the consequences of congestion at some point. For example, passenger volumes at increased by 28% at Oxford Circus (Figure 3) and by 21% at King's Cross between 2010 and 2015 (Parmenter, 2015).

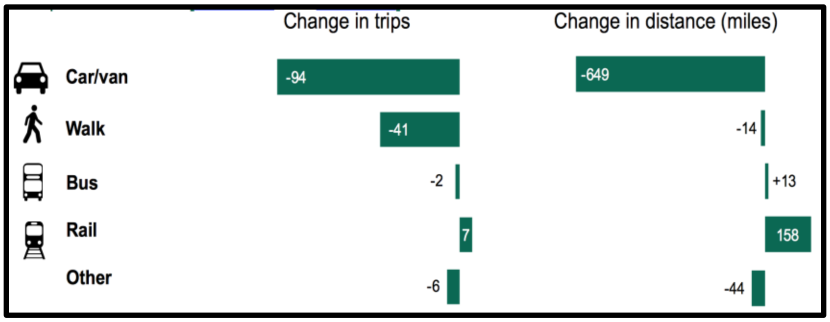


Figure 2: Change in Average Trips Annually Per Person, by Mode of Transportation (Sullivan et al., 2015)

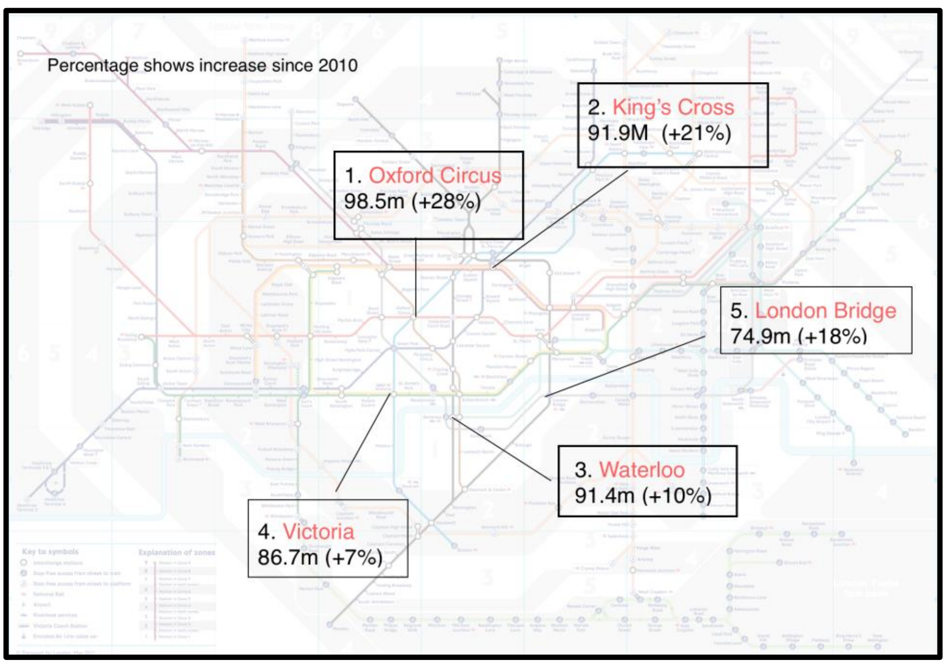


Figure 3: Top Five Busiest Tube Station (Parmenter, 2015)

As one of the busiest railway systems in the world, the Tube has faced numerous instances of overcrowding at stations, especially at interchange stations. For instance, at Victoria station, where five tracks come together, about 90,000 passengers pass through between 7am and 10am on weekdays, and getting in and out of the station during peak hours can be difficult (Topham, 2014). Passenger congestion in the station is one of the main causes of train delay.

As Figure 4 shows, the Jubilee, Central, and Northern lines suffer most from passenger delays due to overcrowding. In the year 2016, Londoners riding the Jubilee Line lost 147,451 hours due to passenger congestion, followed by the Central Line with 60,695 hours (Smith, 2017). A significant portion of the hours lost due to delays are caused by incidents involving passengers, or overcrowding in stations by passengers (*London Underground Performance Report,* 2017). Congested platforms may also be a major safety concern. For example, in March 2015, The Rail, Maritime and Transport (RMT) Union reported that a woman fell off the platform when her coat was jammed into the door. She was dragged by the train for 60 feet at Clapham South station during morning rush hour, and suffered a black eye and broken arm (RMT, 2016).

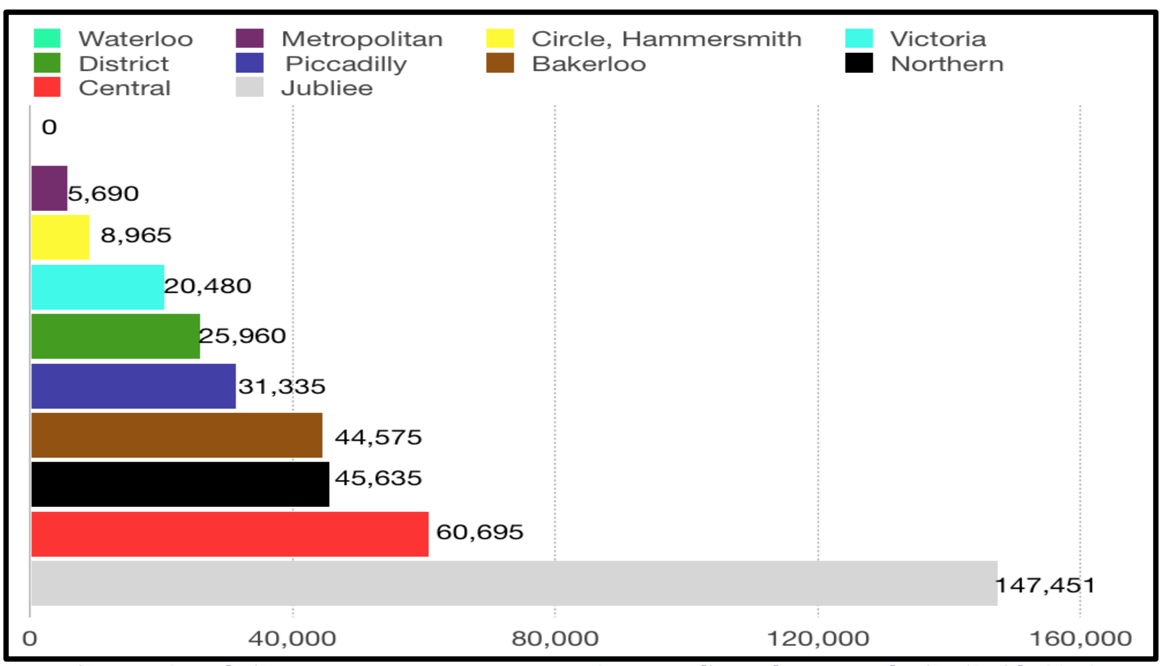


Figure 4: Cumulative Passenger Hours Lost Due to Overcrowding Delays on Each Line (Smith, 2017)

Due to all of the consequences caused by severe congestion at Tube stations, TfL has implemented policies to help reduce problems. One of the plans to reduce congestion on

Underground lines is to install the Crossrail line (rebranded as the Elizabeth line in 2016). The new line is estimated to reduce peak crowding in the morning by eight percent (Barber, 2016). Ongoing research and work in London Underground stations, including some experiments on passenger flow, also continue to improve passenger flows through the station and alleviate congestion. Section 7 of TfL's 2016/2017 Budget and Business Plan Efficiencies Programme outlines their intention to be transparent about their spending and savings through a quarterly report, with their revised savings and efficiencies to be included in the Mayor's 2017/2018 budget ("Efficiency Plans," n.d.). In addition to transparency about spending, TfL has also committed to having their data be accessible to developers who wish to use it to provide services or products to customers to improve their experience. This will help ensure that the passengers are receiving the information they need to get to their destination efficiently and without confusion ("Open Data Policy," n.d.).

2.1. Passenger Flow

Passenger flow is the number of passengers that move through a given transportation system, such as to or from buses or train carriages ("Quality of Service Manual," 2013). In Section 2.1.1, we provide some background on passenger flow standards, detailing how flow is categorized and why. Passenger flow also encompasses the way that those passengers move about, and includes such components as the number of passengers traveling through a system and the time and routes taken to travel through a system (Loukaitou-Sideris, Taylor, and Voulgaris, 2015). In Section 2.1.2, we discuss measurement of these phenomena. The determinants of passenger flow are extremely complex as the flow depends not only on each individual passenger's entry point and destination but also on how that passenger interacts with other passengers and objects in the station. Labelled in Figures 5 and 6 are the locations in Euston and Liverpool Street stations that we focused our observations on, and they are problem areas such as escalators and ticket halls. In Section 2.1.3, we explore how flow can be analyzed using comparison to established properties of passenger flow in order to extrapolate more information.

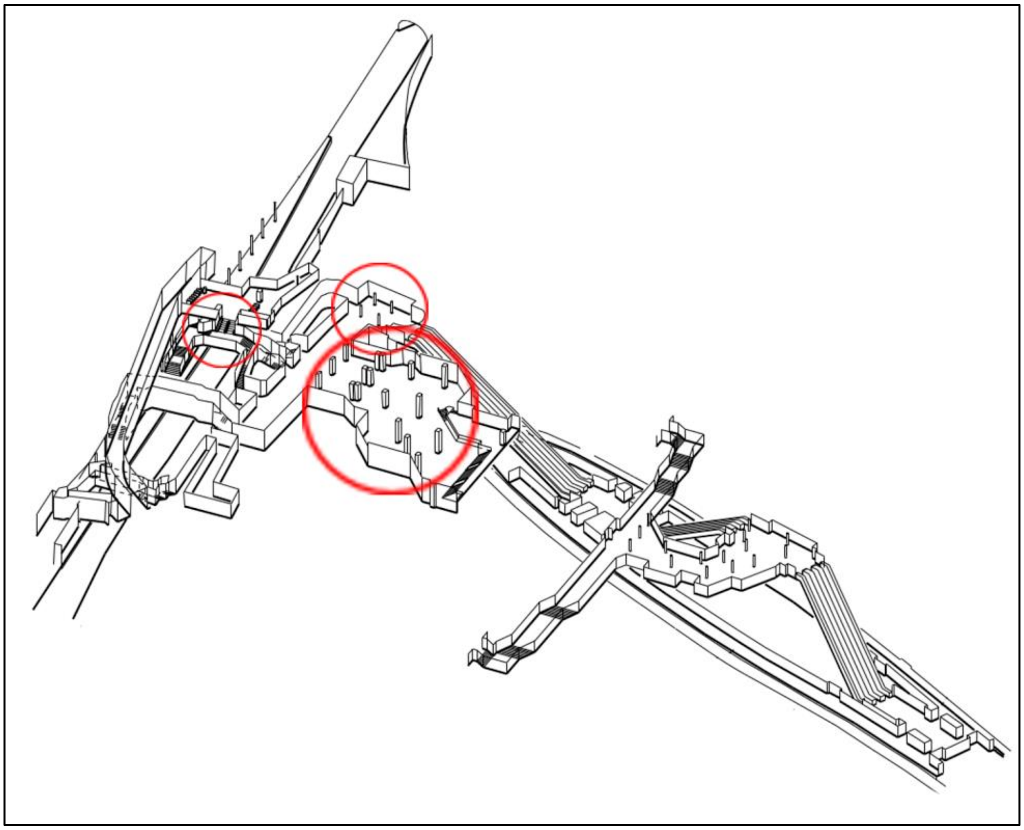


Figure 5: Liverpool Street Station Layout, TH A (left), Escalators 1,2,3 (top), TH B (Center)

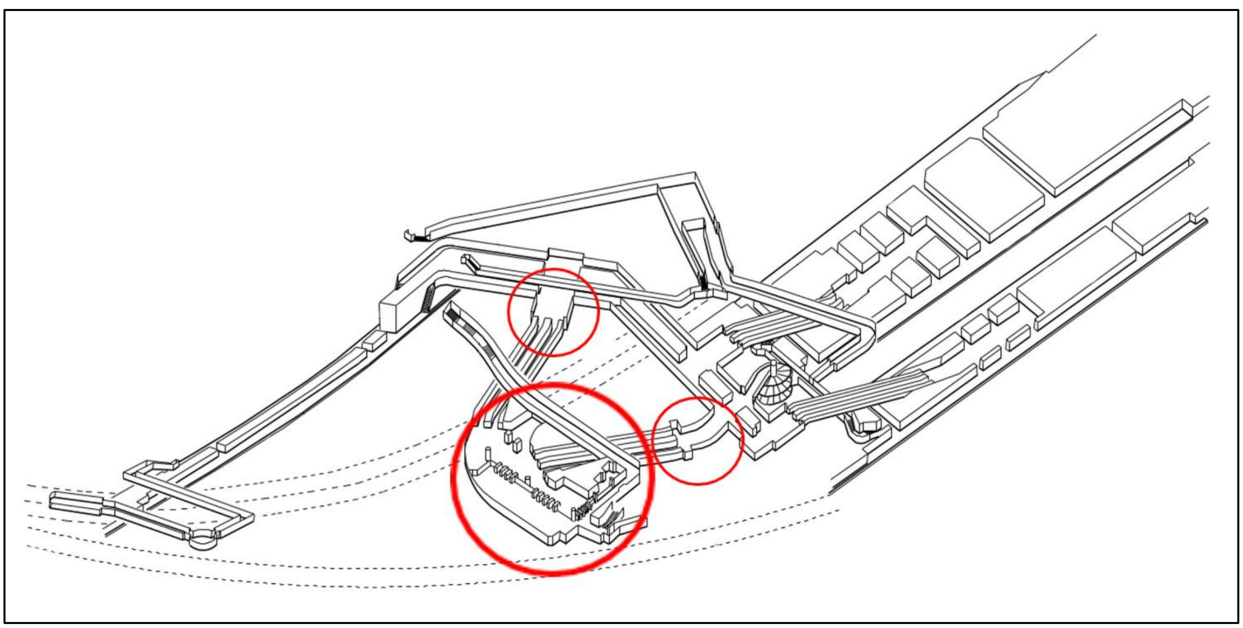


Figure 6: Euston Station Layout, Escalators 7,8 (top left), Escalators 5,6, (top right), Main TH (center)

2.1.1. Standards and Measurements Used to Define and Measure Passenger Flow

Due to its inherent variance, passenger flow can be hard to measure consistently. Even attempting to keep all conditions the same, passenger flow can vary dramatically from hour to hour, day to day. The first foray into measuring passenger flow was done in the late 1950s when Hankin and Wright conducted experiments and made observations that led to the development of some empirical relationships between passenger density, speed, and flow rates. Their work was later expanded upon by John Fruin in 1971, when he observed similar relations in passenger flow and developed a system to categorize the conditions of the flow called the Level of Service (LOS). LOS gives a ranking from A to F based on the space available to an individual, with A being the highest and F the lowest. There are different LOS values for each letter for walking, queueing, and stairs (Loukaitou-Sideris et al., 2015). These standards of measuring passenger and pedestrian flow are still in use today, and forms the basis for our measurements as well.

As passenger flow changes, three main types of peaks appear:

1. directional peaks occur where many passengers are heading a single direction (e.g., narrow corridors);
2. spatial peaks occur where many passengers accumulate in particular locations (e.g., at the bottom of escalators or at ticket barriers); and
3. temporal peaks occur at different times of the day and week (e.g., during rush hour or special events).

Our report focused on spatial and temporal peaks more than directional peaks, although all three peaks tend to occur simultaneously.

2.1.2. Measuring Passenger Flow

To measure passenger flow, already established systems, such as ticket counters and turnstiles, can be used to record passenger throughput without further experimental measurement. However, this is often either infeasible or simply insufficient. The simplest way to measure passenger flow is by hand—both by counting the number of passengers that flow through a system in a given time frame and by measuring how long it takes passengers to travel through the system. While these methods don’t require a lot of equipment, they require a lot of effort to obtain sizeable amounts of data.

Visually recorded data is a useful way for people to better picture the problem areas and to get real time data. Previous studies have utilized cell phone data to analyze passenger flow and throughput (Aguilera et al, 2014), although such a system raises concerns about privacy and can therefore be difficult to implement. A less invasive method of measuring passenger flow is through analysis of video footage. CCTV footage can be used alongside human observation to make it easier to collect large amounts of data–video may be sped up, and the flow of a whole day can be recorded in only a few hours. More ambitiously, computer analysis of CCTV footage can be used to not only measure passenger flow but also to identify problems and blockages that are causing congestion (Zhengyu, 2015). Microsimulation models can be used to better visualize movements and interaction of diverse passengers under highly congested scenarios and emergency evacuation. However, due to time and budget constraints, we do not consider these methods to be our source of analysis.

2.1.3. Analysis of Poor Passenger Flow

Poor passenger flow can often be attributed in part to insufficient vertical transportation, such as stairs or escalators, or suboptimal hallway width. In underground stations, vertical movement needs to be considered just as horizontal movement is; passengers will often need to move up or down in order to traverse the station, and halting either vertically or horizontally will impede flow. According to Hankin and Wright, "Movement on stairs is slower than movement on a level passageway, and movement up stairs is slower than movement down stairs" (Hankin and Wright, 1958). This means that stairs will often cause bottlenecks. Hallway width will also affect passenger flow: past 1.2 meters, flow increases linearly with the size of the passageway. As passageways become more crowded, pedestrians increasingly slow down to avoid contacting other pedestrians (Loukaitou-Sideris et al., 2016). The rate of this slowdown is well studied, and relationship graphs can be seen in Figures 6 and 7. Figure 5 demonstrates the relationship between passenger speed up a set of stairs or an escalator, and the space available per person.

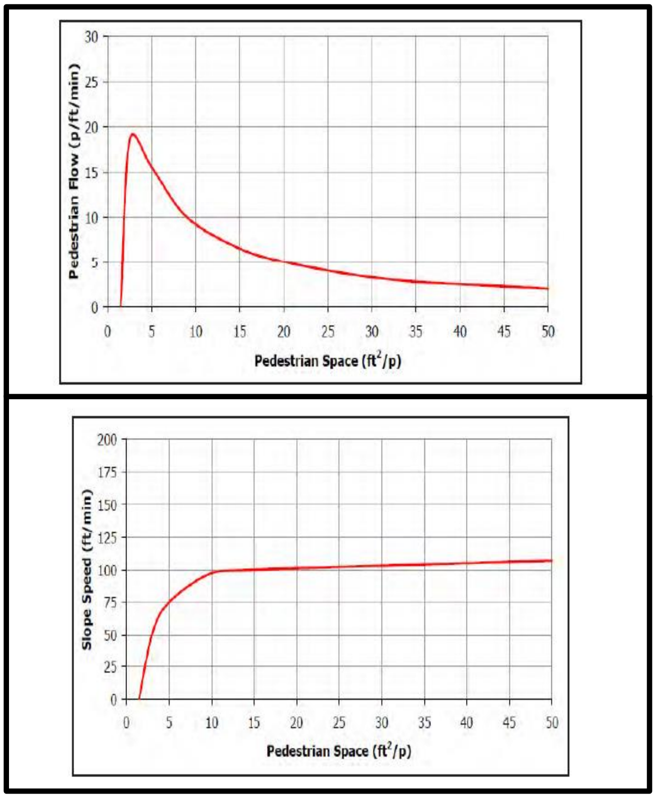


Figure 7: Pedestrian Space and Stairs (Fruin, 1971)

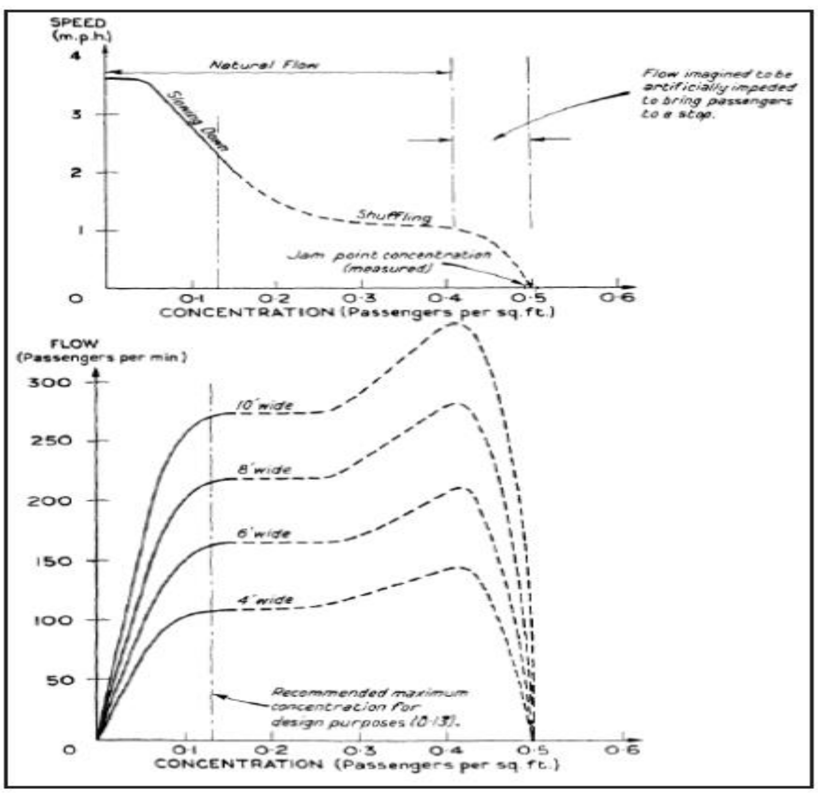


Figure 8: Speed-Density and Flow-Density Relationship (Hankin and Wright, 1958)

As the red line indicates, when people get closer together, they slow down dramatically, especially around at ten square feet per person. Figure 7 contains two charts: the first shows the relationship between passenger flow (speed) and space per person, and the second shows the relationship between flow and concentration (in passengers per square foot) for various sizes of passageway. Much like Figure 5, these charts show that as the number of passengers per area increases, passenger speed decreases.

Horizontal flows through passageways follow a fairly common-sense pattern, where the rate of passengers per minute increases until it reaches a critical density of passengers, at which point traffic grinds to a halt. Flow rate will increase up until passenger density reaches approximately 0.1 passengers per square foot (1.07 passengers per square meter). The flow rate then plateaus until a small bump in flow rate at 0.4 passengers per square foot (4.28 passengers per square meter), after which the flow rate plummets to a passenger per minute value close to 0. Since the rate of passengers per minute is directly correlated to passengers per square foot, the data suggests that Level of Service, a measure of approximate passenger density in an area, is a good representation of the congestion and approximate flow rate of a system. We can also see that the size of a passageway will increase the absolute amount of passengers per minute flowing through the system but will maintain the same pattern no matter the size.

Quantified passenger flow in an area may seem acceptable, but even slightly suboptimal passenger flow can cause untold effects on the system as a whole. Poor flow might cause more passengers to be grouped up on one end of the station rather than spread out evenly along the station. This would cause passenger discomfort due to overcrowding, which would in turn lead to more delays in passenger loading and unloading, with some carriages packed full and some almost empty. In a system as large as the London Underground, small delays quickly add up. Recently, passengers in the Tube wasted almost 400,000 hours in the last twelve months because of delays to their journeys due to overcrowding (Jones, 2017).

2.2. Improving Passenger Flow

The London Underground, while one of the oldest mass transit systems, has made a lot of progress since its founding over 100 years ago. Looking at similar transit systems, including the Hong Kong Mass Transit Railway, the New York City Subway, and Chicago's "L," our group can find some developments that may be adaptable to the London Underground. There have also been in-depth studies on passenger flow in other jurisdictions, such as the Mineta Report and Hankin and Wright's work, that provide many general suggestions and conclusions that can be applied elsewhere. Some of the recommendations presented the Mineta Report were also present in our final recommendations, and the Mineta Report's full table of recommendations can be found in Appendix B. Transport for London has already implemented many changes of their own to improve stations, such as performing preliminary passenger flow analysis and renovating problematic stations, including notably the Victoria station, which is currently undergoing renovation. More information about Transport for London's improvements can be found in both Appendix A: Sponsor Description and section 4.3.

2.2.1. Signage/Messaging Analysis

Improving station signage, including announcements, and information kiosks, has proven to affect passenger satisfaction. It may help to assist tourists and travelers who are unfamiliar with the location and prevent them from impeding others.

Stations around the world have moved into using **dynamic digital signage systems** in order to provide passengers with more up-to-date information. Providing information about delays and issues on lines through better signage can make passengers feel more at ease compared to stations with only static signage (Loukaitou-Sideris et al., 2015). The London Underground has implemented dynamic signage and announcements on many of its stations, and staff members are frequently available to help out passengers who require assistance ("Improving customer service," n.d.). Hong Kong also has dynamic signage, but announcements are made in multiple languages both over the intercom system (Yu, 2015) and on information panels and screens to help passengers know where the next stop will be ("Special Needs Booklet," n.d.). Support for multilingual signage is the next step to improving passenger flow through informing tourists where to go.

New York City has taken a modern approach to signage, replacing maps of stations with a **digital "Help Point" system**. The Help Points are easily visible communication stations that allow passengers to be helped by attendants and station staff upon activation ("Help Points," 2011). The Help Point system was designed by Motorola, who looked at the resources currently present in NYC subway stations and improved on them to provide more reliable service. Available intercom and speaker systems allow passengers that don't need emergency or immediate service to talk to station operators remotely. Help Points are also compliant with Americans with Disabilities Act regulations, which helps to make the stations more accessible to passengers that might have disabilities that would otherwise preclude them from being able to use the station in a normal manner (Motorola, 2014).

Transport for London, notably, already have Help Points in many of their stations to assist with passengers, but the understated appearance of these stations can lead to them being overlooked by passengers who don't know what they're looking for (See Figure 9).

Figure 9: Example of a London Underground Help Point (London Particulars, 2011)

On the Go Stations

New York City's implementation of **"On The Go Stations"** in addition to the Help Points in their subway system to allow commuters and passengers to view train delays at a glance. These small kiosks allow passengers to check their trip information and receive directions to their next train or a station to walk to. The stations also provide elevator and escalator statuses, which may help disabled guests to navigate the stations more easily. Like the "Help Points," On The Go stations are designed with tourists in mind (Nelson, 2011). This system is very similar to Transport for London's existing "TfL Journey Planner" but has the added benefit of being a permanent installation and working without needing a cell phone or other Wi-Fi-enabled device. Tourists are a significant cause of delays and other complications on the London Underground, with an average of 5.1 passengers with luggage causing delays on a train for every 10 trains in service (Kelley, Ko, Mazza, & Robinson, 2016).

Handicap-accessible Improvements

Hong Kong's Mass Transit Railway also offers a significant amount of **signage aimed at disabled riders**, some of which is completely missing from London Underground stations. Station layout maps are available for visually impaired riders to enable them to navigate most, if not all stations, on a given line. Transport for London does offer a guide to step-free station access and an audio train map, but no equivalent for finding your way through the station itself. They also provide guide paths along walls to help blind passengers navigate between stations and down to the platform level ("Special Needs Booklet," n.d.).

2.2.2. Operation

The construction of the train station is one of the most important factors in passenger flow. Insufficient exits, entrances, or vertical transportation sites can bottleneck passenger flow. Improvements in train station architecture and layout have contributed to alleviating poor passenger flow and congestion in New York City and Chicago. The goal of New York City's system is to relieve the crowding around terminals and MetroCard stations by providing alternate entrances to busy stations, including opening entrances that were previously closed. By turning some currently exit-only areas into entrances as well, New York City may be able to relieve congestion at many stations, at a lower cost than creating a completely new entrance (NYC Transit Riders Council, 2001).

Chicago has addressed overcrowding in a similar way through renovation, but as it is an even older system than New York City, Chicago has generally resorted to complete overhauls of stations as opposed to gradual changes. The Red Line, in particular, was singled out in 2011 for having a long-awaited renovation to several stations along the line, with many stations being entirely demolished and replaced. Some other changes in Chicago include overhauls of already in-place routes, adding modern stations in lieu of some older stations in a slightly different area. The overhauls are to be carried out over a long period of time- large scale improvements to existing systems can cause delays; they must be planned meticulously before they can be implemented. As can be seen in Figure 10, which contains the timeline for the first phase of Chicago's Red Line overhaul, completed in 2015. Even the first phase took several years to complete. The London Underground takes special care to ensure that their upgrades and overhauls do not impede service where possible. The Washington/Wabash station is an example of a successful but pricey upgrade and was created to replace two stations that were over a century old, Randolph and Madison, and should provide better, more modern infrastructure, but it came at a high cost overall (Hilkevitch, 2011).

Figure 10: Timeline of Improvements for Chicago's Red/Purple Line Modernization ("Red & Purple Modernization," 2016)

A good analogue to the London Underground’s ongoing Victoria renovation project—which aims to install more escalators, increase handicapped accessibility, and optimize efficiency for passengers travelling through the station—is the largest project in Chicago’s mass rail transit history, the renovation of Wilson Station. This renovation resulted in a complete rebuild of a station that was first built in 1923. The renovation was sought as the old Wilson Station had deteriorated past the point of repair and needed to be updated to comply with ADA standards. By adding elevator and wheelchair access as well as providing more spacious facilities and stairless entryways, passengers that must pass through the station will be able to do so more freely. Wilson Station will also sport wider stairwells, as well as three entrances (as compared to the more typical single entrance found on subway stations) and signage improvements, which should overall, improve the flow of traffic through the station to a significant degree (“Wilson Station,” 2013).

2.2.3. Responses to Congestion

Cities around the world have mixed approaches to dealing with congestion on their mass transit system. All of these approaches must be revamped before they can be considered for use in the London Underground. New York City has yet to undergo a major overhaul in passenger management since 2005, when they began to implement computerized train operation starting on the “L” line (Chan, 2005). Instead, passengers have been packed into overcrowded subways for years, resulting in safety concerns and uncomfortable riders as far back as 2007. Urban planners even believe that many lines may be years away from being fixed or renovated so that they may resume operating under capacity (Neuman, 2007). The throughput of New York City's subway system has ballooned in recent years. Ridership is the highest it has been since 1948, resulting in increased delays for commuters and disgruntled passengers (Fitzsimmons, 2016) (See Figure 11). Overall, New York City appears to be unable to approach the issue without major expenditure, and as the city expands every year, they grow closer to a very expensive problem.

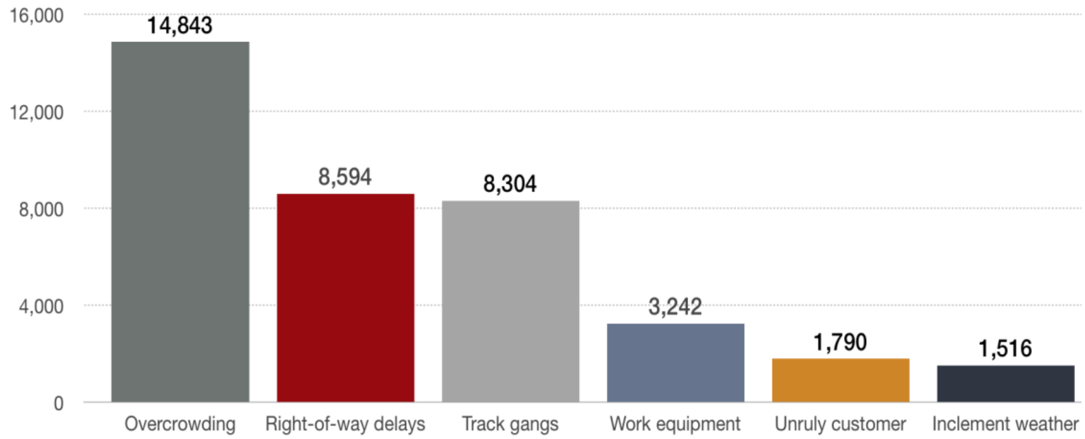


Figure 11: Chart of Frequency of Delays on NYC Metro (>1,500 instances) (Ballaban, 2015)

Hong Kong's Mass Transit Railway has taken a more productive approach to addressing congestion on the metro. Hong Kong employs a set of by-laws to specifically disallow overcrowding on trains. Passengers who are found to be pushing onto trains that are already at capacity will be subject to punishment (MTR By-Laws, n.d.). However, this may leave passengers stranded to wait on the platform for another train. Passengers are also prohibited from bringing large luggage onto trains as the process of embarking with oversized bags can lead to delays. The removal of buskers, smokers, and loiterers in the Mass Transit Railway system may also lead to better passenger flow, but this has not been explored in full yet (MTR By-Laws, n.d.). During instances of extremely high congestion, the station's Customer Service Manager will ask incoming trains to skip their station in order to provide some relief. Occasionally, congestion will be so severe that the station must be evacuated to a nearby street or concourse, where passengers will slowly be let back in. On the train itself, as more than a third of passengers in the morning rush hour have to stand, the introduction of flip-up seats helps provide more space for standing passenger. According to London-based transport consultancy firm PriestmanGoode, these designs boost passenger capacity by thirty percent (Holmes, 2016).

2.2.4. Encouraging Good Flow

Passenger flow can be improved in a variety of ways, from the obvious, such as stairways and rails, to the more subtle, such as ambient temperature differences in the air that might make it more preferable to be in one part of the station as opposed to another (Kelley, Ko, Mazza, & Robinson, 2016). Maintenance of efficient, effective passenger flow can be accomplished through changes to a rail station's operating procedures and layout. Frequent, audible instructions and readily available transit staff can help passengers find their way through a station much more effectively, reducing the number of blockages or congestion incidents due to lost passengers (Loukaitou-Sideris et al., 2015). Changes to the vertical flow of passengers in order to induce more people to use escalators or elevators in a shorter amount of time also encourages better flow and can reduce congestion (Loukaitou-Sideris et al., 2015). Station platforms should also provide passengers with enough space to comfortably group on the platform and within the train, as passenger congestion within a train can negatively affect people's outlooks (Seriani, Fujiyama and Holloway, 2016). We took into account these previously proposed ideas for improving passenger flow when we performed our own analysis.

2.3. Conclusion

As more people use public transportation each year, Transport for London faces a serious problem with passenger congestion. With this information informing us of the state of the London Underground and various approaches to similar projects around the world, we are prepared to begin looked into passenger congestion. With knowledge of previous studies and their results, we formulated a set of methods to define our data collection and analysis.

3. Methods of Measuring Congestion and Effects on Passenger Flow

The goal of this project is to assess the issue of passenger congestion and flow in the London Underground and suggest potential solutions and improvements. Our main objectives were:

- Conduct a detailed analysis of passenger flows at selected interchange stations to identify major areas and causes of congestion;
- Evaluate passenger opinions about congestion to determine links between public opinion and congestion; and
- Recommend approaches to better manage passenger congestion.

We initially expanded our understanding of the nature of passenger management by consulting with transportation experts at TfL and London universities. We conducted detailed assessments of passenger flow at the Euston and Liverpool Street stations by interviewing employees from Transport for London (TfL), and by analyzing CCTV footage and on-site observational data. We supplemented our analysis of passenger flow by analyzing survey information from Transport for London's databases. We finalized our recommendations following a focus group discussion with TfL employees to identify potential improvements in controlling overcrowding and congestion.

3.1. Passenger Flow Observation

We conducted an in-depth analysis of passenger flow at selected stations to define the scope of the problem. Our analysis was informed by staff interviews, observation of CCTV footage, and real-time observation of passengers in stations. Our first task was to identify the sample of stations for our analysis, which we discuss below.

3.1.1. Station Selection and Preliminary Interviews

Station Selection Criterion: Initially, our sponsor identified a list of eight possible stations to analyze (Table 1). Due to time and other constraints, we determined a set of criteria in conjunction with our sponsor to select a subset of these stations for data collection. First, stations that we identified as having serious ongoing construction were immediately ruled out as being unsuitable for our experiments, as construction can significantly affect our results. Next, we determined which stations had severe congestion to divide them into two groups. After determining the likelihood that we would get CCTV access at each of the stations, we looked to focus on stations with a Network Rail station attached, as these would receive significantly more traffic than a normal interchange station.

(Table 1: Station selection criteria)

	Interchange station	Construction	Severe Congestion	CCTV	Handicap Accessible	Network Rail Interface
Bank/Monument	Y	Y	Y	N	N	N
Embankment	Y	N	N	N	N	N
Euston	Y	N	Y	Y	Y	Y
Liverpool Street	Y	N	N	Y	N	Y
Oxford Circus	Y	N	N	N	N	N
Paddington	Y	N	Y	N	Y	Y
Victoria	Y	Y	Y	Y	N	Y
Waterloo	Y	Y	Y	N	N	Y

Our final decision narrowed down our primary focus to two stations. Our primary stations are Euston and Liverpool Street, which we determined based on discussion with our sponsor, our ability to access CCTV footage, and their position as stations that interface with network rail. These stations have many similarities, but differ in handicapped accessibility and congestion level, and provide us with suitably diverse data to get a better view of the London Underground as a whole.

3.1.2. Employee Interview

Employee interviews targeted employees who have hands-on jobs, such as standing beside barriers answering passengers' questions, at Euston Station and Liverpool St. Station. At each station, we interviewed ten staff members on the spot during off-peak hours throughout the station and asked a series of questions, found in Appendix C, about the station and the customers inside. We took many precautions to ensure that we protected the identities of the employees that we interviewed. Interviews were conducted in pairs, with one group member asking the questions and conducting the interview, and the other group member taking notes digitally. Employees that were too busy to answer questions or that did not want to answer questions were skipped over and only full interviews were taken into account for this project.

Questions were revised after an initial set of test interviews to become less redundant and to provide us with more pointed areas of observations. The data from these interviews helped select primary areas of observation for the CCTV observation that took place afterward. Our primary conclusions were that escalators were trouble points, and that most questions were by tourists looking for tourist destinations. These answers also were the foundation of the suggestions that we have provided in our conclusions.

3.1.3. CCTV Observation

We determined which locations to observe (limited by the locations of the cameras) using data gathered from employees about highly congested choke points in the station and from the Mineta Report. Eventually, we aimed to look at choke points at escalators and ticket hall because these are where queues happen at our primary stations. We utilized CCTV recordings covering the peak times, according to information received during employee interview, which are 07:00 to 09:00 and 17:30 to 19:00 on Friday, and 09:30 to 12:30 and 17:30 to 19:00 on Saturday at Euston Station, 06:30 to 09:30 and 16:30 to 19:30 on Tuesday, and 0930 to 12:30 on Saturday at Liverpool street Station, to ensure that we were able to see the stations at their most congested.

CCTV cameras provided data, which we collected at each station during multiple time periods for each camera view. We collected data at both peak and off peak times to provide a point of comparison between each camera. Density data was collected by screenshotting the CCTV per minute and counting the number of passengers in a given area for 90 minutes or 180 minutes (varied with weekdays and weekends). Given privacy concerns, we deleted every screenshot after finishing counting the numbers and no data was retained aside from aggregate counts. This density data was plotted over time and compared with other areas of the station, as well as with itself at peak or off-peak times. The density data was then compared with data on the conditions of the station of the time in order to explain anomalous data and establish a cause and effect relationship with regards to congestion. The data was plotted in various line graphs, with moving averages and trend lines plotted alongside them to show the flow of passengers through the day that can be seen in Figure 12.

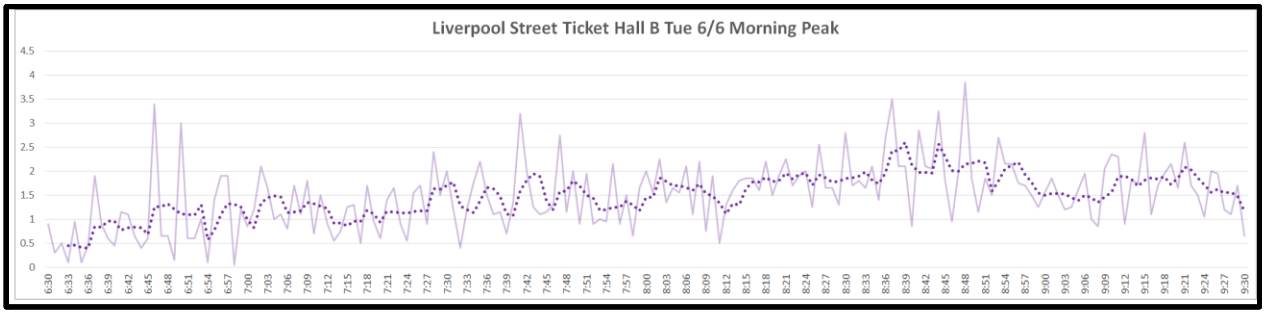


Figure 12: Example of Passenger Density Graph with Normalization

3.1.4. Data Analysis

Data analysis was handled through applying Level of Service (LOS) measurements (Fruin, 1971) to the data collected about passenger congestion and through comparing passenger satisfaction per line with known ridership data for each line. The LOS letter grades and their corresponding values can be seen in Table 2. First, we determined the average LOS in various areas in the station using our passenger density data.

(Table 2: LOS Values)

LOS Rating	A	B	C	D	E	F
density (p/m^2)	0.3	0.3<d<0.43	0.43<d<0.718	0.718<d<1.08	1.08<d<2.15	2.15<d

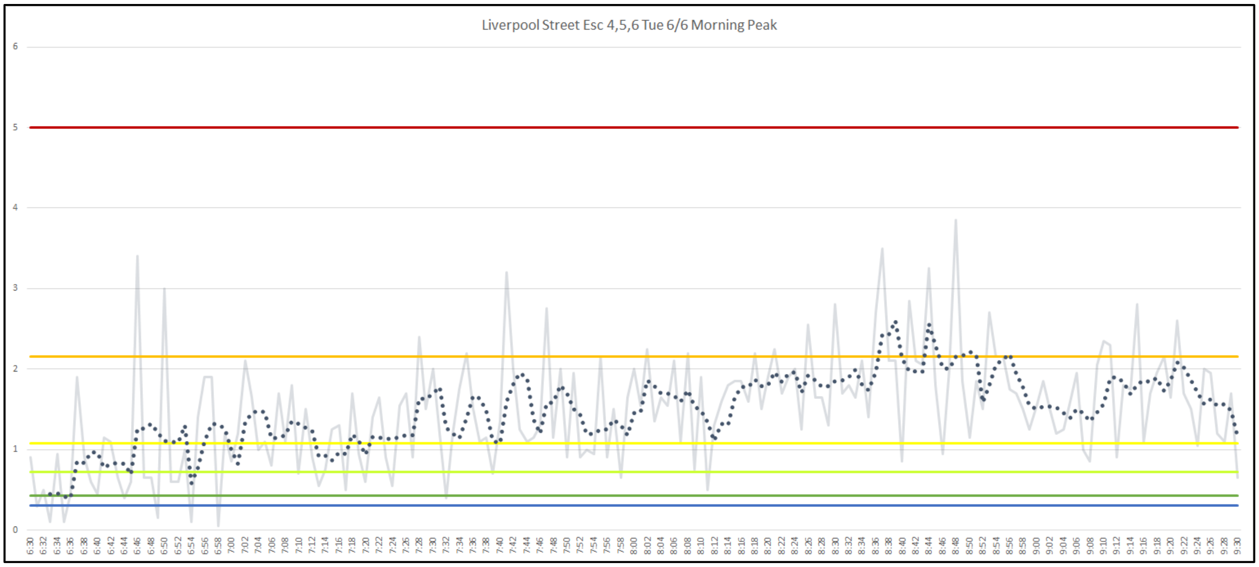


Figure 13: Early Design for Data Representation

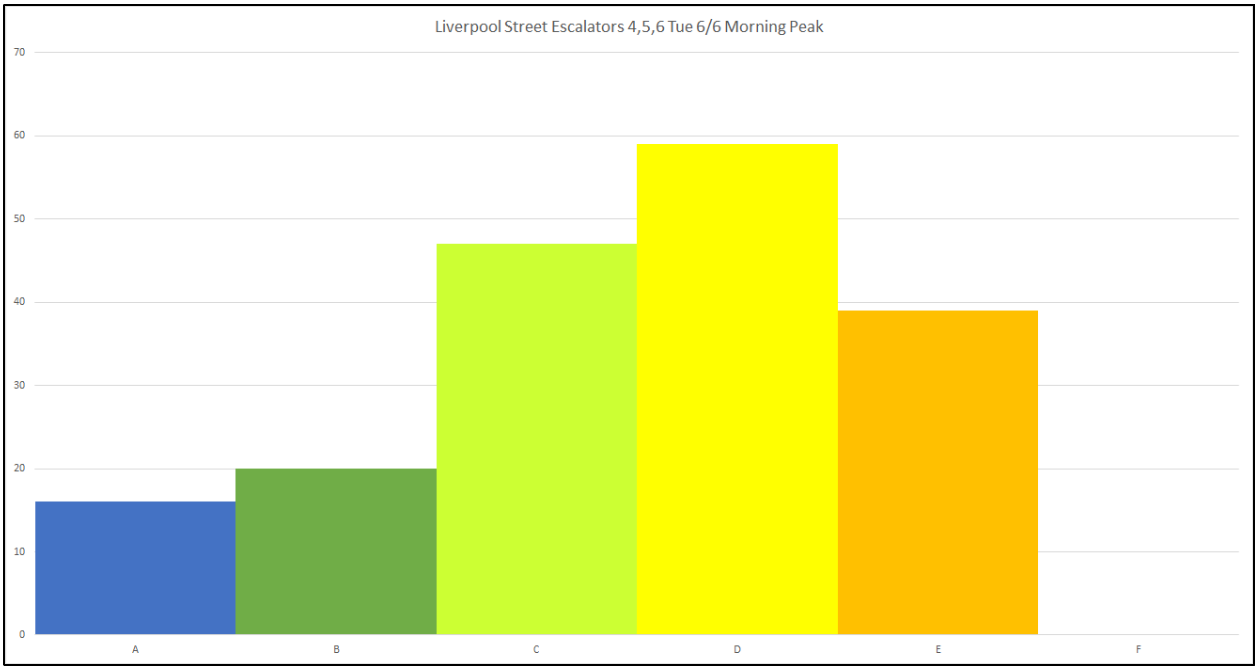


Figure 14: Example of Histogram displaying LOS Data

This was done by taking the data points for number of passengers passing through a location and dividing by the area through which they were moving. We considered using a graph of passenger density over time with the different bars for each LOS labelled on the graph as shown in Figure 13, but due to the clustered and confusing nature of such a graph we opted for a histogram style of data visualization.

Using spreadsheet software to calculate the frequency of each LOS value, the frequency data was used to create a histogram with uneven bins which can be seen above in Figure 14. Each bin is color coded according to its LOS, and the values used are reported in Table 2. The height of the bar corresponds to the number of minutes that the location the graph represents was at that LOS, and all of the heights sum to 180 total. Averages were taken using the set of LOS data arranged and put in order. If a location had a poor average LOS, which would be an average of D or lower as in Table 2, cited above, we knew that that area would need to be targeted for emergency or short-term improvements to help the stations manage the increasing numbers of passengers coming through each year. In addition, we plotted peak values of congestion and passenger density at each area of Euston and Liverpool Street against the theoretical maximum functional density in each area of the station based on the values in Loukaitou-Sideris, et al., (2016), as can be seen in Figure 15 below. The data represented is passenger density versus time for Euston ticket hall on a weekday peak and a weekend off peak. The red line represents the "recommended maximum concentration for design purposes" which was indicated in Hankin and Wright's work and cited in Loukaitou-Sideris et al.

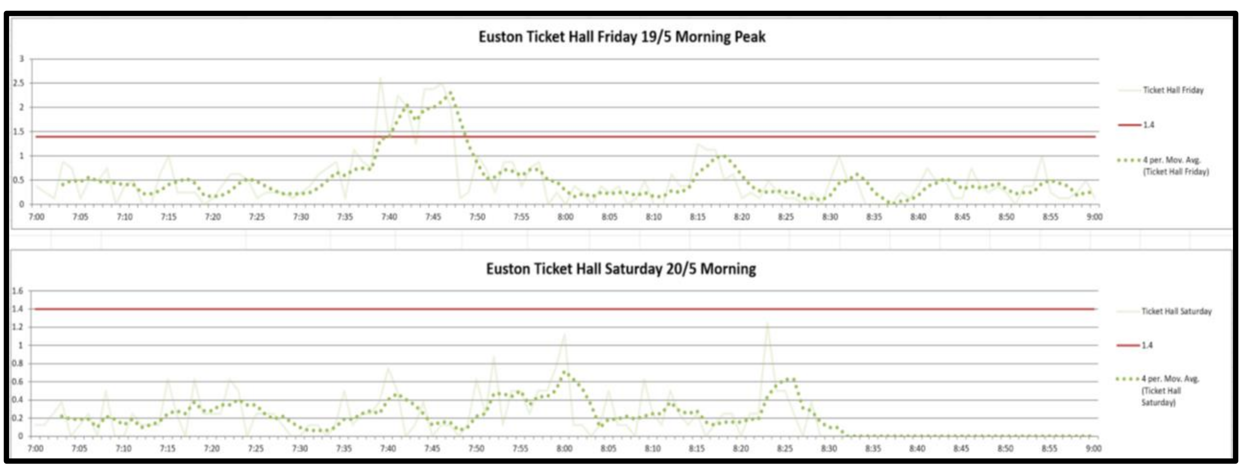


Figure 15: Example Graph Comparing Density Over Time with Reference to Operational Maximum

The line represents 1.4 passengers per meter squared, which corresponds to a LOS of E. If an area is consistently near or exceeding this recommended maximum, then we concluded that that area of the station is operating at or near their maximum capacity and may need an additional focus in relieving the passenger flow in their area. For example, as can be seen in Figure 15 and Figure 16, the Euston ticket hall greatly exceeded this maximum design capacity for several minutes starting at 7:39 on Friday morning, finally returning below the maximum at 7:48. During that time, the LOS was an average of F. This can be seen on the histogram in Figure 17 by the height of the red and orange bars, which represent almost the entirety of this time. This means that the passengers were packed tightly together and were not moving, leading to more people piling up behind them as they entered the area. When compared to the graph of Saturday at the same time, the values hardly exceed 50% of the design maximum, while on Friday the data regularly reaches 60% or more.

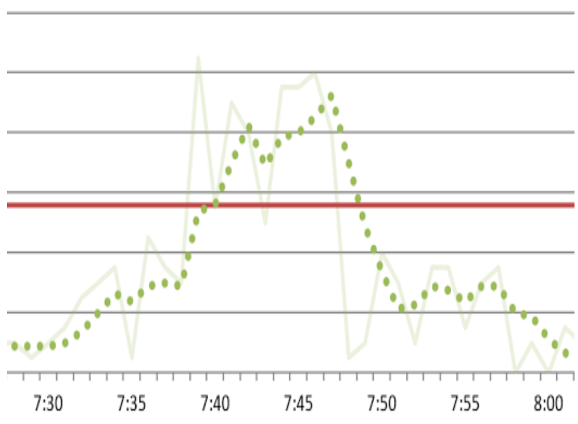


Figure 16: Euston Ticket Hall Major Disruption

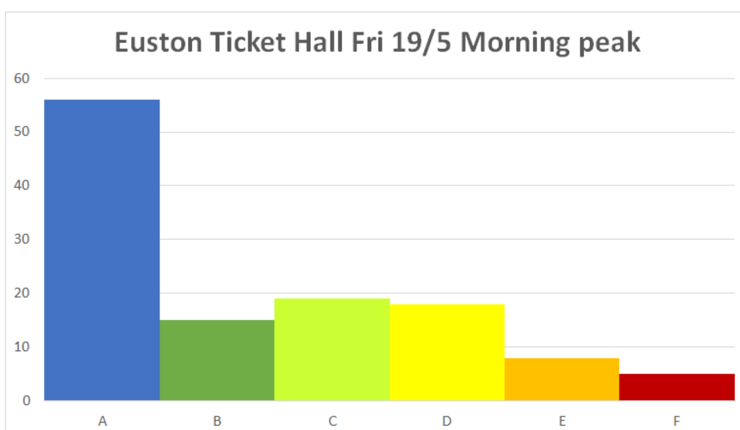


Figure 17: Histogram of Euston Ticket Hall

3.2. Passenger Satisfaction Measurements

In order to supplement the data gathered on congestion, our next focus was on the public's reaction to congestion in various areas, to predict how they might respond to various congestion relief procedures. We analyzed prior customer surveys, and we gathered their existing data from TfL sources regarding crowdedness of stations, ease of use, clarity of signage, and station preference in order to identify other problem areas to better suggest improvements.

3.2.1. Data Analysis

Passenger satisfaction data was taken from a Transport for London survey conducted in Q1 2016/17 (herein referred to as Customer Satisfaction Survey, or CSS) and analyzed with regards to the system averages. Each line was compared to the London Underground as a whole on sets of metrics involving every part of the operation of the train lines. The areas this report focuses on are primarily areas of satisfaction relating to signage and station operations. This report also takes into account frequency of delays and train operations, but these are not as much of a priority.

Passenger satisfaction data was also compared to annual lineload summaries, also taken from Transport for London, in order to determine if there is a correlation between customer satisfaction and congestion. Annual lineloads refer to the number of trips taken on a line over the course of a year and do not necessarily all come in and out of the stations we are looking at. Again, overall satisfaction for each line going into Euston and Liverpool Street was compared to the annual lineload in order to determine if there were any matching trends. Individual areas of train and station operations regarding congestion satisfaction were also compared to the lineloads to find any correlation.

3.3 Vetting Preliminary Analysis

The ultimate goal of this project is to develop a set of potential solutions that will potentially aid in reducing the problems with passenger flow in the stations we observed as well as the London Underground as a whole. In addition, our report includes graphical representations of our results in order to easily show how we formed our conclusions. This section discusses how those solutions were formed and then selected as our final recommendations for this project.

After we performed our testing and data collection, we tapped into the expertise of TfL and Tube employees to help refine our solutions and get better insight on what we've proposed. Our primary focus was from a group consisting of senior TfL employees and operational staff, in order to get a broader range of opinions on our solutions. We asked questions, as seen in Appendix E, to validate our proposed solutions and to gain some insight on the validity and feasibility of solutions. As a result, solutions were revised and in some cases removed in order to ensure that our report did not contain any unreasonable suggestions. This focus group, combined with a very successful presentation of our findings to our sponsor and his team, provided us with new ideas and insights for our solutions and strengthened our findings overall.

Using the information gathered both from our own analysis and from the focus group, we identified potential improvements that could be made to the Tube that would improve passenger flow or passenger satisfaction. Suggestions were evaluated as to how they will affect service during implementation, as well as their cost, effect on customer satisfaction, effect on passenger capacity, and the potential barriers to introduction. Then, using the information gathered from our focus group along with consulting with experts at TfL, we determined the size of the barrier to implementation for each suggestion and the overall feasibility for each. An improvement that has a very large barrier to implementation, such as expanding a station, might only be a worthwhile suggestion if it also has a very large efficacy. We went through our list of potential improvements, identifying the potential improvements that are both effective and relatively easy to implement, and compiling those into our final list of suggestions to be presented in our final report.

4. Findings and Analysis

Overall, our findings indicate that while Euston and Liverpool Street currently operate within comfortable bounds, influxes of passengers over time and ongoing improvements and maintenance projects may cause them to reach critical mass. As the number of trips taken on the tube is increasing annually, we can expect passenger density in these stations to grow at a fairly linear rate of about 4-5% per year. This annual growth is compounding and can result in some areas, such as the escalators in Euston, to quickly become overcrowded and create an unsustainable situation in the station. The introduction of Crossrail 2/High-Speed 2 would also cause many issues at Euston, as the projected increase in traffic into London by 270,000 people per day would almost certainly cause operations in Euston, in its current state, to grind to a standstill (“Crossrail 2,” 2017).

Signage is an area of concern that tends to confuse passengers including experienced commuters and is often located in inaccessible areas. Signage in Euston station included some questionable and confusing choices, especially around escalators. The two escalators at the entrance are each individually labelled, with one being indicated as the “Northern line” and the other as the “Victoria line” (See Figure 18). In reality, both escalators go to the same place and allow both lines to be accessed. This leads to one escalator backing up while the other is entirely clear due to passenger confusion. Liverpool Street, conversely, has problems with signs being too inconspicuous. Some signage around maps is located about one foot off the ground, directly in the line of sight of no one aside from small children (See Figure 20). In addition, some “way out” signs are not lit, resulting in them not being able to grab passengers’ attention (See Figure 19). Signage needs to be more visible and placed where passengers are more likely to see it so that it can better guide passengers (Loukaitou-Sideris et al., 2015).

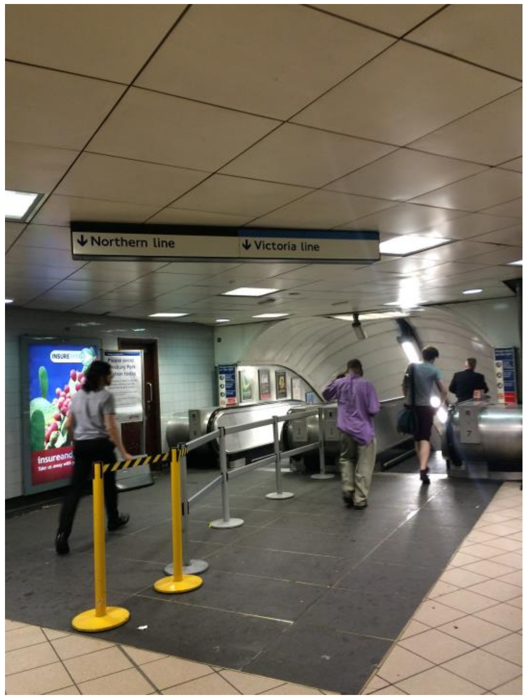


Figure 18: Example of Unclear Signage at Euston Station

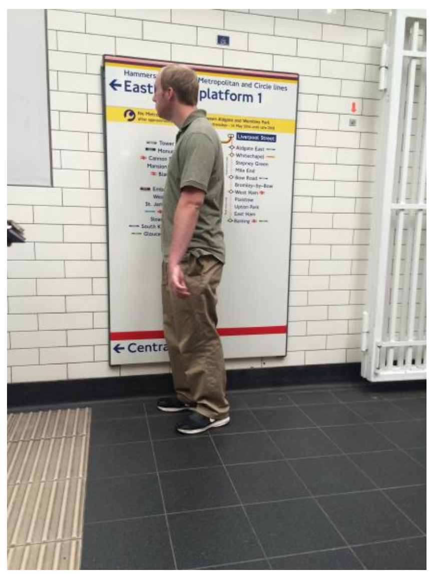


Figure 19 and 20: Unclear Signage Examples at Liverpool Street- Way Out Lighting (19), Low Signage (20)

Customer density is too high at peak times, resulting in frequently problematic level of service measurements across both Euston and Liverpool Street. Level of service measurements at a D or above tend to result in passengers moving slowly and being uncomfortable during their journey. Some areas of Euston and Liverpool Street stations suffer poor levels of service (E and F) for extended periods during rush hour. As shown in Figure 21, Ticket Hall C in Liverpool Street spent over 100 minutes in a three-hour section of observations at a Level of Service of F. This represents a massive amount of time where passengers are pressed into each other, unable to move easily and are unhappy with the congestion around them. Areas like Ticket Hall C need special care taken to alleviate the congestion and should be prioritized over areas like Euston's ticket hall, which as previously shown is operating well at the moment.

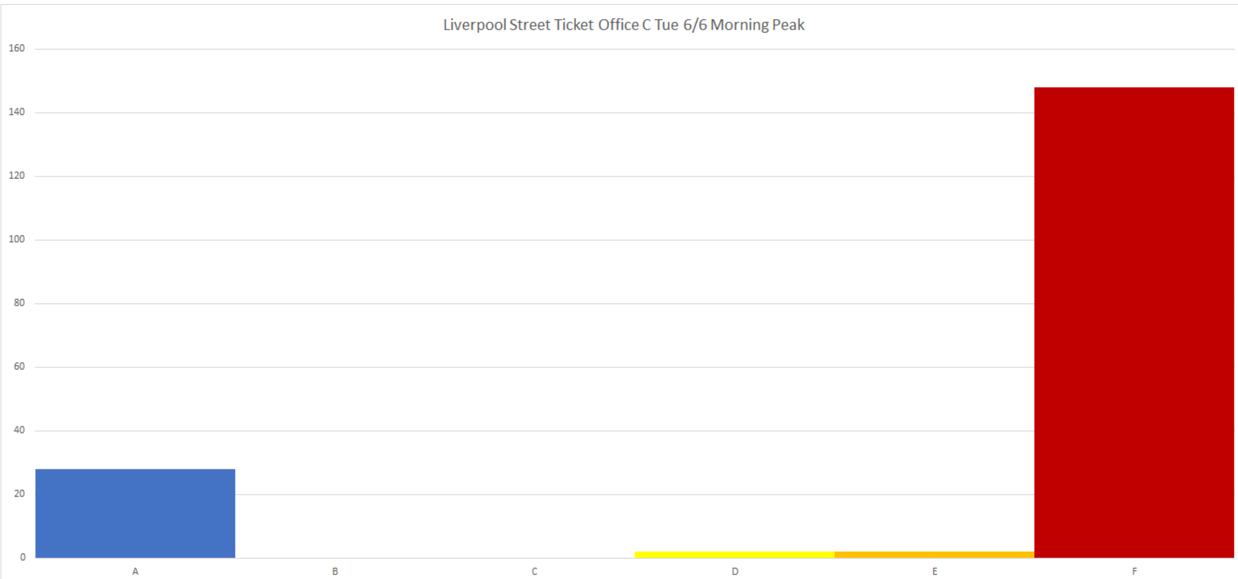


Figure 21: Liverpool Street Ticket Office C, Morning Peak Level of Service Frequency

Passenger flows at ticket halls in Liverpool Street tends to be multimodal, but the flow is different depending on the time of day. For example, Figure 22 shows a comparison of passenger density in Ticket Hall B of Liverpool Station during morning peak, off-peak, and evening peak hours. It is immediately obvious that during off-peak hours, Ticket Hall B maintained a reasonable Level of Service, with the average value never passing 1.5 passengers/meter. Morning and evening peak hours, however, were much worse in terms of passenger density. The average passenger density was consistently at an uncomfortably high value throughout peak hours, demonstrating that Ticket Hall B during peak hours is incredibly congested. In some cases, the passenger density approached the critical point where passenger flow rates begin to decline precipitously and the station grinds to a standstill.

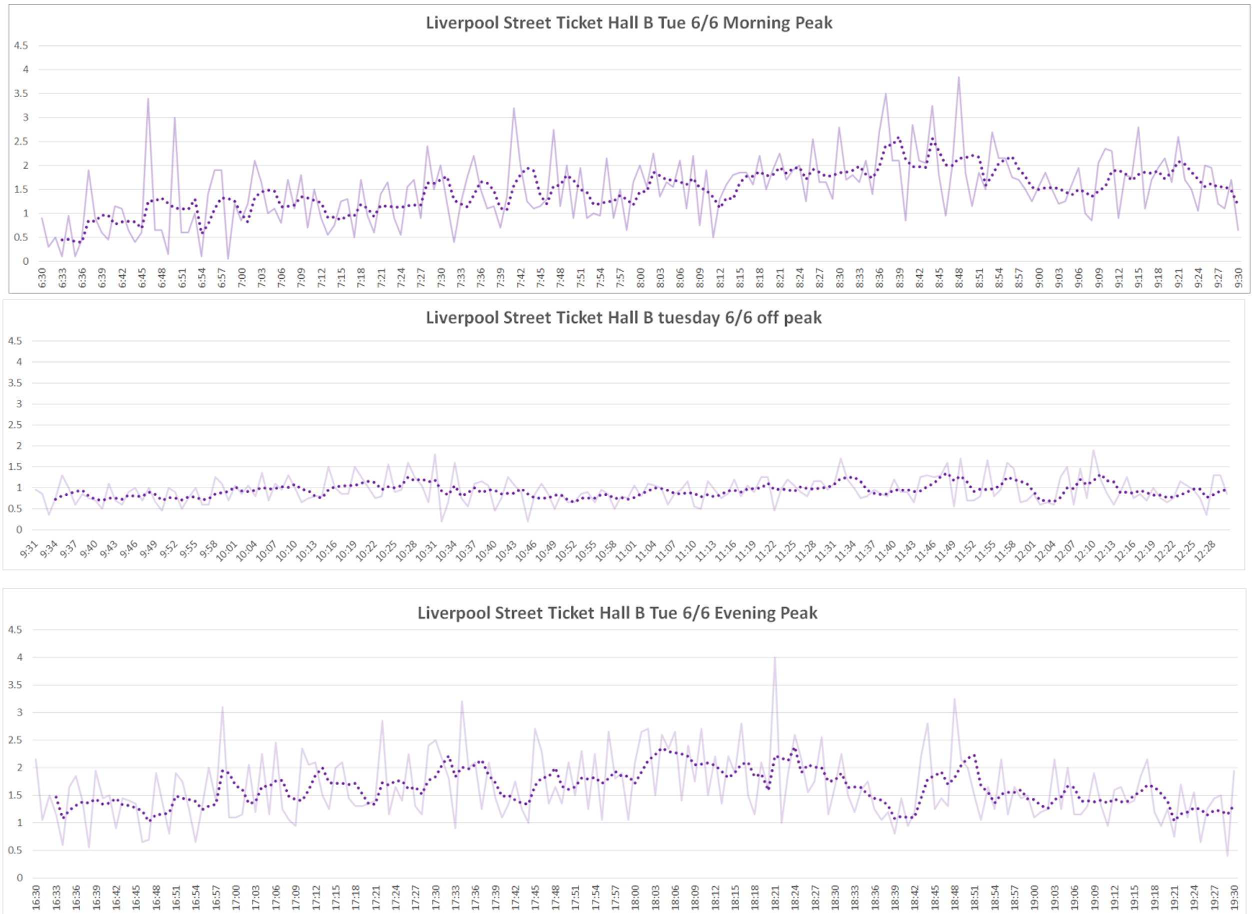


Figure 22: Ticket Hall B Density Comparison: Morning Peak, top; Off-peak, middle; Evening Peak, bottom

Figure 23 and Figure 24 show passenger density at one of the worst spots in Liverpool Street, Ticket Hall B. As seen in Figure 23, the level of service inside the ticket hall is dismal during the morning rush hour, where the level of service is at E or F for extended periods. The overwhelming majority of recorded time was either an “E” or “F,” both of which are too congested for passenger flow and comfort. This is similar to what we have seen in Ticket Hall C during the same time period, where the level of service is at a rating of F for most of the time. The graph in Figure 24 shows that density rose slowly over time: for the first hour, the density stayed below the line at 1.4, indicating that the LOS was in the A-C range. However, past 8:10, passenger density hardly dipped below 1.4, indicating that passengers were most likely unhappy. Overall, we can see that Figures 23 and 24 show two sides of the same coin: Figure 23 indicating the overall severity of congestion, and Figure 24 showing the trends in congestion during the peak.

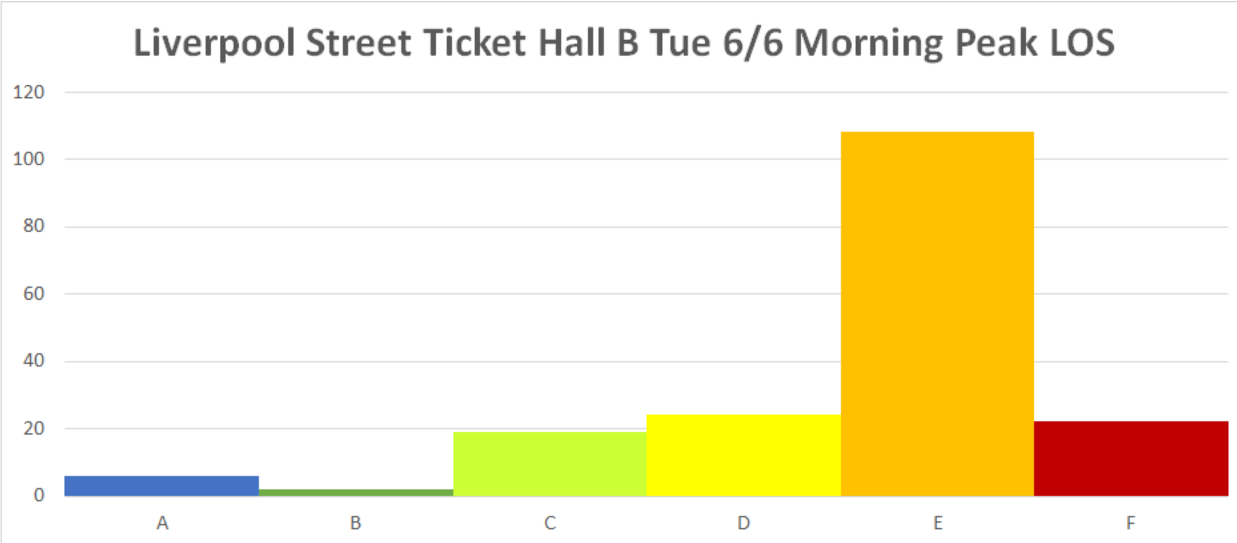


Figure 23: Liverpool Street Ticket Hall B Morning Peak Level of Service Frequency

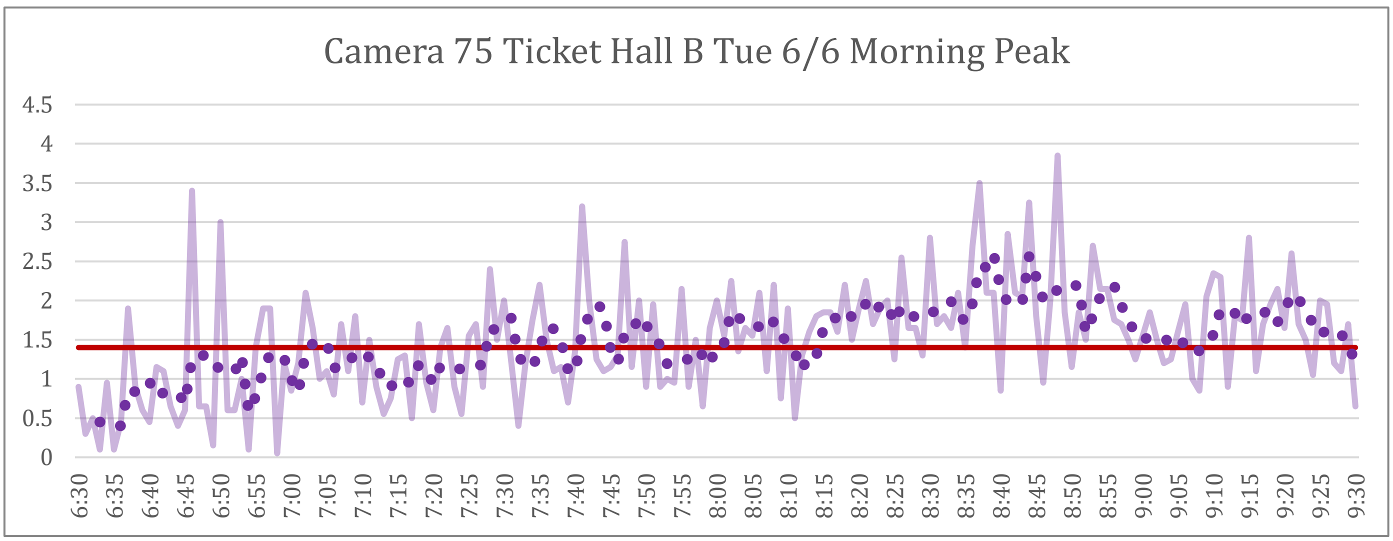


Figure 24: Ticket Hall B Morning Peak Passenger Density, 1.4/m Line in Red

Areas outside of the ticket halls in Liverpool Street tend to follow similar patterns of congestion throughout the day, despite being in very different areas around the station. Figure 25 shows key relationships between passenger density in different areas at Liverpool St. The top graph shows density in Ticket Hall C, the middle graph shows the top of escalators 1, 2, and 3, and the bottom graph shows the bridge leading to Ticket Hall A. These three locations are spread across the station, and yet our data indicates that passenger density in these locations tended to follow the same patterns. At 7:00AM, the opening of the Central line causes an increase in passengers at Ticket Hall C, which is almost immediately seen all the way across the station at the bridge. A little after 8:10, a lull in trains caused density in all areas to drop, and at 8:50, all three cameras pick up a sudden spike in passenger density. This can be attributed to a large train from National Rail, a particularly heavily packed train coming in on one of the lines, or to the mere coincidence of multiple trains arriving at once. Alternatively, we theorize that the peak at 8:50AM may consist of commuters arriving at the last possible moment that will allow them to walk to their offices before work starts at 9AM. Either way, crowding tends not be a localized issue: problems in one area quickly distribute themselves across the station.

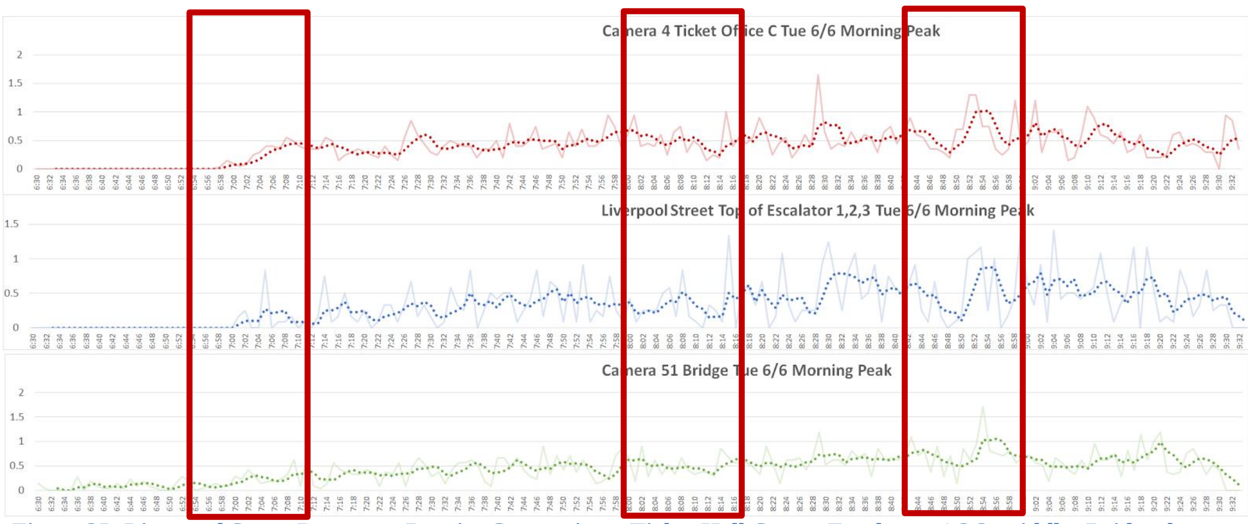


Figure 25: Liverpool Street Passenger Density Comparison: Ticket Hall C, top; Escalators 1,2,3, middle; Bridge, bottom

Liverpool Street's escalators 1, 2, and 3 generally perform well, but do occasionally face problematic changes in level of service. For a majority of the morning peak, as shown in Figure 26 the Level of Service around the escalators was given a rating of A, indicating exceptionally good passenger flow. However, this level of service deteriorated to a D or E rating for almost half an hour of this period. Queues for escalators can cause poor level of service, but the level of service is more an indication that there is not enough vertical flow in the area. Figure 26 shows us that escalators 1, 2, and 3 are bimodal- they are either full or mostly clear. Controlling the surges of passengers entering the station and travelling on these escalators becomes an area of concern when the level of service drops so much.

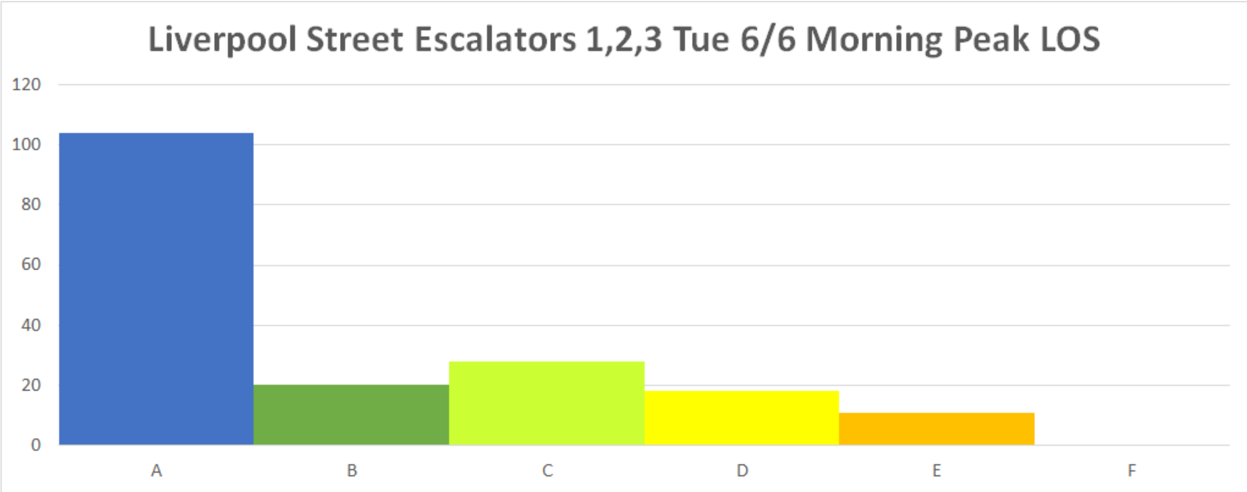


Figure 26: Liverpool Street Escalators 1, 2, and 3 Morning Peak Level of Service Frequency

In contrast with passenger flow patterns at escalators 1, 2, and 3, Liverpool Street's escalators 4, 5, and 6 had consistently poor level of service measurements. As seen in Figure 27, almost 100 minutes of the morning peak saw these escalators at a level of service D or above. This contrasts with escalators 1, 2, and 3—whereas those escalators face a problem with surges, escalators 4, 5, and 6 face a consistent rush of people. Too many people are trying to board these escalators at a time, and the limitations inherent with escalators mean that people cannot get on as fast as they arrive. This is a case where having an additional escalator to relieve pressure or increasing the speed at which escalators move would increase passenger flow and satisfaction greatly.

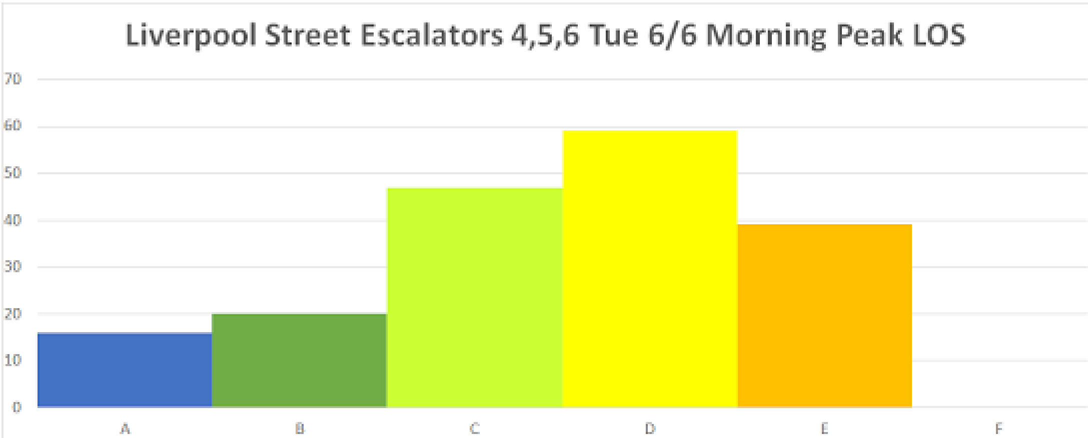


Figure 27: Liverpool Street Escalators 4, 5, and 6 Morning Peak Level of Service Frequency

Two sets of escalators meet at Liverpool Street's Ticket Hall C, and we see a similar pattern of Level of Service in the ticket hall when compared to the escalators. Escalators 7, 8, and 9 and 1, 2, and 3 meet in Ticket Hall C and as previously shown suffer from surges of passengers attempting to board them. As shown in Figure 28, Ticket Hall C suffers from a similar fate. Without the surges of passengers boarding and alighting from the escalators, it may be possible for Ticket Hall C to remain at a Level of Service of C or below for an entire morning peak. Changing the directions that escalators are running during the peak could alter flow enough to bring passengers through quickly.

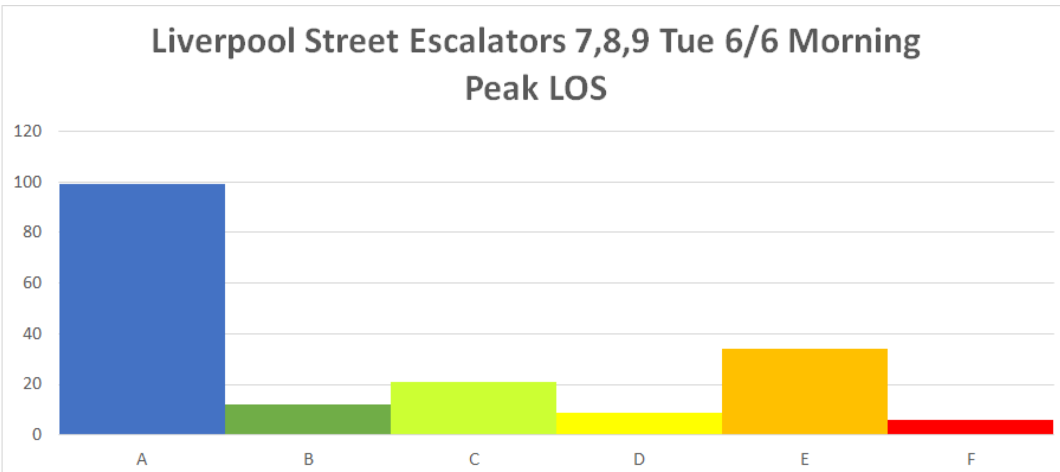


Figure 28: Liverpool Street Escalators 7, 8, and 9 Morning Peak Level of Service Frequency

The two less popular ticket halls in Liverpool Street, Ticket Halls A and C, follow a similar pattern of level of service. Although we did not observe Ticket Hall A directly, we did look at the bridge connected directly to the ticket hall and will use this as the basis for our analysis. From Figure 29 and 30, we can see that both areas follow a similar pattern of level of service, where they are flowing at an acceptable level for a vast majority of the time. We believe that during regular service, neither of these areas are a high priority for changes and can remain as is until passenger counts begin to rise significantly.

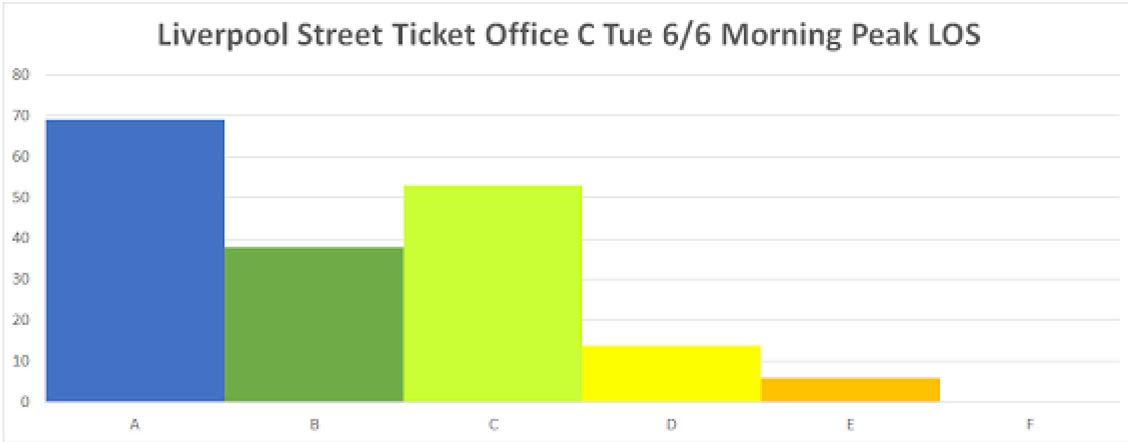


Figure 29: Liverpool Street Ticket Hall C Morning Peak Level of Service Frequency

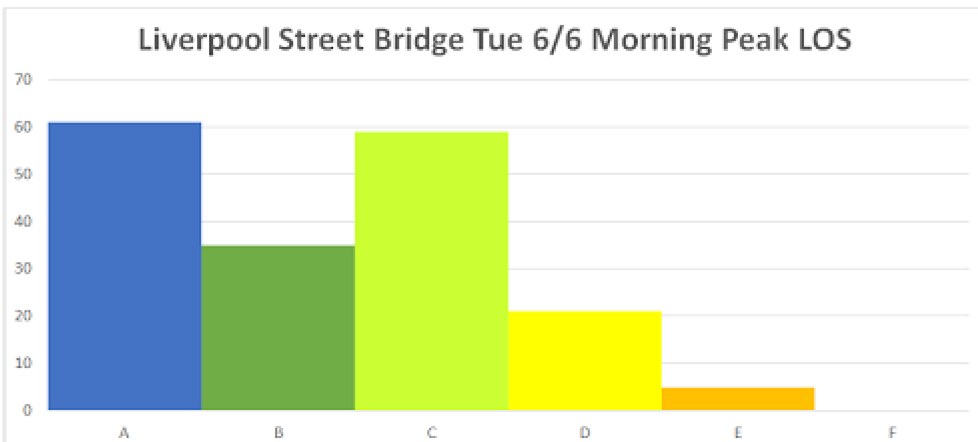


Figure 30: Liverpool Street Bridge Morning Peak Level of Service Frequency

Ticket halls remain a concern across the system, especially in stations that do not have a suitable secondary location. Euston, a station with only one ticket hall, occasionally grinds to a standstill when passenger inflow from Network Rail becomes too much for the sole ticket hall. This is better explained in section 3.1.4, where we use Euston's ticket hall to explain our analysis methods. Expanding the ticket hall or providing customers with a second location through which to enter the station can alleviate many, if not all, of the problems due to congestion. Liverpool Street has three ticket halls, but suffers from issues should the main ticket hall be closed for any reason. Ticket Hall B, the ticket hall that interfaces with Network Rail, is able to handle a significant number of tourists buying tickets due to the sheer number of ticket machines located in the hall. When it shuts, Ticket Hall C is unable to handle the lines at the ticket machines and this creates a significant backup.

Ticket halls also face some of the worst level of service across the system that we have seen, especially at Liverpool Street. Figures 21 and 31 paint a very clear picture of the fare-control areas at the station, where passengers spend their mornings moving slowly through the area and beginning to bunch up around ticket gates. While some ticket halls are much worse than others, we see that both ticket halls in Liverpool Street spend the majority of their time during peak hours with densely packed customers. Figure 31 shows that even during one of the smaller peaks, the weekend peak, Ticket Hall B is still at a poor level of service and passengers are overly congested in the area. Congestion relief efforts in the short term should be pushed in order to avoid these stations grinding to a halt during normal operation.

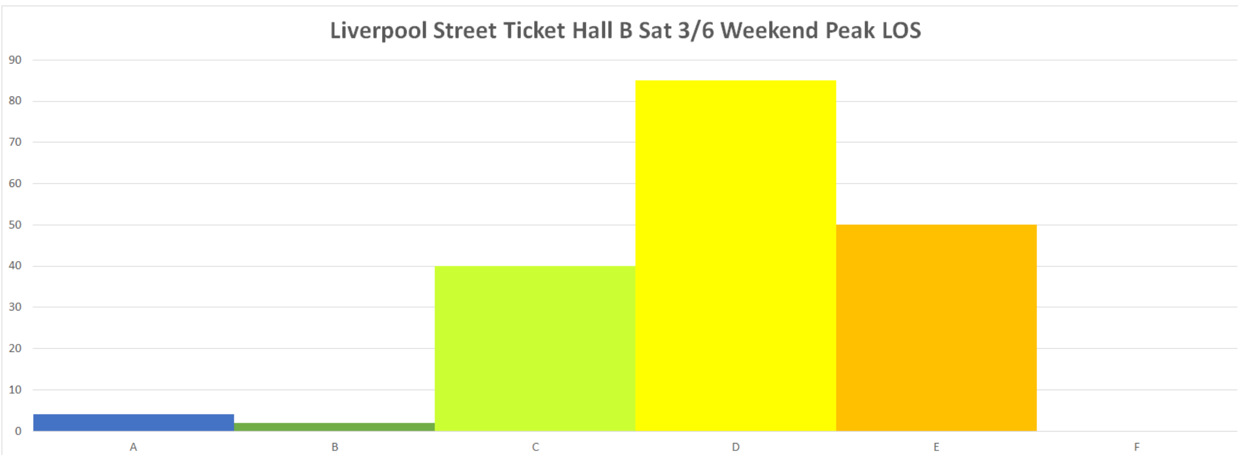


Figure 31: Liverpool Street Ticket Hall B, Weekend Peak Level of Service Measurement

Customer satisfaction does not seem to have any correlation with the overall number of passengers on a line, but is impacted heavily by signage and train crowding. Based on the customer survey data outlined in the 2016-17 Q1 Customer Satisfaction Survey, the Victoria, Circle, and Hammersmith and City lines suffered in overall satisfaction due to their signage problems. The Victoria line is one of the major lines connected to Euston, while the Circle and Hammersmith and City lines service Liverpool Street. Clear and concise signage should be made a priority for the future and delay announcements should be made more frequently.

Euston is serviced by two very popular lines—the Northern and Victoria lines—each with their fair share of issues. Customers for the Northern line are generally satisfied with the service they receive, with signage and information on delays being above average. However, train delays and comfort on trains are below average for the London Underground, and 3% of all passengers have experienced a disruption or delay while riding (Customer Service Survey, 2017). The Northern line is the most taken line on the London Underground, with almost 300 million passengers in the course of a year, but seems to have less delays than average (Lineloads Summary, 2017). The Victoria Line has passengers who are significantly more satisfied than average, but problems with signage as we noted in our observations seem to pervade stations on the line. The Victoria Line has over 250 million passengers a year, but we do not see a correlation between passenger count and rate of delays as the line has below average delays for the London Underground.

Liverpool Street as a whole is more concerning, with all of its lines having average to below average satisfaction and significant issues with crowding or signage. The Central line is one of the most problematic lines on the Tube, with passenger satisfaction having gone down recently, and overall satisfaction being below average for the Tube. Train crowding and congestion is an area of massive concern, with only 69% of passengers being satisfied with train conditions. Furthermore, 6% of passengers on the Central line have faced a delay, well above the average for the Tube (Customer Service Survey, 2017). With the Central line being the second most populated line on the Tube, these statistics seem much less shocking. What becomes immediately clear is that something drastic needs to be done to relieve the increasing crowding of the Central line and to make stations more usable for passengers (Lineloads Summary, 2017).

The other three lines at Liverpool Street, namely Circle, Hammersmith and City, and Metropolitan paint a similarly bleak picture of the state of customer satisfaction on the Tube. The Circle and Hammersmith and City lines have overall passenger satisfaction well below that of the Tube average, with a significant portion of this issue coming from abysmal ratings about signage and delay information. Further, a 9% incidence of delays on these lines show that they are by far some of the least reliable lines on the Tube (Customer Service Survey, 2017) despite being some of the least travelled lines on the whole (Lineloads Summary, 2017). The Metropolitan line is, by comparison, average for the Tube, but should still be given some consideration due to its close proximity to the Circle and Hammersmith and City lines.

Poor vertical circulation across the system has been seen to be a major area of concern, in line with the findings of the Mineta report (Loukaitou-Sideris et al., 2015). A single escalator outage in Euston has caused a significant amount of backup for passengers trying to exit the station. Maintaining a backup plan for escalator outages can help to alleviate congestion over long periods of maintenance. Escalator systems like those in Liverpool Street, where there is always an extra escalator, have a built in backup if one escalator were to be taken out of commission. Increasing the speed of these escalators can also increase the throughput of passengers in the system, but further research would have to be performed to determine the optimal speed that still ensures the safety of passengers.

5. Conclusions

Our exploration into congestion and passenger flow on the Tube has provided insight into some of the problems faced by metro systems around the world, but especially in London. Our literature review provided us with the basis for passenger flow management and research that we used to frame and design our research methods. Our research into other transit systems provided us with inspiration for suggestions that we have put forth at the end of our tenure here. Looking into ongoing efforts on the London Underground allowed us to narrow down our scope and focus in on the areas that were of a major concern to us.

We have outlined a series of proposed solutions in Section 6 ranging from short-term solutions that could be implemented within a year, to overarching changes to stations that may be decades down the road. We feel that by providing the view of an outsider, we have proposed novel solutions and verified internal beliefs held by TfL employees about potential changes. By providing a dearth of changes varying in time and difficulty of implementation, we think that this report provides a good starting point for research into widespread congestion relief efforts throughout the London Underground.

Our primary concerns with regards to Euston and Liverpool Street, and the system as a whole, is that congestion during peak hours is already at an unsustainable level. The London Underground is aware of the issues during peak hours and that projects like Crossrail and Crossrail 2 will bring even more passengers into the system from the outskirts of London. Congestion relief needs to be a priority for London Underground and Transport for London as a whole in order to ensure that customers are not plagued with delays during their commute. Systems like the Tube and London’s bus system keep the roads clear and reduce pollution, so ensuring that they are a useful and efficient option for customers must be a priority such that commuters do not move towards taking cars into the city.

Our findings show that major areas of congestion include the fare-control gates and escalators, and that any disturbances in normal operation in these areas can have a “ripple” effect of congestion throughout the station. Oyster cards have made it easier for passengers to enter the station, but passengers who do not have enough funds and must go against the flow to top-up their cards can cause massive delays at gate lines. In addition, the absolute limitation of passenger flow posed by the problem of vertical flow on escalators leads to bottlenecks in the station that are compounded during periods of maintenance and escalator shutdowns. While the interface with Network Rail can't be changed from within, occurrences of several trains letting off passengers and once can grind stations to a halt. These issues should be looked at and optimized through diverting traffic and adding more ways for passengers to get up and down in stations in the future.

Signage concerns and overall congestion also pose problems for staff members and passengers alike and can lead to lower customer satisfaction. Currently, signage on the Tube is confusing due to things like platform numbers that are mostly unused, conflicting signage in important areas, and complicated lines like the Northern line and the Hammersmith and City, Metropolitan, and Circle lines. More care should be taken when designing signage for the Northern line and any of the overlapping lines in Central London to ensure that passengers can tell where they need to go at a glance. In addition, a move to dynamic signage to explain delays and direct passengers to the most clear and quick routes through a station can ease the burden placed on staff members in the station and result in more satisfied customers.

This report provides a good starting point for research into passenger flow on the Tube, and should be expanded upon by further university groups and potentially Transport for London teams. This project and report are limited in scope based on the time restrictions that our team has had while working in London. As such, this report does not provide a conclusive, thorough explanation of congestion on the Tube, nor could it hope to cover every potential solution or problem that may arise. Instead, this report should be viewed as a springboard for other groups to expand upon. We recommend that a more widespread, large-scale observational analysis be carried out in popular stations to identify any major bottlenecks and issues with congestion. We would also suggest that Transport for London consider implementing and utilizing widespread modeling of the system to test changes before rolling them out onto stations in service.

6. Recommendations

Our recommendations are directed at London Underground unless otherwise noted. Recommendations for each section (Overall and station specific sections) are divided into priority levels. A recommendation given a "high priority" rating represents an issue that we believe is critical and should be addressed at the soonest possible time. "Medium priority" ratings represent recommendations that will have a significant impact on passenger flow, but are not necessarily as time sensitive as high priority recommendations. "Low priority" recommendations may be prohibitively expensive or require more research, or may be a less concerning problem at the moment. After analyzing passenger survey data and CCTV footage, our preliminary conclusions/recommendations include:

OVERALL: HIGH PRIORITY

Increase quality of all CCTV systems throughout the Tube. The current CCTV system suffers from poor camera quality and difficult to operate software on outdated laptops and operating systems. In addition, both stations that we looked at used different software and had different conventions for numbering and labelling cameras. A Tube-wide program to upgrade and standardize CCTV software and equipment will result in the system being easier to operate and more useful for passenger flow analysis.

Perform ongoing analysis of passenger flow and congestion through direct and CCTV observation. The usefulness of up-to-date analysis of congestion and flow patterns in stations cannot be understated, and should be pushed as a way to help LU avoid delays and unsatisfied customers. Projects that are ongoing can be scoped to larger areas of the stations and report on their findings monthly in order to provide Group Station Managers (GSMs) with up-to-date data to inform their station management decisions.

Perform a large-scale, system-wide analysis of congestion to **develop standard short-, medium-, and long-term strategies** to improve passenger flow. With the advent of both Crossrail projects coming to the London Underground, it becomes much more important to develop a framework for system-wide improvements and spending and to optimize passenger flow. By performing a project on a larger scale, TfL and the London Underground can standardize improvement efforts and create a five-year, ten-year, and twenty-year improvement plan. Planning for the increased traffic on the network in coming years remains the single highest priority for LU as they move forward with major improvement projects.

Implement widespread dynamic signage in stations to inform passengers about delays and maintenance efforts in the station. Static signage has been commonplace in all stations since the beginning of the London Underground, but the advent of inexpensive dynamic signage should result in a move to digital signs and displays in stations. The current dynamic signs in the ticket hall and platform areas are the minimum that each station should have. We recommend that stations be outfitted with dynamic signs for wayfinding to platforms, as these can be modified to change traffic patterns and to indicate if there are problems or congested areas along a path. Dynamic signs throughout the station will significantly increase customer engagement and result in passengers being more informed throughout their journeys.

OVERALL: MEDIUM PRIORITY

Remove platform numbers from signs and replace them with larger print indicating which lines are serviced by platforms. From a customer's perspective, the platform number does not matter nearly as much as which line a platform services and in what direction. Station staff, when interviewed, were in many cases unable to ascertain which platforms serviced which lines by number. We contend that replacing platform numbers for customer facing signage will result in passengers being more easily able to find their way through a station. We recognize that platform numbers are useful for CSMs and maintenance staff and should be kept for behind-the-scenes employees to use.

Prototype and test color-coded lines on the ground to indicate what direction passengers should travel to get to platforms and the way out. We believe that creating direct lines on the ground that represent the colors of the London Underground lines will allow passengers to more easily find their way to platforms than the current signage system. These lines will be most useful during weekend peaks, when tourists who are unfamiliar with the station need to find their way to various lines. The use of color-coding also allows for non-verbal indications of where customers need to go, which can help when customers are not able to read current signage.

Provide contractors and cleaning staff with a version of an Oyster card that allows them to swipe in and out at the station they are working in and only the station they are working in. Cleaning staff in Liverpool Street were observed to enter and exit the fare-controlled areas of the station more than 40 times in an hour. Each time cleaning staff had to exit the station, an employee working the gate line had to step aside and enter in a code to let them out of the station. Providing them with a custom Oyster or another method to enter and exit the station unassisted, without enabling them to abuse a permanent Oyster as has happened in the past, will allow employees to be available to help customers for more time.

OVERALL: LOW PRIORITY

Allow passengers to swipe in and out of the same station for no charge within a small time period (<10 min) to allow alternative routing for transfers within a station. Relieving congestion in areas like Liverpool Street's Ticket Hall C by removing passengers who are just passing through on their way to transfer can help to bring up the level of service in the area. Passengers can instead swipe out from Ticket Hall C and instead walk around outside the station in order to board the Hammersmith and City, Metropolitan, or Circle lines from Ticket Hall B.

Make Help Points more visible from a distance and separate the "emergency" and "help" buttons into two separate points. The current semi-gloss white Help Points don't draw attention from a distance, which can be detrimental to disabled passengers or those in need of assistance. Help Points should be redesigned to catch the eye of passengers as they walk past them. In addition, the layout of the Help Point was described as "intimidating" due to the presence of the emergency button. Splitting the help and emergency systems into two separate entities may result in Help Points being used more often than they are currently.

Install contingency escalators at every set of bidirectional escalators. In any station where only two escalators service a particular area of the station, scheduled escalator maintenance and unexpected closures can result in congestion around the escalators. A "contingency" escalator is an extra escalator than is required to provide good bidirectional flow at an area that can be turned on or reversed during periods of intense congestion in order to aid in passenger flow. By redesigning areas with only two escalators to instead use three, congestion can be avoided and abated due to the increased potential vertical passenger flow in the area. King's Cross St. Pancras is a good example of this system, where one escalator goes up, one down, and one is left stationary to be used as a staircase.

EUSTON: HIGH PRIORITY

Revamp the station to include disused entrances and tunnels within the station to allow passengers alternate routes to their lines. As it stands, the single ticket hall in Euston is frequently unable to handle the sheer number of passengers delivered by Network Rail trains. Entrance to the Euston ticket hall is sometimes completely halted in order to allow the large queues of passengers to cross into the fare-controlled area. Renovating one of the closed entrances around the station to act as a second entrance into the station could help to alleviate traffic into the station by allowing local commuters to funnel into a separate entrance.

Increase the width of all major passageways and add escalators to prepare for incoming Crossrail 2/High-Speed 2 traffic. With Crossrail 2 being projected to bring in over 200,000 more passengers into London per day, it becomes increasingly important to allow a high passenger throughput in corridors and on escalators ("Crossrail 2," 2017). Increasing the width of passageways results in a linear increase in passenger throughput, and adding escalators can increase the vertical flow by a significant amount (Loukaitou-Sideris et al., 2015). Renovation efforts should be started soon to avoid any complications upon completion of the Crossrail 2/High-Speed 2 project.

EUSTON: MEDIUM PRIORITY

Fix signage over Escalators 7 and 8 to not make them appear as if they divide the two lines (Northern and Victoria) into two separate areas at the bottom of the escalator. As shown in Figure 18 above, the signage on the primary escalators heading into Euston denotes that one escalator is for each line. However, both escalators travel to the same place at the bottom and both escalators allow access to either line. Removing the confusing barrier between the escalators and reworking the sign to show that the escalators lead to the same place can reduce customer confusion and lets passengers stop crowding onto one escalator.

Move maps to the back walls to stop passengers from bunching up in the center of the floor. Currently, the tube maps at the bottom of Escalators 7 and 8 are located just after the area where passengers disembark the escalators, on either side of the passageway. This results in passengers bunching around the maps during weekend peaks as tourists unfamiliar with the London Underground trying to figure out where they need to go. If this map was instead located on the back wall of the corridor, passengers would be grouping up out of the way and not impeding passenger flow in the corridor.

Revamp Northern line to instead become two lines to avoid confusion. Currently, the two branch system of the Northern line is one of the most confusing elements of the London

Underground. Both branches function mostly independently, and the signage should represent them as such. By changing signage to represent the Charing Cross branch and the Bank branch as two separate lines, tourists and passengers unfamiliar with the Northern line will be able to understand where they need to go better than they currently do.

EUSTON: LOW PRIORITY

Consider a station rebuild upon the start of Crossrail 2/High-Speed 2 development. A second choice for renovating Euston station to handle the traffic is to perform a full rebuild of Euston. This is a much more expensive option, but is also more flexible than working with the current station layout. This option will allow the London Underground to address all of the current issues with Euston station.

Ask Network Rail lines to adjust their schedules to avoid surges due to several trains letting off passengers at once under normal operation. Currently, surges in passengers entering the station from Network Rail trains can overload and severely congest the ticket hall during peak hours. If Network Rail trains instead arrive at staggered times throughout the morning, Euston can sustain a steady passenger flow without major surges during normal operation. This is not an easy solution for Transport for London to implement, but may be worth considering for the future.

Move the glass cubicle (See Figure 32) from the middle of the main thoroughfare to a location that is out of the way of passengers. Currently, the cubicle takes up a significant amount of space in the main passageway past the gate line. The cubicle is approximately one meter wide, which can create a bottleneck in the passageway and lower the overall flow of the area, despite the rest of the area being wider. If this cubicle was instead moved to a less-traveled area of the station, it would not impede flow in this way and contribute to better movement in the fare-controlled area.

Figure 32: Glass Cubicle at Euston

LIVERPOOL STREET: HIGH PRIORITY

Add more ticket machines to Ticket Hall C (Central Line) to avoid crowds during a Ticket Hall B shutdown. Ticket Hall C is already very congested during peak hours, averaging a level of service rating of F during the morning peak. If Ticket Hall B was to ever be shut down for any reason, Ticket Hall C will begin to take on the flood of people who would normally enter the station through Ticket Hall B. Ticket Hall C only has 4 machines that can sell tickets and load Oyster cards, which poses a problem when tourists coming in on Network Rail need to purchase tickets. This backup of people trying to purchase tickets leads to the entire ticket hall grinding to a standstill and being unusable for large portions of time.

Expand the platforms for all lines by 1 meter in width to accommodate for more passengers. Currently, platforms for both lines at Liverpool Street can become overly crowded in the event of delays, resulting in passengers waiting for their trains in front of the yellow lines denoting the area of the platform passengers should not be standing on. This is a safety hazard and can result in passengers falling onto the tracks. Expanding the platforms by 1 meter in depth across the entire length of the platform will add significantly more area for passengers to stand while also relieving congestion on the platforms and providing a better level of service.

LIVERPOOL STREET: MEDIUM PRIORITY

Implement the platform door system seen on the Jubilee line instead of expanding platforms in order to prevent passenger crowding on platforms from becoming a major safety concern. If expanding the platforms is unfeasible, implementing the platform door system found on Jubilee line trains can help to prevent safety hazards from becoming a reality on the platform. A physical barrier on the edge of the platform will prevent passengers from intentionally or unintentionally finding themselves on the tracks.

LIVERPOOL STREET: LOW PRIORITY

Consider adding a second bridge near Ticket Hall A to avoid clumping during peak hours. The current bridge that allows passengers to cross from Ticket Hall A to the rest of the station is one of the more congested areas of the station due to being small, cramped passageways. Expanding the current bridge or adding a second option for passengers entering and exiting from Ticket Hall A will reduce the congestion.

6. References

Aguilera, V., Allio, S., Benezech, V., Combes, F., & Milion, C. (2014). Using cell phone data to measure quality of service and passenger flows of Paris transit system. Transportation Research Part C: Emerging Technologies, 43, 198-211. doi:10.1016/j.trc.2013.11.007

Attwooll, J. (2016, February 05). London Underground: 150 fascinating Tube facts. Retrieved March 25, 2017

Ballaban, M. (2015). You are not insane, the NYC subway is getting worse. Retrieved from http://jalopnik.com/you-are-not-insane-the-new-york-city-subway-is-getting-1687817007

Barber, L. (2016, March 11). 15 plans for the future of London transport. Retrieved June 21, 2017, from http://www.cityam.com/1406825517/plans-future-london-transport-night-tube-crossrail

Big Map of London Underground/Subway Stations. (n.d.). Retrieved April 09, 2017, from http://pgoh13.com/london_tube.php

Blunden, Mark, Pippa Crerar, and Arjun Neil Alim. (2016, July 13). Tube passengers lost 26 million hours to delays last year. Retrieved April 23, 2017, from http://www.standard.co.uk/news/transport/tube-passengers-lost-26-million-hours-to-delays-last-year-a3294551.html

Campbell, S. (2015, March 12). Underground horror: Woman dragged under tube after battling in 'overcrowded' tube station. Retrieved March 26, 2017 http://www.express.co.uk/news/uk/563435/Clapham-South-tube-London-Underground-accident

Caring for our Customers with Special Needs Booklet. (n.d.). Retrieved June 21, 2017, from http://www.mtr.com.hk/en/customer/services/caring_booklet.html

Chan, S. (2005). Subways run by computers start on L line this summer. Retrieved from https://www.nytimes.com/2005/01/14/nyregion/subways-run-by-computers-start-on-l-line-this-summer.html

Coldwell, W. (2016, May 20). London visitor numbers hit record levels. Retrieved March 25, 2017 https://www.theguardian.com/travel/2016/may/20/london-record-visitor-numbers-2015-31-5-million

Crerar, P. (2016, February 11). Delays caused by overcrowding on the Tube have doubled since

2013. Retrieved March 26, 2017 http://www.standard.co.uk/news/transport/delays-caused-by-overcrowding-on-the-tube-have-doubled-since-2013-a3177881.html

CTA red line wilson station reconstruction project. (2013). Retrieved from http://www.transitchicago.com/wilson/default.aspx

Crossrail 2 in numbers. (2017). Retrieved June 18, 2017, from http://crossrail2.co.uk/discover/in-numbers/

Fitzsimmons, E. G. (2016). Surge in ridership pushes new york subway to limit. Retrieved from https://www.nytimes.com/2016/05/04/nyregion/surge-in-ridership-pushes-new-york-subway-to-limit.html

Fruin, John J (1971). Pedestrian planning and design. Metropolitan Association of Urban Designers and Environmental Planners, New York

Guibourg, C. (2015). London underground tube delays worst on central, jubilee and northern lines. Retrieved from http://www.cityam.com/221295/london-underground-tube-delays-worst-central-jubilee-and-northern-lines

Hankin, B. D., & Wright, R. A. (1958). Passenger Flow in Subways. Operational Research Quarterly, 9(2), 81. doi:10.2307/3006732

Help points to make subway safer, easier to use. (2011, Apr 5,). Targeted News Service Retrieved from http://search.proquest.com/docview/860211560

Hilkevitch, J. (2011). Renovation in sight for red line eyesore. Retrieved from http://articles.chicagotribune.com/2011-09-26/classified/ct-met-getting-around-0926-20110926_1_subway-station-new-l-station-red-line

Holmes, Alexander. (2016, September 21). Is THIS the solution to Britain's overcrowded trains? Flip-up seats 'would boost capacity by 30%' and could be introduced within a year. Retrieved April 09, 2017, from http://www.dailymail.co.uk/travel/travel_news/article-3800266/Is-solution-Britain-s-overcrowded-trains-Flip-sits-boost-capacity-30-introduced-year.html

Jones, A. (2017, February 03). Tube passengers wasted 400,000 hours in 2016 because of overcrowding delays. Retrieved March 26, 2017 http://www.independent.co.uk/news/uk/home-news/tube-delays-wasted-hours-passengers-a7561346.html

Kelley, J., Ko, D. H., Mazza, L., & Robinson, S. E. (2016). Reducing dwell time: London underground central line. Worcester, MA: Worcester Polytechnic Institute.

Kırlangıçoğlu, C. (2015-06-04). Modeling passenger flows in public transport stations. International journal of human sciences, 12(1), 1485.doi:10.14687/ijhs.v12i1.3275

Lin, J., Dai, J., & Song, R. (2016). Status and problems in location model research for guidance signage in comprehensive passenger transportation hubs. International Review for Spatial Planning and Sustainable Development, 4(3), 27-35. doi:10.14246/irspsd.4.3_27

London Plan. (2017, January 27). The London Plan 2016 PDF. Retrieved April 09, 2017, https://www.london.gov.uk/what-we-do/planning/london-plan/current-london-plan/london-plan-2016-pdf

London Particulars. (2011, April 2). Posts about Transport on London Particulars. Retrieved June 17, 2017, from https://londonparticulars.wordpress.com/category/transport/page/3/

[London Underground Customer Service Survey, Q1 2016-17]. (2017, May 11). Unpublished raw data.

[London Underground Annual Lineloads Summary, 2016]. (2017, May 17). Unpublished raw data.

London underground - More Photos. (n.d.). Retrieved March 25, 2017 http://cargocollective.com/cafe8/london-underground

London Underground Performance Report (Publication No. Period 13 2016/17). (2017). Retrieved June 18, 2017, from Mayor of London, Transport for London website: http://content.tfl.gov.uk/lu-performance-report-period-13-2016-17.pdf

London, V. (2017, January 12). London Underground. Retrieved March 29, 2017 http://www.visitlondon.com/traveller-information/getting-around-london/london-tube#LqKRetmBLcOPpTGh.97

Loukaitou-Sideris, A., Taylor, B. D., & Voulgaris, C. T. (2015). Passenger Flows in Underground Railway Stations and Platforms. MTI Report, 12-43. Retrieved April 22, 2017.

Mass Transit Railway By-laws. Retrieved May 25, 2017 from http://www.mtr.com.hk/en/customer/main/mtr_by_laws.html

McAteer, Ollie. (2015, December 09). Guess how many people got the Tube on its busiest day EVER. Retrieved April 09, 2017, from http://metro.co.uk/2015/12/09/guess-how-many-people-got-the-tube-on-its-busiest-day-ever-5555575/

Motorola. (2014). *The New York City subway system improves passenger safety and emergency services with Motorola WLAN technology* [Press release]. Retrieved from http://www.boycetechnologies.com/wp-content/uploads/2015/05/NYCTransit_HelpPoint_CaseStudy.pdf

Nelson, S. (2011). MTA unveils new "on the go" touch-screen plaything at bowling green subway station. Retrieved from http://gothamist.com/2011/09/19/mta_unveils_new_touch-screen_playth.php#photo-1

Neuman, W. (2007). Some subways found packed past capacity. Retrieved from https://www.nytimes.com/2007/06/26/nyregion/26mta.html

New York City Transit Riders Council. (2001). *Reopening closed subway entrances using high entry/exit turnstiles.* (). New York: New York City Transit Riders Council.

O2, T. (n.d.). Tube: Getting Here. Retrieved March 26, 2017 http://theo2.s3.amazonaws.com/doc/standard-tube-map.pdf

On the go: 155 kiosks, 31 stations (2015). New York City MTA.

Parmenter, C. G. (2016, April 21). The 10 busiest Tube stations (yes, they are more crowded). Retrieved April 21, 2017, from http://www.cityam.com/220725/london-underground-really-getting-more-crowded-here-are-10-busiest-tube-stations

Red and Purple Modernization Phase One Project Redevelopment Project Area Transit Tax Increment Financing [PowerPoint slides]. (2016). Retrieved from http://www.transitchicago.com/assets/1/media_relations_documents/RPM_Transit_TIF_9-13_Public_Meeting_Preso_FINAL.pdf

RMT. (2016, November 02). Woman dragged 60 feet by train was saved by tube driver and station workers. Retrieved April 22, 2017, from http://www.rmtlondoncalling.org.uk/content/woman-dragged-60-foot-train-was-saved-tube-driver-and-station-workers

Seriani, S., Fujiyama, T., & Holloway, C. (2016, October 07). Estimation of the passenger space in the boarding and alighting at metro stations. In *44th European Transport Conference*. Retrieved May 22, 2017, from https://iris.ucl.ac.uk/iris/publication/1209285/1

Smith, R. (2017, February 03). Tube delays from overcrowding have tripled in five years. Retrieved April 09, 2017, from http://www.cityam.com/258375/tube-passengers-lost-nearly-400000-hours-last-year-thanks

Sullivan, J., Kershaw, K., & Cummings, J. (2016, September 8). National Travel Survey: England 2015. Retrieved June 6, 2017, from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/551437/national-travel-survey-2015.pdf

Topham, G. (2014, September 21). Overcrowded and getting busier: why new train lines can't come fast enough for London. Retrieved March 29, 2017, https://www.theguardian.com/uk-news/2014/sep/21/tube-overcrowding-london-train-lines

Transit capacity and quality of service manual. (2013). Washington, D.C.: Transportation Research Board.

Transport for London. (n.d.). Equality policy and future plans. Retrieved March 26, 2017 http://content.tfl.gov.uk/your-accessible-transport-network-3-main-document.pdf

Transport for London. (n.d.). Efficiency plans. Retrieved April 09, 2017, from https://tfl.gov.uk/corporate/publications-and-reports/efficiency-plans

Transport for London. (n.d.). Facts & figures. Retrieved March 25, 2017 https://tfl.gov.uk/corporate/about-tfl/what-we-do/london-underground/facts-and-figures

Transport for London. (n.d.). Four Lines Modernization. Retrieved March 30, 2017, from https://tfl.gov.uk/travel-information/improvements-and-projects/four-lines-modernisation?intcmp=37984

Transport for London. (n.d.). How we are governed. Retrieved March 26, 2017 https://tfl.gov.uk/corporate/about-tfl/how-we-work/how-we-are-governed

Transport for London. (n.d.). How we are funded. Retrieved March 26, 2017 https://tfl.gov.uk/corporate/about-tfl/how-we-work/how-we-are-funded

Transport for London. (n.d.). Improving customer service. Retrieved June 5, 2017. https://tfl.gov.uk/campaign/tube-improvements/what-we-are-doing/improving-customer-service

Transport for London. (n.d.). London Underground. Retrieved March 25, 2017 https://tfl.gov.uk/corporate/about-tfl/culture-and-heritage/londons-transport-a-history/london-underground?intcmp=2777

Transport for London. (n.d.). Open data policy. Retrieved April 09, 2017, from https://tfl.gov.uk/info-for/open-data-users/open-data-policy

Transport for London. (n.d.). The Mayor's Transport Strategy. Retrieved April 09, 2017, from https://tfl.gov.uk/corporate/about-tfl/how-we-work/planning-for-the-future/the-mayors-transport-strategy

Transport for London. (n.d.). Victoria. Retrieved March 26, 2017 https://tfl.gov.uk/travel-information/improvements-and-projects/victoria

Transport for London. (n.d.). What we're doing. Retrieved March 26, 2017 https://tfl.gov.uk/campaign/tube-improvements/what-we-are-doing?intcmp=1586

Underground, overground. (2013, October 19). Retrieved March 25, 2017 http://www.economist.com/news/britain/21588072-london-has-built-about-good-transport-network-it-could-given-its-constraints-time

Yu, A. (2015, March 07). Mind the gap... Meet the woman behind those MTR announcements. Retrieved June 21, 2017, from http://www.scmp.com/news/hong-kong/article/1731267/mind-gap-meet-woman-behind-those-mtr-announcements

Zhengyu, X., Limin, J., Yong, Q., & Li, W. (2015). Passenger flow detection of video surveillance: a case study of high-speed railway transport hub in China. Elektronika ir Elektrotechnika, 21(1), 48+. Retrieved from http://dx.doi.org/10.5755/j01.eee.21.1.9805

7. Appendices

Appendix A: Sponsor Description

The London Underground (LU), or Tube as it is familiarly known, is the oldest underground rail system in the world. The Tube opened in 1863, with one line and six stations from Paddington to Farringdon ("London Underground," n.d.). After more than 150 years of operation, the Underground has grown to include 11 different lines with 402 kilometers of rail that service 270 stations across greater London and three adjacent counties ("Facts and Figures," n.d.) (See Figure 33).

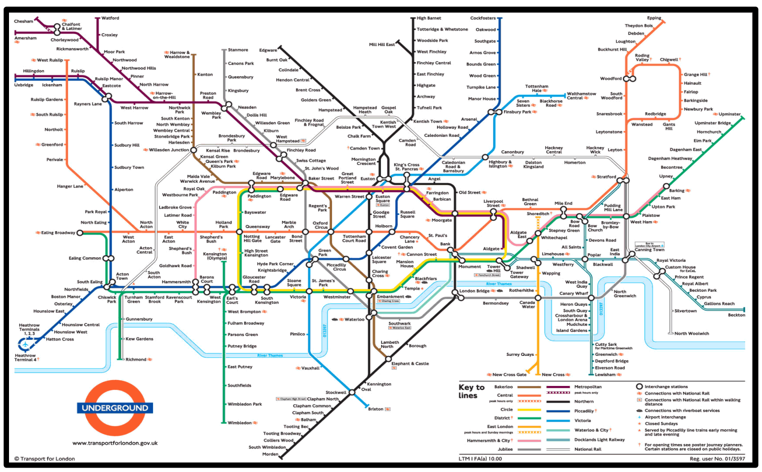


Figure 33: All Lines and Stations of the Tube ("Big Map," n.d.)

Greater London has a population of 8.7 million, and attracts 35.1 million international tourists annually, many of whom use the Tube (Coldwell, 2016). In 2013/2014 1.265 billion passengers journeyed via the Tube, making it the third busiest metro system in Europe (Attwooll, 2017). Figure 34 shows that the number of journeys by Tube has climbed steadily since 2003, while car usage has declined over the same period. ("Underground, overground," 2013).

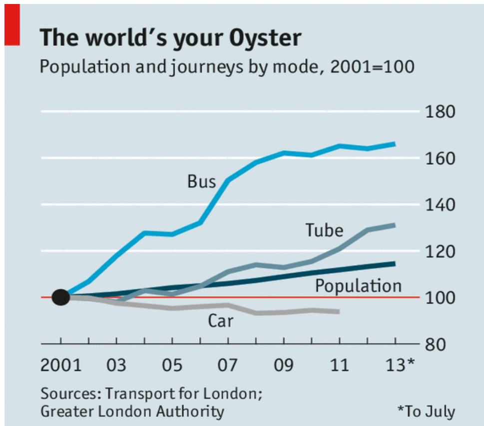


Figure 34: Population and Journey by Mode ("Underground, Overground," 2013)

Transport for London is a statutory body that was created by the Greater London Authority Act of 1999 to manage public transport in the city of London. Under this act, the Mayor of London is obliged to create policies that make travel in London safe, easy, and cost-effective for all citizens and visitors to the city ("Governed," n.d.). In 2016/17, passenger fares made up almost 40% of the £10.4bn of funding Transport for London (See Figure 35). TfL also receives money from grants, property rental income, and funding for the Crossrail extension that is being developed by a subsidiary of Transport for London ("Funded," n.d.).

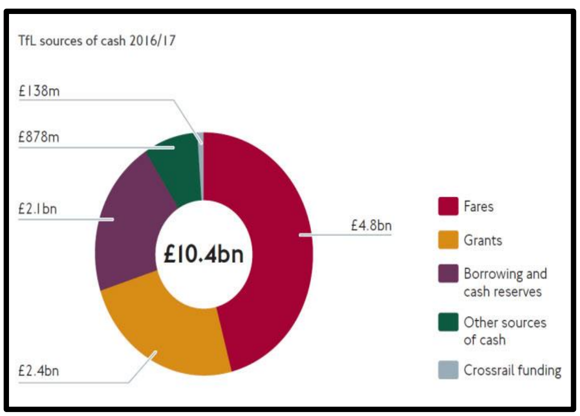


Figure 35: Funding Breakdown by Source ("Funded," n.d.)

According to the equality policy and future plans section of Transport for London's website, TfL is "committed to improving transport in London by making it more accessible, safer and reliable" ("Equality Policy and Future Plans," n.d.). In May of 2015, Transport for London released a document outlining its plan for increasing disabled access on the London Underground and other transportation methods in London. The plan is known as "Your Accessible Transport Network," and includes changes to the infrastructure and organization of Underground stations. The proposed infrastructure changes include running 40% of the Tube network with newer more accessible trains by 2017, and removing steps at Bank station between the Waterloo, City, and Northern lines before 2021. There are also plans to improve customer experience by adding 150 new automated ticket machines, which will free the staff to provide more personal help to customers in the ticket halls, on platforms and in gate lines. Staff will be issued new uniforms, so they can be more easily identified and sought out for help, and they will also be equipped with the latest mobile technology so that they can respond quickly to customer requests ("Equality Policy and Future Plans," n.d.).

Figure 36: Subsection of the Tube Map, Central London ("Tube: Getting here," n.d.)

In spite of ongoing infrastructural and operational improvements, overcrowding and congestion on the Tube is becoming a real problem in the daily life of London commuters. Overcrowding in the Tube not only raises concerns about passenger safety at congested stations, but also wastes passengers' time due to delays (See Table 3). According to Caroline Pidgeon, Liberal Democrat London Assembly member, passengers wasted almost 400,000 hours because of delay to their journeys due to overcrowding (Jones, 2017). As shown in Figure 5, hours lost on the Tube have increased from 2013 to 2015. Moreover, Jubilee line appears to be the most adversely affected with 129,200 lost hours in 2015.

(Table 3: Overcrowding Delays)

OVERCROWDING DELAYS

	2013		2014		2015	
	Incidents	Lost hours	Incidents	Lost hours	Incidents	Lost hours
Bakerloo	17	19,703	21	9,461	69	24,997
Central	12	13,990	23	69,667	45	36,472
District	24	18,087	17	3,901	15	15,997
H&City / Circle	11	14,764	15	10,920	8	8,358
Jubilee	39	43,971	36	43,504	90	129,200
Metropolitan	1	326	3	5,356	1	343
Northern	8	5,119	29	24,583	29	51,234
Piccadilly	28	14,853	13	5,915	25	13,754

Source: TfL

Transport for London is embarking on several improvement projects to reduce congestion, starting with work on the Victoria station. Expansions to various areas, connections between ticket halls, and changes to passenger flow through the creation of one-way queues will help to enhance passenger flow in the station ("Victoria," n.d.). Other planned projects, including the Bond Street Station improvements and the "Four Lines Modernization" plan, will offer improved capacity both in stations and in trains ("What We're Doing," n.d.). Our proposed project will feed new data and suggestions into these ongoing efforts.

Appendix B: Tables of Recommendations

Station components	Design recommendations	New station design	Station retrofit
Overall station	- System design; good integration, connections with surrounding streets and parking lots	X	
Entrances	- Location of entrances in relation to surrounding streets and parking structures	X	
	- Multiple entrances	X	
Signage/ messaging	- Real-time electronic displays of train arrivals	X	X
	- Location and distribution of signs on platform to facilitate visibility and avoid crowding	X	X
	- Signage for emergency directions and indicating exit routes	X	X
	- Visual displays and audible instructions for boarding and alighting	X	X
Fare gates	- Replacement of turnstiles with smart cards or tap cards	X	X
Vertical circulation elements	- Appropriate location	X	X
	- Variable escalator flow rates		
	- Escalator sensors		
Platform	- Appropriate platform width	X	
	- Good platform visibility; elimination of obstacles, blind spots		X
	- Column-free design	X	
	- Platform screen doors		X
Mezzanine	- Arrangement of surface and track vertical circulation elements	X	
	- Sufficient space for purchasing tickets and processing passengers to and from the trains	X	
	- Retail, restrooms, and other passenger-serving amenities	X	X
Transit vehicle	- Longitudinal versus transverse seating arrangements		
	- Number of doors on each car		

Station components	Design recommendations	New station design	Station retrofit
Overall station	- System design; good integration, connections with surrounding streets and parking lots	X	
Entrances	- Location of entrances in relation to surrounding streets and parking structures	X	
	- Multiple entrances	X	
Signage/ messaging	- Real-time electronic displays of train arrivals	X	X
	- Location and distribution of signs on platform to facilitate visibility and avoid crowding	X	X
	- Signage for emergency directions and indicating exit routes	X	X
	- Visual displays and audible instructions for boarding and alighting	X	X
Fare gates	- Replacement of turnstiles with smart cards or tap cards	X	X
Vertical circulation elements	- Appropriate location	X	X
	- Variable escalator flow rates		
	- Escalator sensors		
Platform	- Appropriate platform width	X	
	- Good platform visibility; elimination of obstacles, blind spots		X
	- Column-free design	X	
	- Platform screen doors		X
Mezzanine	- Arrangement of surface and track vertical circulation elements	X	
	- Sufficient space for purchasing tickets and processing passengers to and from the trains	X	
	- Retail, restrooms, and other passenger-serving amenities	X	X
Transit vehicle	- Longitudinal versus transverse seating arrangements		
	- Number of doors on each car		

(Loukaitou-Sideris et al., 2015)

Appendix C: Interview Instrument for Experts

Interview Preamble:

We are a group of student from Worcester Polytechnic Institute's (WPI) London Project Center (LPC). We are conducting the interview to extend our understanding of the nature of passenger management, as well as for our project on passenger flow. This project is being done in collaboration with the Transport of London (TfL) and we appreciate with your assistance. You are not required to answer every question and may stop at any time. Your participation in this interview is completely voluntary. We ask that you provide your consent to allow us to record this conversation, or take notes otherwise. If you so choose, your identity will remain confidential, and any responses that you provide will be anonymized. If interested, we are happy to provide you with our research result at the conclusion of this study. If you have specific question about the research, please feel free to contact us at: Tube_E17@wpi.edu. You may also contact our project advisors, Dominic Golding and Jennifer DeWinter, at golding@wpi.edu and jdewinter@wpi.edu.

1. Describe the background and experience regarding to public transportation, more specifically in the analysis of passenger flow.
2. What are some typical issues that leading to the constraint in passenger movement at the Tube and other railway systems?
3. What are you opinions on current approaches of TfL, as well as approaches indicated in other literatures? For example, improving vertical circulation, clearer signage and messaging, increasing train capacity/frequency and station layout.
4. What other innovations/techniques could be implemented to improve passenger movement at the tube station?
5. What are other materials do you recommend us to get in touch to extend our understanding of passenger flow?

Appendix D: Interview Instrument for Station Employees

Interview Preamble:

We are students from Worcester Polytechnic Institute in Worcester, MA. We are working in conjunction with Transport for London on improving passenger flow in the stations here in the London Underground. Your answers to these questions may be recorded and be used in a published report at the end of our project. You will have the opportunity to review the final report before it is published. You are not required to answer every question and may stop at any time. Your participation in this interview is completely voluntary. If you have a specific question about the research, please feel free to contact us at: Tube_E17@wpi.edu, or our project sponsor from TfL, Steve Walling, at Steve.Walling@tube.tfl.gov.uk.

1. Station Crowd Levels
   i. Do you notice any trends in passenger level across the station?
   ii. Do you think that passengers tend to group in some areas of the station more than others? Is there any pattern to where they group?
2. Problem Areas
   i. Have you noticed any specific areas of congestion in your station?
      1. What major points of interest in the station are around this area of congestion? Are there any major points of interest where passengers group, or do they group in other areas of the station?
3. Customer Opinions
   i. What are your most frequently asked questions from customers?

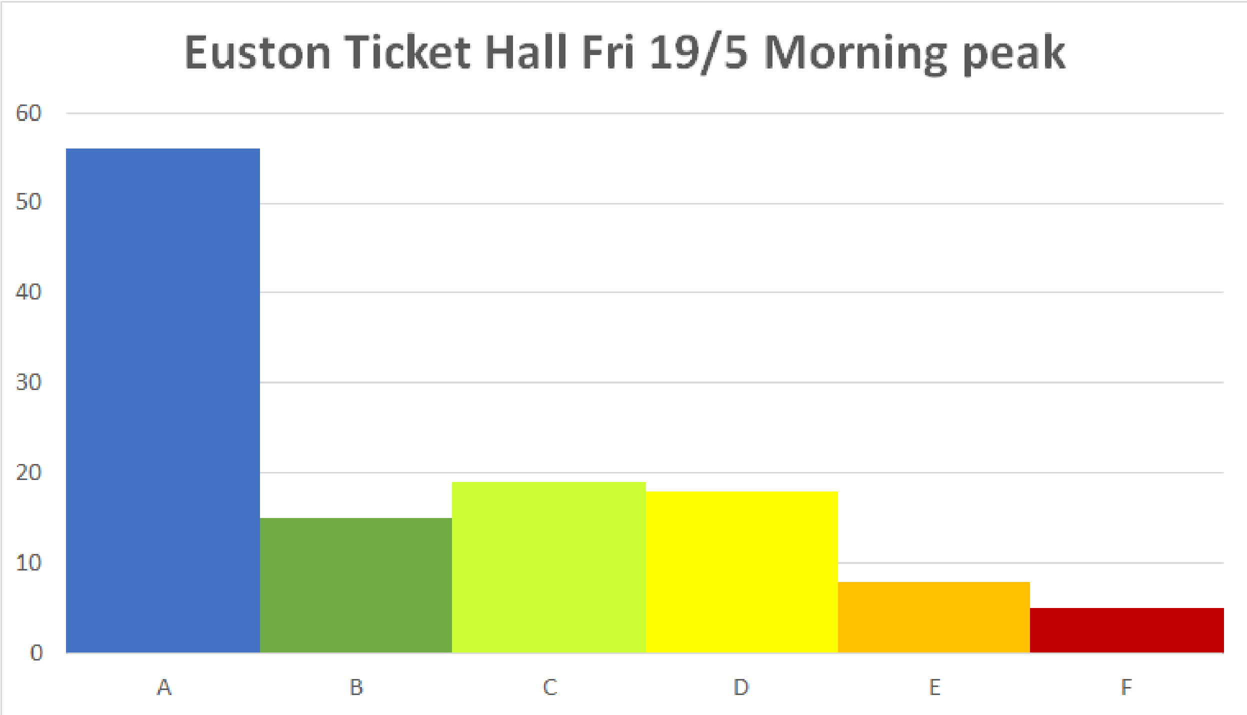
Appendix E: Group Discussion Questions

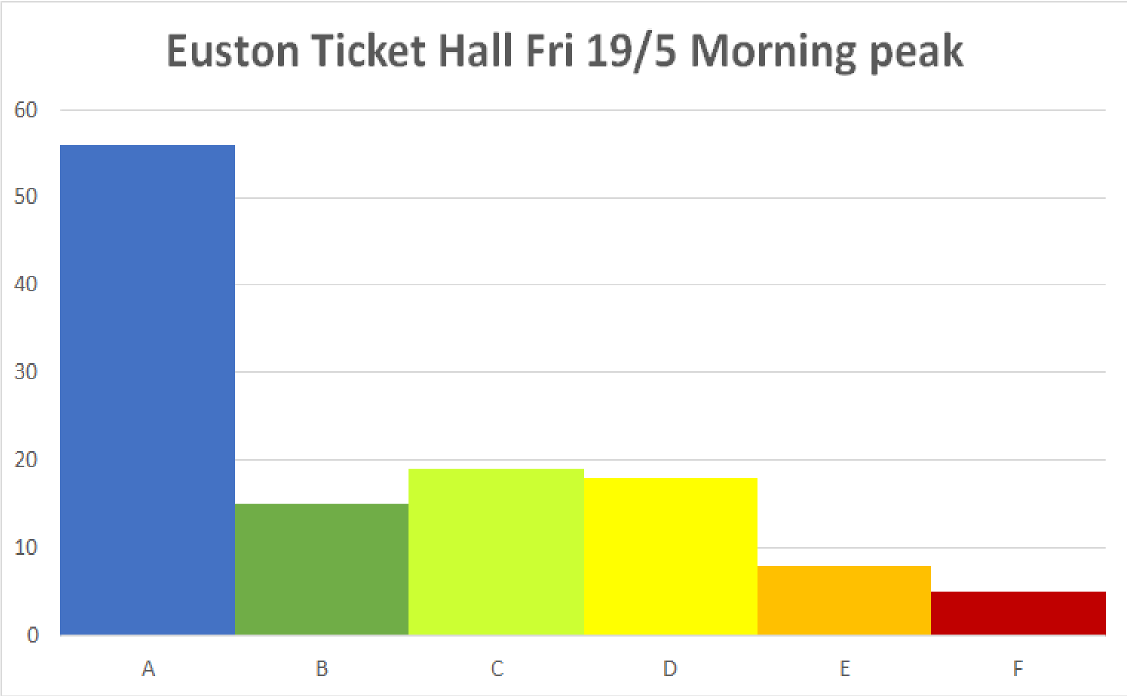
Discussion preamble:

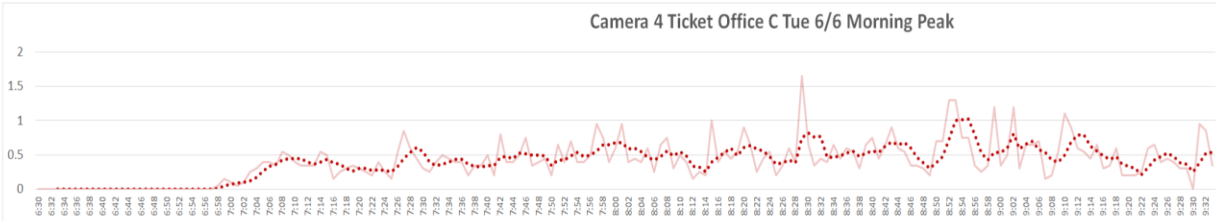
We are a group of student from Worcester Polytechnic Institute's (WPI) London Project Center (LPC). We are conducting the discussion to narrow down our data down into conclusion for our project on passenger flow. This project is being done in collaboration with the Transport of London (TfL) and we appreciate with your assistance. By completing the discussion, you consent that any information given can be used in our research. Please remember that your identity will remain confidential. If interested, we are happy to provide you with our research result at the conclusion of this study. If you have specific question about the research, please feel free to contact us at: Tube_E17@wpi.edu. You may also contact our project advisors, Dominic Golding and Jennifer DeWinter, at golding@wpi.edu and jdewinter@wpi.edu.

1. Which, if any, pieces of this summary do you find surprising or not surprising?
2. What, if any, improvements do you see suggested by this summary?
3. What suggestions, if any, do you see that you would like to see implemented across the Tube?
4. What suggestions, if any, do you see that you would not like to see implemented?

Appendix F: Extra Data Visuals



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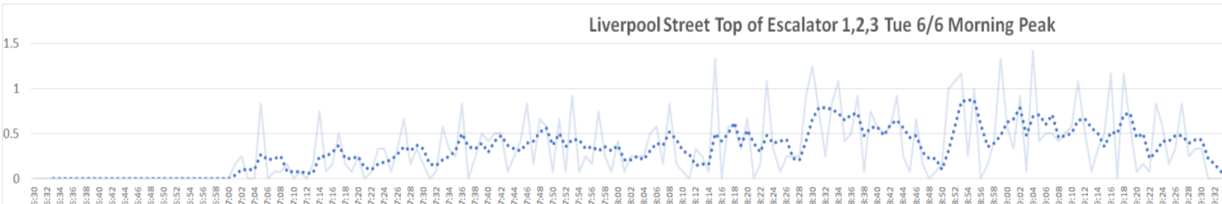
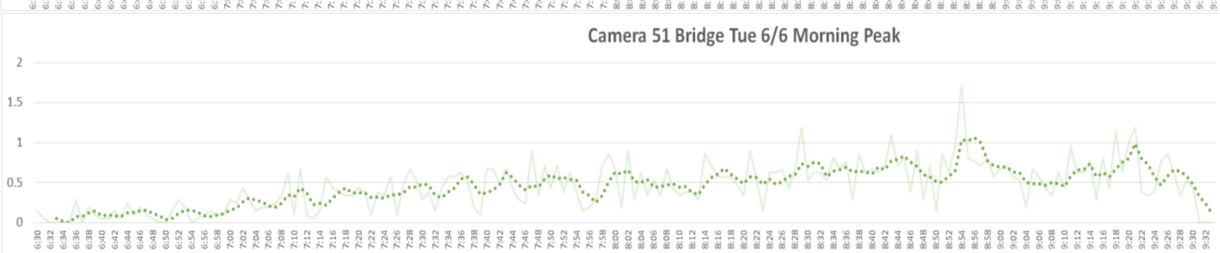
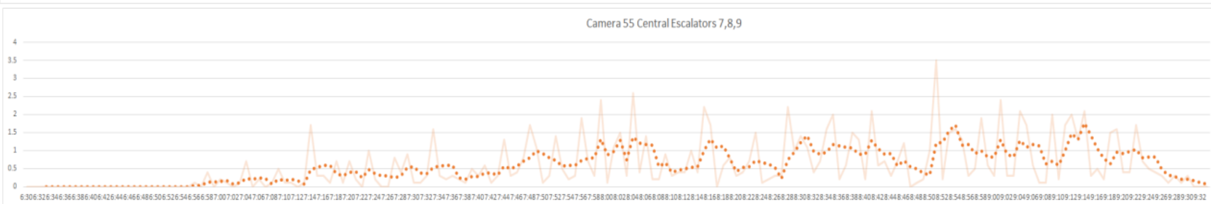
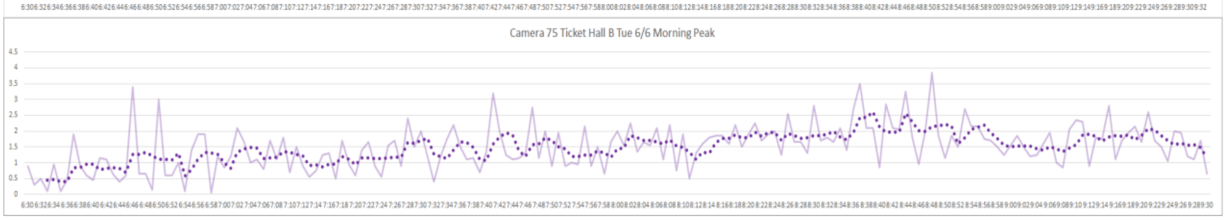
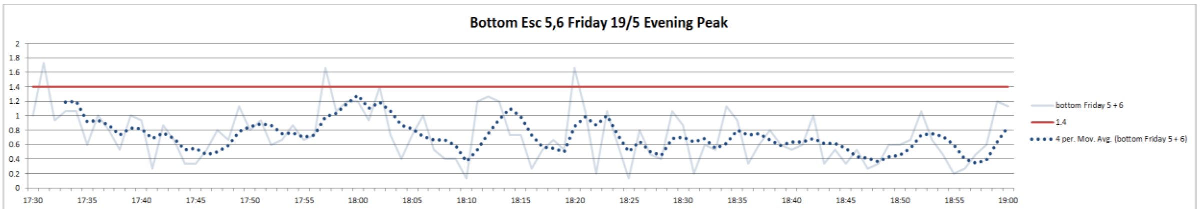

Liverpool Street Top of Escalator 1,2,3 Tue 6/6 Morning Peak


Camera 51 Bridge Tue 6/6 Morning Peak


Camera 55 Central Escalators 7,8,9


Camera 75 Ticket Hall B Tue 6/6 Morning Peak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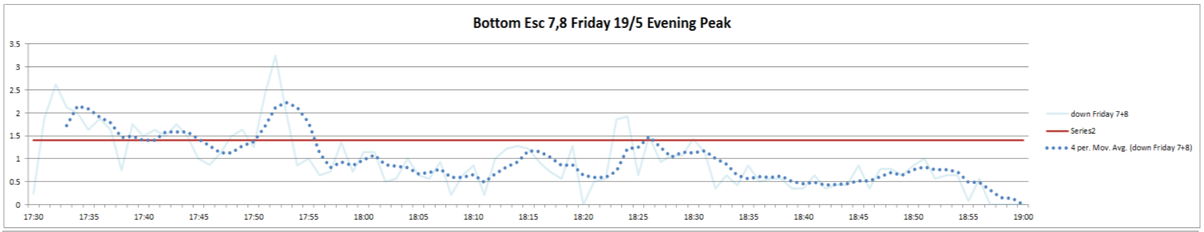
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down Friday 7+8
Series2
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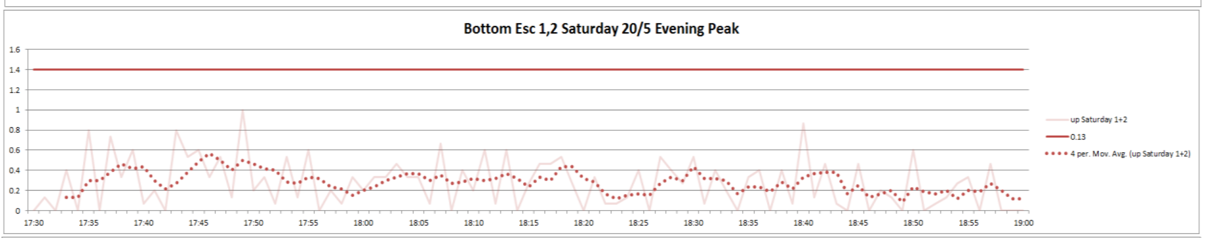
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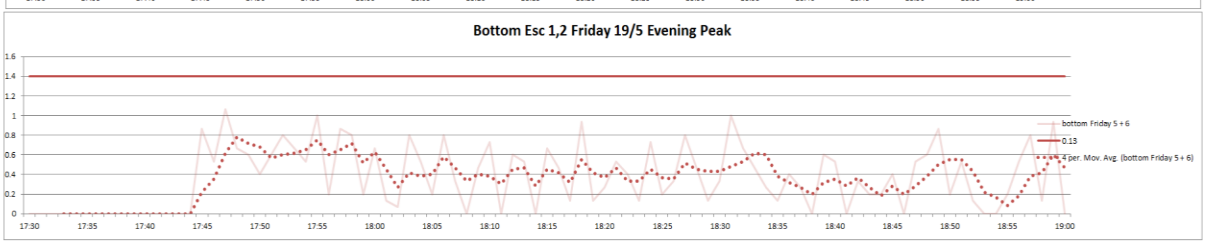
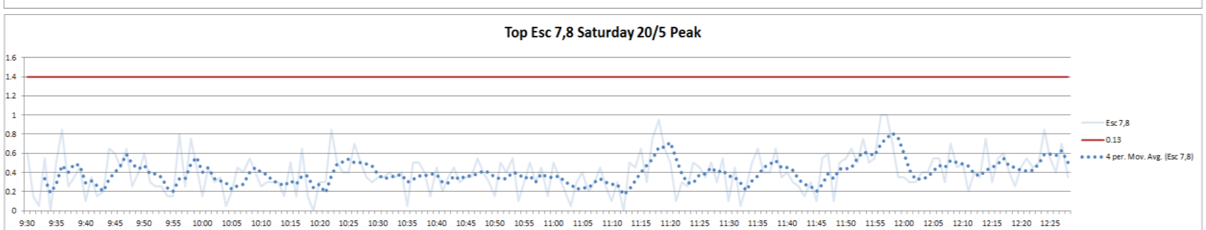

Bottom Esc 1,2 Friday 19/5 Evening Peak
bottom Friday 5 + 6
0.13
4 per. Mov. Avg. (bottom Friday 5 + 6)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Esc 7,8
0.13
4 per. Mov. Avg. (Esc 7,8)