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Investigation into Reliability of the Jubilee Line

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Investigation into Reliability: London Underground Jubilee Line

An Interactive Qualifying Project
submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfilment of the requirements for the
degree of Bachelor of Science

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Report Submitted to:

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Abstract

Metro systems are often faced with reliability issues; specifically pertaining to safety, accessibility, train punctuality, and stopping accuracy. The project goal was to assess the reliability of the London Underground's Jubilee Line and the systems implemented during the Jubilee Line extension. The team achieved this by interviewing train drivers and Transport for London employees, surveying passengers, validating the stopping accuracy of the trains, measuring dwell times, observing accessibility and passenger behavior on platforms with Platform Edge Doors, and overall train performance patterns.

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Authorship

Throughout the completion of the project, the responsibilities were shared equally between the four group members. Each section of the paper was iteratively written and edited by each group member. Individual group members were in charge of sections of the paper, but fellow group members helped to edit and contribute to the sections. Every diagram created was collaboratively designed before one group member completed the final design steps. We believe the collaborative nature of our group contributed to the success of this project.

Table of Contents

Abstract.....	ii
Acknowledgements.....	iii
Authorship.....	iv
Table of Contents.....	v
Table of Figures.....	viii
Executive Summary.....	1
1 Introduction.....	11
2 Background.....	14
2.1 Rail Transportation.....	14
2.1.1 Transportation Overview.....	14
2.1.2 Modernization of Railway Transportation.....	15
2.2. Modern Train Technologies.....	17
2.2.1 Automatic Train Control.....	17
2.2.3 Platform Doors.....	20
2.3 Case Studies of Modernized Railway Systems.....	21
2.3.1 Singapore Mass Rapid Transit (MRT).....	21
2.3.2 Copenhagen Metro (CM).....	23
2.3.3 Paris Métro (M).....	25
2.4 London.....	26
2.4.1 Transport for London.....	26
2.4.2 London Underground.....	27
3 Methods.....	35
3.1 Goals and Objectives.....	35
3.2 Data Collection.....	36
3.2.1 Passenger Surveys.....	36
3.2.2 Driver Interviews.....	38
3.2.3 Senior Jubilee Line Manager Interviews.....	39

3.2.4 Platform Train Interface Observation.....	39
3.2.5. Stopping Accuracy	40
4 Findings.....	43
4.1 Safety.....	43
4.2 Accessibility	46
4.3 Train Punctuality	48
4.4 Stopping Accuracy	52
5 Discussion	56
5.1 Brief Recap of Findings	56
5.2 Significance of Findings.....	57
5.2.1. Safety.....	57
5.2.2. Accessibility	60
5.2.3. Train Punctuality	60
5.2.4 Stopping Accuracy	62
5.3 Recommendations to the Sponsor	64
5.3.1. Triple Pole	64
5.3.2. Platform Markings.....	65
5.3.3. Metal Railings.....	65
5.3.4. Connected Cars.....	66
5.3.5. Mechanical Gap Fillers.....	67
5.3.6. Door Obstructing Fee	68
5.3.7. Accessibility Card.....	69
5.3.8. Investigation of the Effectiveness of Signs	70
5.4 Limitations and Future Research.....	70
5.5 Conclusion.....	72
5.6 Reflections.....	73
Jack Arnis Agolli.....	73
Marianna Bailey	73
Errando Berwin Jayapurna	74
Yiannis Kaparos	75
References.....	76

Appendix A: Paris Metro map	81
Appendix B: London Underground map	82
Appendix C: Step-Free Tube Map.....	83
Appendix D: Methods Schedule	84
Appendix E: Jubilee Line before 1979	85
Appendix F: Survey Consent Form	86
Appendix G: Survey Questions	87
Appendix H: Informational Handout	89
Appendix I: Interview Consent Form	90
Appendix J: Driver Interview Questions	93
Appendix K: Senior Jubilee Line Manager Interview Questions	94
Appendix L: Observation Checklist.....	95

Table of Figures

Figure 1. Picture of Platform Edge Doors (PEDs) in North Greenwich Station	2
Figure 2. Recommendations. Top Left: Visualization of Triple Pole. Top Right: Visualization of Platform Markings. Bottom Left: Photograph of Metal Railings. Bottom Right: Computer Render of New Train Stock	9
Figure 3. Hierarchical structure of the ATC system	18
Figure 4. TBTC system overview diagram.....	19
Figure 5. Inductive Loops	20
Figure 6. Left: Total Rail Ridership for Singapore MRT; Right: Total delays for Singapore MRT	22
Figure 7. Demonstration of all three sub-systems in the Copenhagen Metro.....	24
Figure 8. Paris PEDs	25
Figure 9. Passenger risk by accident type	29
Figure 10. Mind the Gap	30
Figure 11. History of the Jubilee Line	31
Figure 12. Geographical Path of Jubilee Line with Highlighted Stations with PEDs	32
Figure 13. Picture of the stopping accuracy measurements.....	41
Figure 14. Performing a manual measurement of the stopping accuracy, second method.....	42
Figure 15. Passengers Favorite Line	44
Figure 16. Reasons for Preferring the Jubilee Line	44
Figure 17. Favorite Line of Passengers who require assistance	47
Figure 18. Left: Level boarding. Right: Platform hump.	47
Figure 19. Wheelchair and Baby Buggy Space on Jubilee Line Train.....	48
Figure 20. Total Dwell Time - Non-PED vs. PED	50
Figure 21. Total Dwell Times Comparison - No Outliers	51
Figure 22. Stopping accuracy of the entire Jubilee Line fleet for March - Data obtained from VCC	53
Figure 23. Stopping accuracy - Manual Measurements.....	54
Figure 24. Visualization of Triple pole in a Jubilee train car	64

Figure 25. Visualization of Markings demonstrated on the non-PED Jubilee Line platform at Stratford.	65
Figure 26. Metal Railing in Shanghai	66
Figure 27. New Tube for London train stock.	67
Figure 28. In-Train picture of the trains used currently in the Metropolitan, Circle, District, and Hammersmith & City lines	67
Figure 29. Mechanical Gap Fillers on a German Train	68
Figure 30. Demonstration of camera detection for fee.	69
Figure 31. Mockup of an accessibility Oyster card to identify persons that require accessibility accommodations.	70

Executive Summary

Public transportation is one of the key pillars of any modern metropolis. With growing populations in cities, public transportation inevitably faces challenges. In order to continue being a valuable service, these systems need to be reliable, accessible, and safe for passengers. A proven solution to all of these challenges, applicable around the world, is modernization of public transportation systems (UITP, 2016). Rail transportation is a major part of public transportation networks and is one of the best alternatives to driving, due to its improved speed and convenience (Eagling & Ryley, 2015). An ideal rail system in a major global city would be equipped with the latest technologies and would operate at peak efficiency by every possible measure. In reality, most systems cannot afford the initial costs necessary to modernize and are plagued with a wide variety of problems. London Underground (LU) for instance, the underground rail transportation system in London, faces serious problems across its lines due to the combination of excessive demand and a relatively outdated system (Morley, 2017).

Background

In accordance to the Disability Discrimination Act of 1995, London Underground is committed to creating a seamless journey for anyone who may need special assistance, including riders who are elderly, pregnant, those who have mobility, hearing, or vision impairments. In the United Kingdom alone, there are 10 million people living with a disability, making up 20% of the population (Customer Standards & Experience Manager, 2008). As of April 2017, however, only 71 of the 270 stations on the Underground provide any form of step-free access for mobility impaired users. This means that only about a quarter of the network can be used by everyone, including those with disabilities. In December of 2016, Mayor Sadiq Khan promised to spend £200 million on making at least 30 more stations step-free, but this is a long and complicated process (Pring, 2016).

Safety is another important aspect that London Underground is committed to improving. The Platform Train Interface (PTI), or the gap between the train and the platform, poses the greatest safety threat for passengers. The PTI accounts for 21% of safety risks and 48% of fatality risks (RSSB, 2015). Moreover, overcrowding on the platform and inattentive riders getting too close to the train can lead to accidents. To ensure the passengers travel safely,

London Underground has numerous regulations and strategies. The PTI is monitored by the train driver and control center through CCTV and customer behavior is influenced by the “mind the gap” and other announcements, signs, and yellow lines. There is also additional station staff present at the platforms during peak hours to direct passengers, provide organization, and prevent any potential track intrusions (Customer Standards & Experience Manager, 2014).

One of the most recently constructed lines is the Jubilee Line. In 1932, the first part of what is now the Jubilee Line was built to connect Baker Street and the Stanmore branch as a part of the Bakerloo Line. Since then, the line has been extended in two phases. In 1979, the branch was extended to connect with Charing Cross tube station in central London, and the section from Stanmore to Charing Cross became the Jubilee Line, separate from the Bakerloo Line. In 1999, the Jubilee Line Extension (JLE) connected the line to Stratford Station in east London (London Underground: Jubilee Line, 2017). The JLE involved building 11 new stations, 8 of which have Platform Edge Doors (PEDs), as shown in Figure 1, a unique feature in the London Underground. In mid-2000s, a new signaling and train control system, called Transmission Based Train Control (TBTC) was introduced in the Jubilee Line. Today, Jubilee Line accommodates 213 million passengers per year throughout its 27 stations (Jubilee Line, 2017).



Figure 1. Picture of Platform Edge Doors (PEDs) in North Greenwich Station

Project Goal & Objectives

The project goal was to investigate the reliability of the modern train technologies implemented during the Jubilee Line Extension. We completed this in collaboration with CPC Project Services, a private consultancy firm that is working with Transport for London (TfL). For this project, we defined reliability as the benefits and limitations of the modern technologies, their effect on dwell time and safety, and their accessibility for all train riders. We evaluated this by surveying passengers about the modern technologies, interviewing drivers, duty reliability managers (DRMs) and senior Transport for London (TfL) staff, observing accessibility, behavior of passengers around the PTI, station signage, and overall train performance patterns, and measuring the stopping accuracy and dwell times on the Jubilee Line stations.

Our definition of reliability can be broken down into four objectives from both human and technical perspectives:

1. Investigation of the safety measures on Jubilee line, including how passengers behave at stations with and without PEDs and the precautions taken at each platform.
2. Evaluation of the accessibility of the trains and stations for all passengers, and how the PEDs affect accessibility.
3. Assessment of how modern technologies, specifically Automatic Train Operation (ATO) and PEDs, affect the punctuality of the Jubilee line trains, particularly in relation to changes in the dwell time.
4. Validation of the TBTC system that currently measures the stopping accuracy of trains on stations that are PED equipped.

Once the objectives were fulfilled, we formed recommendations on how to improve the reliability of the line.

Methods

To analyze the social implications of improving the reliability of the Jubilee Line, we collected a wide array of data, ranging from passenger surveys and employee and driver interviews, to station observations and stopping accuracy measurements. In order to gather information about riders' opinions on the reliability and accessibility of trains in the Jubilee Line, we conducted an in-person and online version of a survey. We collected 104 survey responses

from a diverse group of riders, with 35% of riders being between ages 18 and 24, 37% between the ages of 25 and 39, and 26% between the ages of 40 and 65, the majority of whom had ridden the Jubilee Line before. To gain a better understanding of the London Underground system from the employee's point of view, we performed interviews with train drivers, Duty Reliability Managers (DRMs), and senior Jubilee Line staff. Since the PTI is the greatest threat for passengers, we also performed observations of the PTI on various Jubilee Line stations. Finally, we completed manual stopping accuracy and dwell time measurements in order to validate the measurements made by the TBTC system. Stopping accuracy is one of the most significant measurements of an Automatic Train Operation (ATO) system's efficiency (Ma & Zeng, 2014, p. 1237). By determining if a train is stopping accurately and whether the measurement system is accurate, a wide range of systematic problems can be revealed.

Findings & Discussion

Regarding safety, we found that the PEDs improve the safety of the passengers as they act as a barrier to prevent intentional or unintentional falling to the track. Of the 104 passenger survey responses, 74% of passengers felt safer at platforms equipped with PEDs. In addition, only 15% ever had a bad experience with PEDs. In terms of drivers, the unanimous consensus was that all six felt safer and more relaxed driving trains on the Jubilee Line, especially at stations equipped with PEDs. PEDs improve safety as they prevent people from intentionally or unintentionally falling into the track. This means that the train operation is not interrupted by track intrusion, and the number of accidents will significantly decrease. All riders feel safer to stand closer to the PTI when waiting for the train to approach, as there is a barrier separating them from the track. This makes the drivers feel more relaxed when driving the train. PEDs provide positive collateral effects such as providing psychological benefits of reducing staff and riders' trauma from witnessing accidents. The cost to society of a single incident of a person jumping into the track is estimated to be over one million pounds. With around 250 suicide cases in main railways per year, the costs associated with suicide become very significant (Dobell, Personal Communication, March 27, 2017). PEDs also make stations look more modern and new, and we suspected that this was one of the reasons why the Jubilee Line is the most popular among our survey responses. On the other hand, PEDs have various drawbacks, namely the costs of implementation and maintenance. The current system that controls PEDs is independent of

Transmission Based Train Control (TBTC), hence issues arise as a result of the two systems not working in conjunction. It is therefore important to reconsider other factors that may contribute to improving safety. The first one is consumer behavior. According to the SCM and GM of Jubilee Line, consumer behavior is very unpredictable and difficult to control. O'Hare mentioned that TfL has conducted different studies to understand consumer interaction with instructions, signs, announcements, etc. They found that even the smallest detail, such as size of the platform, can change the way people behave. They also noticed that human behavior may be altered in one particular station where relevant signs are in place, but once they move on to a different station, they switch back to their old habits. These findings show that passengers are very unpredictable and thus improving safety is much more complicated than modernizing a system.

Our accessibility evaluation showed that the Jubilee Line is more accessible to all riders compared to other lines in the Underground, due to the physical systems and organizational policies that are in place. The new Jubilee Line stations are all equipped with lifts, escalators, level boarding areas, and signs denoting which cars are level at certain older stations, like Green Park, to allow for easy alighting. This is a result of the relatively new legislation that established regulations to ensure that public transportation is accessible to everyone that wishes to use it. Unfortunately, the previously mentioned features are not implemented at all stations. According to our conversations with senior Jubilee Line staff and the project sponsor, all of the newly built Underground stations will be built to allow for step-free access. The most significant limiting factor in upgrading older stations is the lack of funds. In an ideal world, London Underground would have enough money to install lifts, ramps, and level access at all stations. Moreover, there are significant technical difficulties in upgrading older stations by installing accessibility features. Many of the old stations do not have room to easily install lifts to allow step free access from the street to the platform. As a result, small fixes will have to be implemented to accommodate anyone who needs assistance getting to the platform.

The team's data analysis showed that many factors affect train punctuality. Both of the senior Jubilee Line employees the team interviewed said that passenger behavior is the most significant factor of delays. Therefore, before any further technological improvements are made, TfL needs to reach out to the customers. Both interviews said that the reason behind this behavior is that passengers are not aware of the system around them and the effect their actions can have on it. Inattentive and careless behavior causes delays on the line when passenger try to

rush onto the trains at the last moment and end up running into the doors, drop items down on the track, and miss major announcements. Survey responses support the presence of such behaviors. The interviews also discussed the major impact of a single, small delay on the line. The Jubilee Line General Manager emphasized that if there is a delay in the morning peak, it will ruin the time table for the remainder of the day. Our dwell time analysis showed that the PEDs add very small amounts of time in the total dwell time. The increase in the average dwell time was small enough that the total effect in delays is negligible, even over a full day of operation. Moreover, the stations with PEDs showed more consistency regarding the dwell time. This is very important because the consistency allows for better scheduling, since the dwell times are more predictable.

The team's stopping accuracy data analysis revealed the following important results. First, we compared the stopping accuracy data obtained from the Vehicle Control Centre (VCC) to the manual measurements we performed. We found the VCC to be measuring the stopping accuracy correctly more than 96% of the time at PED stations, in that it matched the measurements of the manual measurement system. This means that the currently installed system is sufficient for measuring the stopping accuracy, although an automated version of the manual measurement system could be developed. Second, the VCC data for all the trains on the Jubilee Line for March 1st to 26th showed that the trains are consistently stopping accurately. Driver interviews also supported this finding as all of them said that in their experience, the trains have never stopped outside the tolerance. Third, the measurements done by the VOBC, at a 5cm resolution, did not match our manual measurements for the majority of cases. It should be noted that the VOBC data analysis was done with very few data points, so a definite conclusion cannot be made at this stage.

The stopping accuracy measurement results affect everyone involved in the Jubilee Line: passengers, train operators, platform and station staff, as well as senior management staff. On the passenger level, it means that it is extremely rare that a passenger will be obstructed while boarding or alighting the trains (at stations with PEDs). This means that more passengers will be able to get in and out of the trains and get to their destination without any disturbances. Moreover, the reliability of the stopping location of the trains at stations both with and without PEDs allows for the passengers on the platform to queue in an orderly fashion around the locations where the train doors will be, resulting in much more efficient alighting-boarding

process; as a result, the passenger-carrying capacity of the line can be maximized, and delays will be positively impacted as well. From the perspective of the train drivers, very accurate, consistent stopping allows them to operate the train doors quickly, keeping the dwell times to a minimum. For the platform staff, accurate stopping is welcome because the reduced customer disturbances mean that the staff members will not have to intervene with passenger behavior as often. Finally, accurate stopping is important for senior staff of the line because it means that the investments in the modernization of the Underground have positive effects on the daily operation, and should therefore continue.

Recommendations

We investigated similar railway systems around the world, including the most advanced and newest ones, and previous research, and came up with original ideas to improve reliability on the line. We examined the Paris Metro because of its similarity as an older system in a large global city, whereas Copenhagen Metro and Singapore Mass Transit were looked at because of their recently built, modern systems. The following recommendations were proposed:

1. Triple poles (Figure 2, Top Left) in the center of train cars to allow passengers to more safely and easily stand near the center of the car, to address safety and punctuality. The team's in-train observations showed it is often difficult for many passengers to stand near the center and grip the single pole during peak times.
2. Platform markings on non-PED stations (Figure 2, Top Right), to address safety, punctuality, and stopping accuracy. These markings would provide passengers with an idea of where the train doors are going to open, allowing passenger to wait and queue in the right area, which will work since our verification showed that the trains are in fact stopping accurately with the TBTC system. The markings will also encourage passengers on the platform to stand on the side of the door opening area, to avoid obstructing passengers exiting the train, a problem the team noticed daily.
3. Metal railings (Figure 2, Bottom Left) to improve safety as a less costly barrier for the PTI than PEDs and to address stopping accuracy and punctuality. Retrofitting PEDs can be very costly, and even impossible in some stations due to their mechanical and electrical complexity. Metal railings serve a similar purpose to PEDs, in that they prevent passengers

from falling onto the track and can also be used to direct passenger flow. These metal railings would be placed along the platforms in the areas between the train doors.

4. Connected cars (Figure 2, Bottom Right), like the ones that are already implemented in the Metropolitan, Circle, District, and Hammersmith & City lines, which would allow better distribution of passengers along train cars, thus addressing accessibility and punctuality. Connected cars also allow passengers to move along the whole train, especially those with wheelchairs, strollers, or luggage.
5. Mechanical gap fillers to bridge the gap at the PTI on platforms where it is large. These mechanical gap fillers are extended from the train upon stopping at stations, and prevent people from falling into or getting trapped in the PTI.
6. Door obstruction fee, which would be charged when any passengers who prohibit the train doors (or PEDs) from closing. A fee could influence customer behavior and reduce the delays caused by customers rushing onto trains as the doors are closing. Two means of implementing this system are discussed from a non-technical standpoint, one being a camera based identification system, the other being Oyster card based.
7. An accessibility card that would be available for riders with disabilities (visible or invisible) who require assistance to navigate around the Underground. This card would be a specially identifiable Oyster card that would notify the system whenever someone with it enters the station, so that station staff can provide assistance immediately.
8. Further investigation of the effectiveness of signs as a focused study or project. The team found from data analysis that there are different perspectives on the provision of signs throughout stations. From the surveys, the team learned that a majority of passengers are satisfied with the provision of information but from the interviews with senior Jubilee Line staff the team learned that there are conflicting opinions on whether the Underground needs more signs or less signs. In order to determine which opinion is valid, the team suggest a study be performed on the distribution and optimization of signs across the Underground network. This study could include the design and placement of signs on the line.

Some of the recommendations are depicted in Figure 2 below.

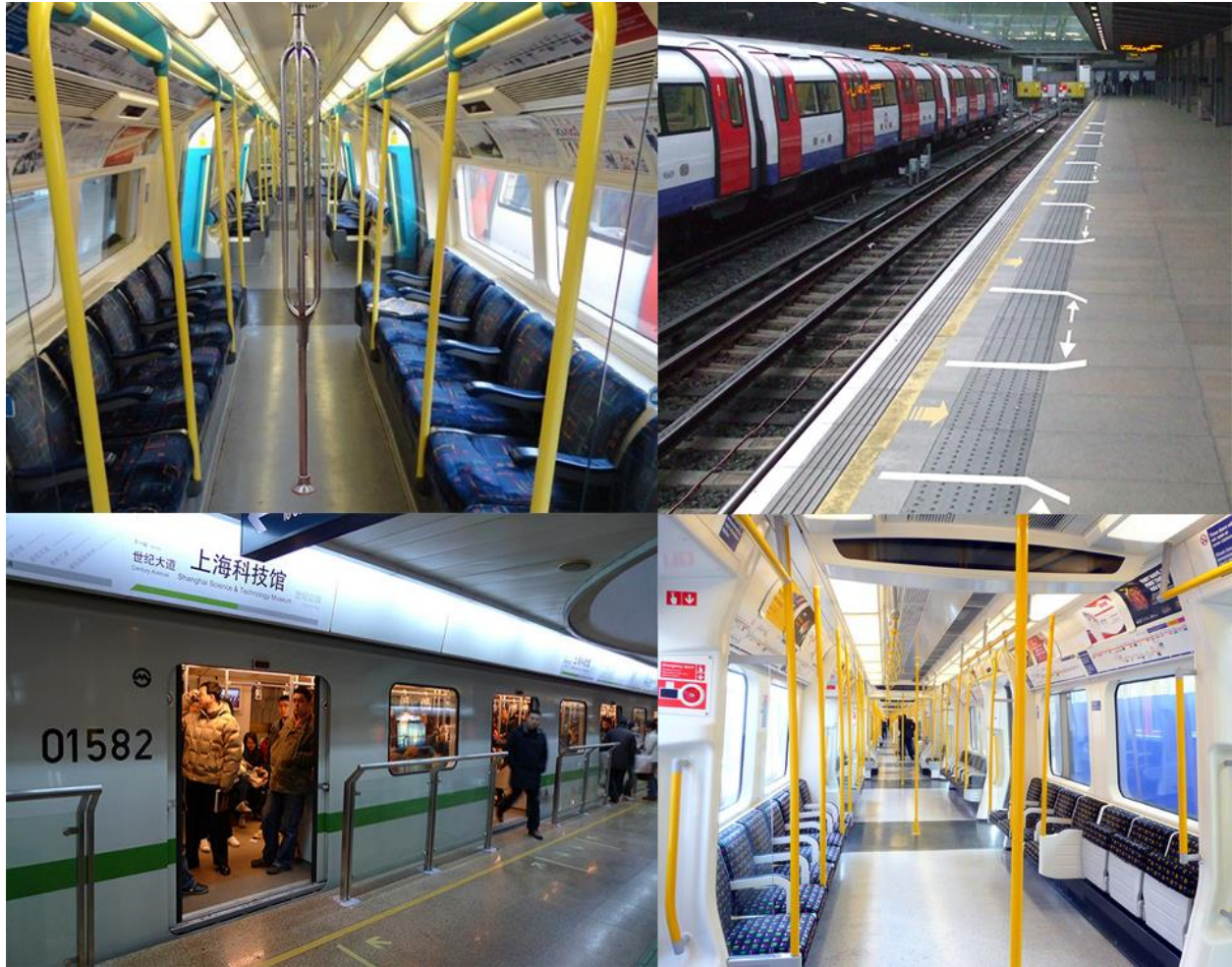


Figure 2. Recommendations. Top Left: Visualization of Triple Pole. Top Right: Visualization of Platform Markings. Bottom Left: Photograph of Metal Railings. Bottom Right: Computer Render of New Train Stock

In conclusion, the team’s data analysis has led to two overarching factors that can improve the reliability of the Jubilee Line; customer behavior and modernization. As a long-term means of improving reliability, further modernization of the Jubilee Line would be the best course of action. It would improve customer satisfaction and behavior through the safety and punctuality benefits of PEDs and new train stock, and because of passenger’s preference for modern renovated stations. This would of course be the costliest approach, as any station construction or renovation or addition of new train stock would be much more expensive than the more cost effective reliability improvement recommendations outlined in this report. Regardless, the team learned that both ends of the Jubilee Line management believe that positively influencing customer behavior is currently the best way to improve service reliability. Based on the team’s findings, they believe that any future modernization plans will be more

effective if the customer behavior is dealt with beforehand. Hence, it is imperative for London Underground to continue the current plans for modernization and improving signage being made on the Jubilee Line, and to do so across the entire network in order to further the growth of London as a global metropolis.

1 Introduction

Public transportation is one of the key pillars of any modern metropolis. A growing population, especially in cities, puts increasing pressure on the existing public transportation infrastructure. The highest number of local public transport journeys in the European Union (EU), 57.6 billion that is, have been observed since the turn of the millennium (UITP, 2016). Moreover, public transportation is part of the solution to a country's economic, environmental, and energy challenges (APTA, 2017). Statistics from the International Association of Public Transport of various EU member states show that the number of public transportation journeys is usually linked with the economic circumstances of the country (UITP, 2014). Public transportation systems also need to be reliable, accessible, and safe for passengers in order to continue being a useful service. A proven solution to all of these challenges, used around the world, is modernization of public transportations systems (UITP, 2016).

Rail transportation is one of the most important types of transportation because it is faster and more organized than motor vehicles (Eagling & Ryley, 2015). An ideal rail system in a major global city would be equipped with the latest technologies and would operate at peak efficiency by every possible measure. In reality, most systems cannot afford the initial costs necessary to modernize and are plagued with a wide variety of problems. The underground rail transportation system in London for instance, the London Underground (LU), faces serious problems across its lines due to the combination of excessive demands and a relatively outdated system (Morley, 2017). Through modernization of the Metropolitan, District, Hammersmith & City, and Circle lines, LU was able to reduce delays by 30 percent in 2015 (Transport for London, 2016).

Modernization of the Underground has been essential in London as both its population and public transportation demand have grown substantially in recent years. In 2015, rail transportation systems accounted for 600 miles traveled per person per year, and this number is predicted to continue to increase (Transport for London, 2016). The London Underground is one of the most popular modes of transport in the city; accordingly, it needs to constantly be improved to meet the demands of the passengers. London Underground's slogan states that "Every Journey Matters", which demonstrates their desire to make their service reliable for all passengers. Reliability in the scope of our project is defined as the benefits and limitations of the

modern technologies, their effect on dwell time and safety, and their accessibility for all train riders.

Our project is focused on the Jubilee Line, which is the most recently updated line in the London Underground. The Jubilee Line Extension (JLE) was one of London's biggest engineering projects to date and cost over £3.5 billion, making it one of the most expensive projects in the world at over £4 million per meter of its 16 km length (OMEGA Centre, 2008). It traverses through some of the busiest stations in the Underground, namely Waterloo, London Bridge, and Stratford, the 1st, 2nd, and 4th busiest stations respectively and the whole line serves around one million passengers each day (O'Hare, personal communication, March 29 2017).

The Jubilee line is equipped with some of the latest railway technologies, accessibility features, and safety measures. Two of the technologies implemented during the modernization of the Jubilee line were Platform Edge Doors (PEDs) and Automatic Train Control (ATC). Platform Edge Doors make the line much safer as they act as a barrier between the tracks and the platforms, and reduce the wind draft produced by the moving trains. Automatic Train Control (ATC) is a collective term describing the automatic system that monitors and manages the movement of trains along the line. The Jubilee Line is the only line in the London Underground that has PEDs. It is equipped with a specific type of ATC called Transmission Based Train Control (TBTC). The TBTC system is semi-automated and currently requires a driver onboard the train to open and close the doors. In terms of accessibility, all 11 stations that were worked on during the JLE have step-free access from the train to the street by means of lifts and a level PTI, and new trains have cars with extra space for wheelchair users.

We investigated the reliability of the Jubilee line by examining safety measures on the line, evaluating the accessibility of the trains and stations, assessing the modern technologies that affect train punctuality, and validating the stopping accuracy of trains. We validated the stopping accuracy to reveal any inherent problems with the train systems and enable future modernization. Our approach consisted of three main objectives, incorporating both human and technical factors. First, we conducted surveys with riders and interviews with staff on the Jubilee Line to understand how they feel about the new technologies and how they are affected by them. Second, with the help of CPC Project Services, we validated the system that currently measures the stopping accuracy on the eight stations of the Jubilee Line equipped with PEDs. Lastly, we formed and provided our recommendations on how to address any potential problems on the line

and improve reliability and accessibility. The data from this investigation was analyzed to form recommendations to improve the reliability of the Jubilee Line primarily through influencing positive passenger behavior, increasing accessibility, and verifying that the system is running efficiently.

2 Background

The background section begins with a broad overview of rail transportation and then discusses significant problems that modern rail transportation systems face: delay times, rider safety and rider accessibility. It then discusses how implementing new train technologies can address these problems and describes some of these technologies in detail. Subsequently, it will discuss how they were implemented in the Singapore Mass Rapid Transport (MRT), the Copenhagen Metro (CM), and the Paris Métro (M). The final section will then focus on London and the Jubilee Line, and how the technologies implemented there improve rider safety, reduce delay times, and improve rider accessibility.

2.1 Rail Transportation

2.1.1 Transportation Overview

Public transportation in the 21st century is growing rapidly, especially with the accelerated rate of modern urbanization. It is projected that by 2050, there will be more than six billion urban dwellers, almost doubling the number today (UN, 2014). This suggests that many urban areas will face challenges in meeting the demands of their growing populations. Some of these demands include housing, infrastructure, energy, employment, and transportation. An effective and reliable public transportation system can serve to not only meet these demands, but is also essential in making a civilization environmentally sustainable and economically competent (Wortman, 2005).

Rail transportation is a suitable way to meet these needs because it is much faster and more convenient than driving (Eagling & Ryley, 2015). Based on the 2015 England National Travel Survey, cars and walking account for 86% of trips in England, although this number is decreasing. Meanwhile, the number of trips by bus and rail are increasing (National Travel Survey, 2015). Despite a seemingly small percentage of rail trips in 2015, rail transport can help save time for riders by reducing road congestion, especially during peak travel hours.

Since the expansion of mass transit systems is often constrained by the lack of space and resources, existing rail systems and infrastructures are being improved to increase efficiency and

reliability, where reliability of rail transport can be defined as the benefits and limitations of the modern train technologies on the line, their effects on dwell time and safety, and their accessibility for all train riders.

One example of expansion is getting more trains to run on the same line at shorter intervals. This can be achieved by reducing the dwell time and improving the stopping accuracy of trains. Dwell time, defined as the period of time in between train stopping and departing, can improve the frequency the trains run on because each station is occupied by a train (which has limited capacity) for a shorter time period. As a result, a new train can come to the station sooner, thus expanding the overall passenger carrying capacity of the line. An accurate stopping and position measurement system allows for better control of trains, which lower the risks of train collisions. Moreover, reduced dwell times and precise control of the train leads to reduced delays. Overall, riders will have a better experience due to the improved punctuality, frequency, and safety of trains. Energy consumption can also be cut down to as much as 30 percent because of the optimized acceleration, traction, and braking processes (Siemens, 2012).

2.1.2 Modernization of Railway Transportation

There are a wide range of unintended consequences and problems facing rail systems in the world today, such as accident rates and high delay times. In 2011, 147 people were struck by trains on the Metropolitan Transportation Authority (MTA, the organization that controls the New York City Subway), equivalent to about one accident every 2.5 days or about one accident per 12.5 million riders (Kabak, 2012). This number increased from the previous year by about 15 percent (Donohue & Feiden, 2012). The MTA, despite being one of the most popularly used train systems in the world with about 1.7 billion riders in 2015, has some of the oldest technology and infrastructure compared to other train lines (MTA, n.d.). The system is roughly 90 years old and 37 percent of NYC's subway signals have exceeded their useful life (Fishbein, 2014). If any mechanical problems were to arise due to the aging machinery and equipment during operation hours, it could lead to significant delays. In March of 2015 for instance, there were 57,000 delays on average on weekdays, which broke the record from the previous year of 52,000 delays on weekdays (NY1, 2016). Every year, however, the MTA tries to address this by proposing the installation of new technologies like Platform Edge Doors (PEDs) or Automatic Train Control (ATC) systems to decrease safety risks and delays. PEDs and ATC will be further

explored in the next section. Tom Prendergast, the former CEO of the MTA, has proposed installing platform doors to address these issues and modernize the system but it has not been done yet due to high costs (Kabak, 2012).

Trains that are driven automatically have shown promise in not only reducing delays, but also improving safety. The most serious safety issue attributable to operator errors are Signal Passed At Danger (SPADs), which is when the train does not stop at a red/danger/stop signal (Hirsch, Kyriakidis, & Majumdar, 2012). Based on Hirsch, Kyriakidis, and Majumdar's safety analysis, this occurs almost exclusively on manually driven lines. This means that installing new technologies on outdated train lines can significantly improve safety. In an incident when a line is shut down for maintenance due to a safety breach, there will be a very significant disruption in the entire network. An improved safety technology can directly improve the train's reliability by reducing operational downtime.

Installing ATC and/or PEDs on existing metro systems can be a complex process for several reasons. For metro systems that run non-stop, installation of the new system would require pausing train operations. A temporary and cheaper alternative to platform doors is implementing a required platform track monitoring system. This monitoring system has sensors that trigger an alarm when an object of a specified "significant" weight is within the track area. If there is a train approaching, the system will automatically initiate emergency braking or shift the train to an adjacent rail station. From here a notification is sent to the control room and service personnel on the platform (Siemens, 2012). An alarm still would not prevent a passenger from falling onto the track; full platform barrier doors need to eventually be implemented to serve as a physical barrier between a person and the track.

Aside from systems on the platform, the technologies and equipment can be implemented on board the train. Switching to automated lines requires trains to have at a bare minimum: emergency brakes, fire detectors and extinguishers, emergency lighting, audible signals, and door monitoring (Siemens 2012). All of these requirements add to the already high costs that are associated with installing these new technologies. Although these technologies have become commonplace on newer train lines, these implicit and explicit costs must be compared with the long-term benefits.

One final important aspect of a modernized mass transit system is accessibility to all passengers. This means that anyone should be able to get from the street to the vehicle, and vice

versa, with minimal assistance. To achieve this, a station needs to have lifts, escalators, bump strips, minimized gap between platforms and the trains, descriptive and evenly distributed signs, knowledgeable and available staff, space for wheelchairs on the train, and ramps (Transport for All, 2017). The problem with making all the stations accessible is the cost associated with building new lifts or escalators in older stations. In most cases, older stations also tend to have very limited space. As a result, the technical difficulties raise the costs significantly (Dobell, personal communication, March 15, 2017).

2.2. Modern Train Technologies

2.2.1 Automatic Train Control

Automatic Train Control (ATC) is a collective term for the system that regulates and controls the movement of railway vehicles to ensure they are safe and efficient. The ATC system is generally made up of four broad areas: Train protection, Train Operation, Train Supervision, and Communication (Office of Technology Assessment, 1976). It is usually divided into three distinct sub-systems that cover each of the previous areas: Automatic Train Protection (ATP), Automatic Train Operation (ATO), and Automatic Train Supervisory (ATS); the structure between them is depicted in Figure 3. ATP is the system that protects passengers and avoids collisions by controlling the speed and position of trains. ATO is essentially the autopilot system that controls the dwell time, braking, and door opening. ATS controls all monitoring systems and serves as a means of overseeing the other two sub-systems (Almar, 2006). ATP is the only sub-system involved in security, so if either of the other two systems fail, ATP is meant to ensure passengers are safe, which could improve the overall rider's experience.

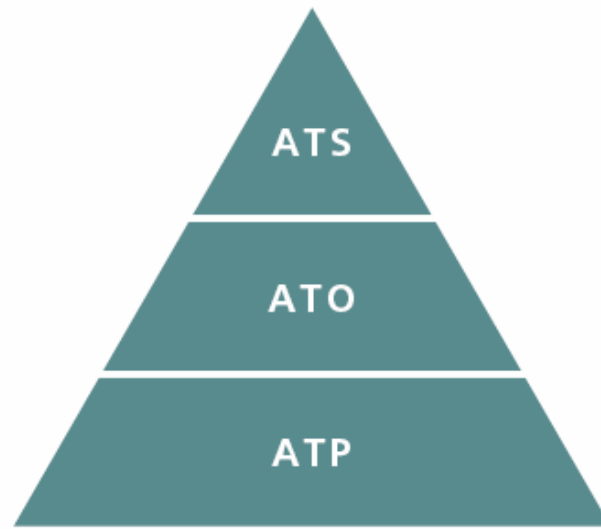


Figure 3. Hierarchical structure of the ATC system

Source: (Almar, 2006), without permission

There are different grades of automation a train can have, ranging from driver-assisting functions for stopping and opening and closing doors, to fully automatic metro operation without drivers (Siemens, 2012). The three main grades are Semi-automated Train Operation (STO), Driverless Train Operation (DTO), and Unmanned Train Operation (UTO) (Mohammed, Al-Azzo, Akaak, & Suroor, 2014). UTO has the highest grade of automation because train operation is controlled and monitored automatically; there is no driver or attendant on board. The system monitors departure, movement between stations, precise stopping of the train, and opening of doors (Siemens, 2012). DTO is also controlled and monitored automatically without human assistance, however a train attendant can intervene in the instance of emergencies. STO, a common system in the United Kingdom, controls brakes and motor, but a driver remains in the front of the train to operate the doors and to monitor the train's overall performance (Georgescu, 2006).

Trains equipped with ATC have many benefits for the railway and riders. They are safer because there is a failure detection system that will automatically diagnose failures and send alerts to the ATC. There is less wear on the train's propulsion and braking systems, and there is essentially no chance of human error. The railway is more efficient and cost effective because the run times are more predictable, energy consumption is optimized, operating cost is reduced, and implementation of the ATC system is much cheaper than building a new line (Georgescu,

2006).

2.2.1.1 Transmission Based Train Control

Transmission Based Train Control (TBTC) is a signaling and train control system that “employs wireless communication technology as a platform for information transmission, bidirectional communication between the train and wayside equipment, and integration of communication and controls” (Balant et al., 2007, p. 1). TBTC, an advanced type of ATC that is semi-automated and requires a driver to be on board the train, is ideal because it is proven to be safe, increases system availability and reliability, and has low initial capital expenditure, operating, and maintenance costs. In addition, TBTC has sub-systems that control and manage the different components of the train. Figure 4 shows the subsystems that make up the TBTC system and how they are connected with each other. The System Management Centre (SMC) and the Vehicle Control Centre (VCC) are the high-level controllers of the system. These two systems collect information from the other sub-systems. All of the trains on the line use this information to plan routes and determine the train spacing. This system ensures that the train spacing is as small as possible without compromising the safety of the underground (Davies & Narin, 2017).

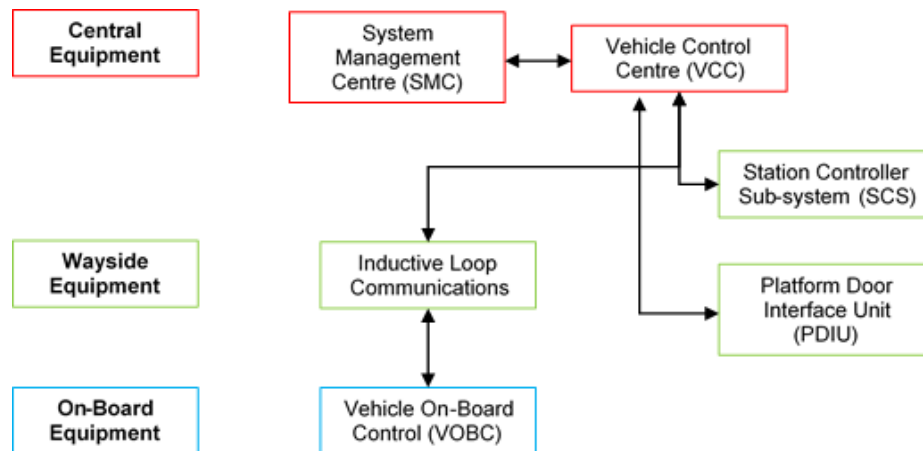


Figure 4. TBTC system overview diagram

Source: (Davies & Narin, 2017), with permission

To measure its position on a line, each train uses a variety of sensors. The coarse measurement comes from detecting the phase change of inductive loops along the track, every 25

meters, and counting how many it has passed over. A schematic of this setup is shown in Figure 5. To know its position with more precision, the train uses its tachometer, which measures the wheel speed, which gives the train position with a tolerance of 20 cm. When a train approaches a station, the VCC, which is one of the two main management systems of TBTC, communicates to the train at which position along the line it should start braking in order to stop on its marks. The train uses the inductive loops and its tachometer to report how accurate the stop was. Each train reports its deviation from the stopping target every time it stops (M. Narin, personal communication, February 9, 2017).



Figure 5. Inductive Loops

Source: (Davies & Narin, 2017), with permission

2.2.3 Platform Doors

Platform Doors are barriers that separate the railway tracks from the platform. When the train arrives at the stop, the train doors and platform doors are aligned and open simultaneously (Platform Screen Doors, 2015). The doors only open when the train driver or ATO system has given permission to allow the doors to open. The first platform doors were installed in Singapore by Westinghouse Platform Screen Doors in 1987, however they did not gain significant popularity until China implemented them on 34 lines in 2002. Since then, they have expanded across all major Asian cities and are slowly being integrated into European railways (Mind the Gap, 2009).

There are two different types of Platform Doors: Platform Screen Doors (PSDs) and Platform Edge Doors (PEDs). PSDs are full train height and make a complete seal between the rails and the platform. PEDs range from about half-height to full train height, but do not create a full seal. One of the main reasons the stations implement Platform Doors is to prevent people from falling or jumping into the train tracks. The doors have been very successful in preventing suicides, especially in Hong Kong, where there was no reported fatalities after the installation of

the doors in 2006 (Mind the Gap, 2009). There are other benefits to PEDs including reduced wind currents felt by bystanders as the trains move through the tunnels, improved climate control, prevention of litter build up on tracks that can be a fire hazard, and reduced excess noise caused by the train that could drown out important announcements (Platform Screen Doors, 2015).

Despite the positive aspects of PEDs, they are difficult and very expensive to install into existing railway systems. All of the stations need to have the doors retrofitted. Because not all stations and lines are identical, this process can cost a substantial amount of money and time. This could cause delays and shutdowns of the whole system, therefore costing the railway company even more money and severely deteriorating the rider experience (Mind the Gap, 2009). There are also concerns about the safety of Platform Doors. There have been cases reported in Hong Kong of the glass doors shattering (SCMP, 2003). In the case of serious emergencies Platform Doors can impede the evacuation of passengers out of the train. These emergencies can include a fire, loss of power, disabled or stopped trains due to emergency conditions, structural collapse and terrorism (NFPA, 2010). During these emergencies the doors on the train might not align with the platform doors, causing a reduction in the exit width and obstructing the riders from safely exiting the train.

2.3 Case Studies of Modernized Railway Systems

2.3.1 Singapore Mass Rapid Transit (MRT)

Singapore is a city state in Southeast Asia known as one of Asia's economic tigers due to their global leadership in commerce, finance and transportation (BBC, 2016). Being an advanced nation requires a modern and effective public transportation system, and Singapore is well known in this sector. The convenience and reliability of their Mass Rapid Transport (MRT) is reflected by 99.9% train service availability and 95.7% train departure punctuality as of December 2016 (SMRT, 2016). This is less likely to be achieved without the different rail technologies that are in place in the MRT.

The North East Line (NEL) of Singapore's MRT has 16 stations and spans 20 km, and is the world's first fully automated driverless rail system (NEL, n.d.). Its rail system is run by the Integrated Supervisory Control System (ISCS), also known as Supervisory Control and Data

Acquisition (SCADA) system. This system is an integrated open software and hardware platform that allows various automation including Automatic Train Supervision (ATS) and Automatic Train Regulation (ATR). ISCS uses state-of-the-art computer technology and has the ability to respond with massive processing power, making it a powerful monitoring performance indicators (Du & Fang, 2013). The basic framework that supports this driverless train operation consists of communication based train control moving block signalling technology, automatic train supervision, and computer- based interlocking. The software itself, which enables Operation Control Center (OCC), Depot Control Center (DCC), and Passenger Service Center (PSC), “remotely supervise and control different systems such as power supply, communications, fire protection, tunnel ventilation, lifts and escalators, and environmental control” (LTA, 2008). Each station is then equipped with platform screen doors, which function as both a safety barrier between the station platform and track to prevent unauthorized entries and service disruption due to track intrusion, and as an environmental screen that conserves energy (LTA, 2008).

Singapore invested a substantial amount of money to incorporate this integrated system, totaling about \$1.13 billion for 6 downtown lines (LTA, 2008). The benefits, however, are very long term as they have a safe and reliable metro system that can support their rapidly growing economy.

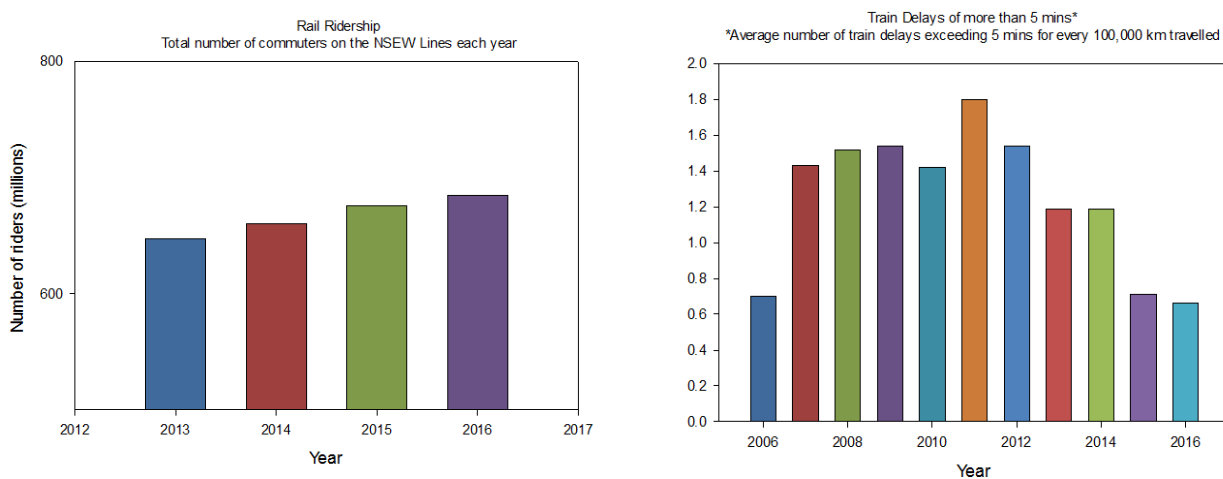


Figure 6. Left: Total Rail Ridership for Singapore MRT; Right: Total delays for Singapore MRT
 Source: Adapted from SMRT, 2016, without permission

In Figure 6, the graph on the left shows how rail ridership is constantly increasing each

year, with 685 million riders in 2016. On the right, the graph depicts how train delays are decreasing rapidly since the new system was implemented in 2011, despite a growing number of riders since 2008. This growing number of riders is expected as Singapore's population has been increasing rapidly since 2004, with the greatest growth in 2007 of 250,000 people (Singapore Population, n.d.). The number of delays is expected to continue decreasing despite the growth of the population due to the newly implemented technology.

2.3.2 Copenhagen Metro (CM)

Copenhagen is the capital and largest city of Denmark and its metropolitan area had a population of around two million people in the beginning of 2016 (Statistics Denmark, n.d.). Its geographic location is very close to southern Sweden (about 41 kilometers) and as such, the city has been a strategic financial point between the two countries (Almar, 2006). In 2015, more than 57 million passengers rode its Metro at least once, which was up by about one million passengers from 2014 (Copenhagen Metro Annual Report, 2015). Facilitating the economic growth of the city has required keeping up with its growing population's transportation needs. Recently, there was also a desire to increase market share for public transport, reduce car traffic, and minimize environmental impact.

To achieve these goals, the Danish government and the Municipality of Copenhagen founded the Ørestad Development Corporation (ODC) to plan the implementation of a new transport mode in the 1990s (Vuk, 2005). The new transport system required the very latest train technology and safety systems, as one of the goals of the project was to have Copenhagen's transport system be comparable to those of the largest European cities. One key aspect of the agreed upon rail system was driverless operation.

The network currently has two lines, Metro line 1 (M1) which runs to Ørestad in west Amager and Metro line 2 (M2) which runs to Lergravsparken in east Amager. Most platforms are located eighteen metres below the surface via island platforms that are accessible by lift. All of these platforms are equipped with PEDs in order to combat several safety risks outlined by ODC (Almar, 2006).

The primary way that the Copenhagen Metro ensures passenger safety and minimizes delays is through their ATC system. Their system follows the same setup described in Chapter 2, Section 2, consisting of the three sub-systems; Automatic Train Protection, Automatic Train

Operation, and Automatic Train Supervisory. The ATP system provides the train's position (whether it is in the block section or not) and communicates to the ATO which controls when the train departs the station (Almar, 2006). Figure 7 shows the structure and communications between these systems.

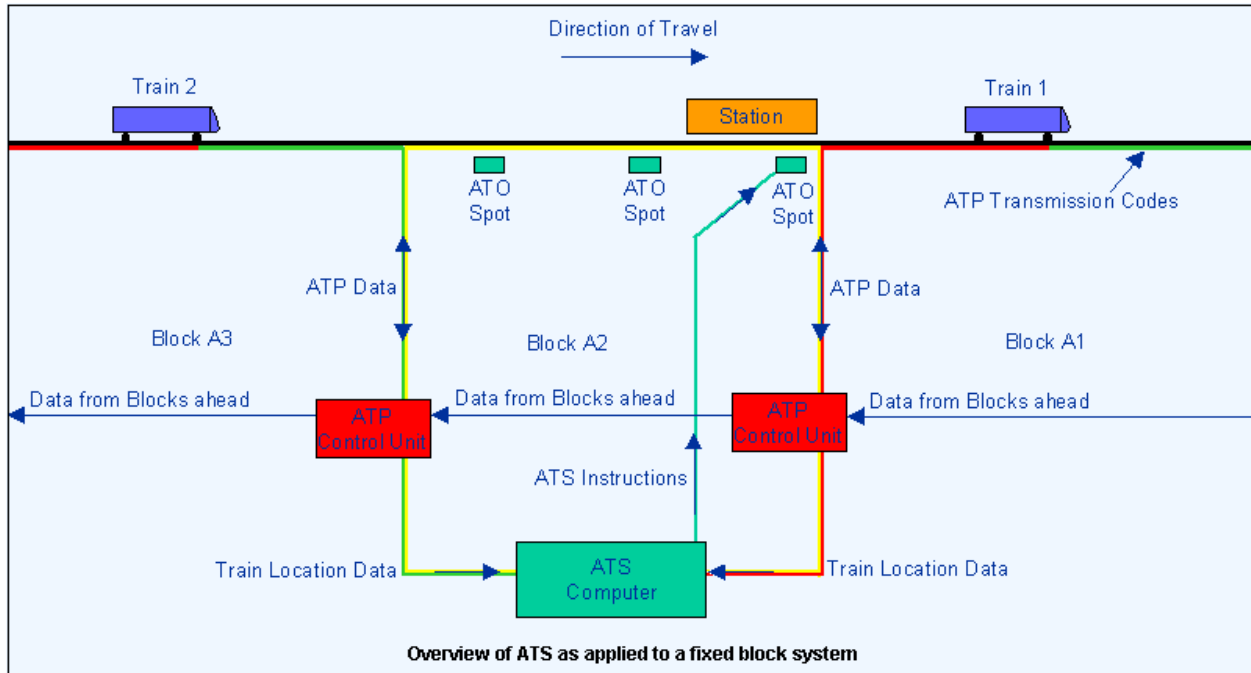


Figure 7. Demonstration of all three sub-systems in the Copenhagen Metro
 Source: (Railway Technical Web Pages, n.d.), without permission

The Copenhagen Metro is unique in that it necessitates very accurate brake operation for the train doors to line up with the platform edge doors. It does this by having the ATC system update the position of the train when approaching the stopping point and obtaining a precise positional reading before the doors are actually opened (Almar, 2006). According to the 2015 annual report, 98.8% of trains departed on time in 2015, which means that the vast majority of trains did not see any delays due to the verification system (Copenhagen Metro Annual Report, 2015). Surveys showed that the number of loyal customers, called “ambassadors”, increased from 44% in 2010 to 52% in 2014 (Copenhagen Metro Annual Report, 2015). Therefore, the various new technologies and safety systems installed in the Copenhagen Metro have reduced delays and improved safety and overall rider experience.

2.3.3 Paris Métro (M)

The Paris Métro, also known as the Métropolitain (M), is overseen by the Régie Autonome des Transports Parisiens Group (RATP), which is a state-owned public transport operator headquartered in Paris, France. The Paris Métro Line 14, originally known as Project Météor, was the first driverless operation in Paris, and was also the first fully automatic major metropolitan line in a capital city. It was inaugurated between Bibliothèque François Mitterrand and Madeleine in October 1998, in 2003 it was extended to Saint-Lazare north-wise, in 2007 it was extended into Olympiades south-wise, and in 2014 it was equipped with the newest automatic trains. The technologies used and the extensions done after the inauguration were all done for the purpose of providing a reliable and efficient transportation for all users. According to a Siemens report, since its inauguration Line 14 has provided RATP with a transport solution that is safe and secure, reliable, and flexible (Siemens, 2012). The line is equipped with platform screen doors at each station, as can be seen in Figure 8, along with complete driverless operation. According to the same report, punctuality and reliability has been guaranteed due to the platform screen doors, which prevented people or objects from falling onto the track.



Figure 8. Paris PEDs

Source: (Siemens, 2012), without permission

At the creation of the Météor project, around 62,000 passengers rode the line in one direction per hour, and there was a desire to offer a sustainable solution to this traffic (Systra,

2013). The system's safety has been guaranteed due to the automatic speed control, audio-video surveillance at all times, and the platform doors. Along those lines, all the new stations that were built during the initial construction of the line and the later extensions have disabled accessibility. Appendix A demonstrates the list of stations with access, and all stations from Saint-Lazare to Olympiades have this.

2.4 London

The population of London in 2016 was approximately 8.6 million people within its city limits, and it is growing by about nine residents per hour (GLAIntelligence, 2015). This makes it the third most populous city in Europe (The European Commission, 2016). The city's history traces back to the time of the Romans; today, it is among the top five leading global financial centers in the world (The Global Financial Centres Index, 2016). Whether it is for business, tourism, leisure, or other purposes, on an average day in London there are more than 30 million journeys utilizing Transport for London, the public transportation agency serving the entire region. With such a large population and economy comes the need for an advanced and comprehensive public transport system. This means keeping the city's transport system technologically up-to-date, ensuring all systems are running as efficiently as possible, and constantly looking for ways improve it.

2.4.1 Transport for London

Transport for London (TfL) is the governing body for all transportation throughout London. It was created as a statutory body by the Greater London Authority Act in 1999. This act gave the Mayor of London a general duty to develop and apply policies "to promote and encourage safe, integrated, efficient and economic transport facilities and services to, from, and within London" (Transport for London, N.d., p. 1). TfL employs more than 25,000 people and provides services for everyone who lives in or visits London. The system is broken into three units: surface transport, underground, and crossrail (Transport for London, n.d.). The underground unit includes the London Underground, which is comprised of 11 lines and 270 stations (A Brief History of the London Underground, n.d.). A full map of the London Underground is shown in Appendix B.

Rail transportation is one of the best alternatives to driving, due to its improved speed and convenience (Eagling & Ryley, 2015). The Travel in London Report for 2016 states that despite the population increase in London, road traffic has decreased by 10% since 2000. At the same time, London Underground use has increased by 39% (Travel in London, 2016). This shows how traffic and use of London underground are correlated. In 2015-2016, the London Underground carried 1.35 billion people throughout central and outer London (Transport for London, 2016). This shows the importance of rail transportation and how it has grown to become a vital mode of transportation in London.

2.4.2 London Underground

The London Underground, colloquially known as the Tube, is the oldest underground system in the world that dates back to 1863 when the Metropolitan Railway, the world's first underground railway, opened to connect Paddington and Farringdon (A Brief History of the London Underground). As more underground railway was built, society has grown to realize that social inclusion and safety needs to be more emphasized. With the goal of creating a “world class Tube for a world-class city”, where all customers are satisfied with every aspect of their journey, London Underground commits to take measures to ensure a safe, reliable, and fully accessible transportation system (TfL: London Underground, 2006, p. 2).

2.4.2.1 Accessibility and the London Underground

In United Kingdom alone, there are 10 million people living with a disability, making up 20% of the population (Customer Standards & Experience Manager, 2008). In 1995, the Disability Discrimination Act was passed, which states that failure by an organization to make reasonable adjustments to allow everyone access to goods, facilities and services is illegal. Prior to this act, there were limited regulations that enforced accessibility of public infrastructure. Once the act was passed, London Underground committed to creating a seamless journey for anyone who may need special assistance, including people who have mobility impairments, hearing impairments, vision impairments, or those who are elderly, pregnant, etc. There are guidelines in place for people with these different types of disabilities. According to the London Underground, during a service disruption they pay special attention to customers with a mobility impairment to help them access the lifts, customers with learning difficulties for planning new

routes if their current one is disrupted, and in announcing disruptions via a whiteboard or other means so that the information is available to as many customers as possible (London Underground, 2017). Similarly, there are guidelines in place for alerting these types of customers when there is a station closure or evacuation. In general, London Underground also has general guidelines in place for speaking with or conveying information to customers that use wheelchairs, have learning disabilities, with hearing disabilities, or mental health problems.

As of April 2017, only 71 of the 270 stations on the Underground provide any form of step-free access for mobility impaired users, as shown in Appendix C. There are two forms of step-free access, street to platform and street to train. The street to platform access means that passengers do not have to use stairs to get to the platform, however they will require assistance boarding and alighting the train, since the platform and the train cabin floor are not level. The street to train access goes a step further; it means that passengers can also board and exit the train without using stairs or assistance. The number of accessible stations is expected to increase, although making all stations fully accessible will require a substantial amount of money, time and effort. There are also various technical difficulties of implementing lifts and platform ramps due to space and structure capacity, as previously discussed. Despite the challenges, in December of 2016, Mayor Sadiq Khan promised to spend £200 million on making at least 30 more stations step-free (Pring, 2016).

2.4.2.2 Safety in the London Underground

Safety is another important aspect that London Underground is committed to improving. In the 1970s, safety regulations gained more traction in parliament and the Health and Safety at Work etc Act was passed in 1973 (Health and safety at work etc act 1974.). Since then, various enforcements were made to ensure higher safety standards, and in 2006, the Office of Rail Regulation passed The Railways and Other Guided Transport Systems (Safety) Regulations (ROGS) as a replacement of the Railways and Other Transport Systems Regulations from 1994 (ROTS) (Burke, n.d.). These regulations ensure that the parties in control of the railway provide a safe environment for the riders. The Office of Rail Regulation also investigates, inspects, and advises on health and safety matters.

When it comes to the London Underground the platform train interface (PTI), or the gap between the train and the platform, poses the greatest safety threat for passengers. The PTI

accounts for 21% of safety risks and 48% of fatality risks, as shown in Figure 9 (RSSB, 2015). The stations throughout the Underground are constructed to different heights and sometimes have curved platforms. Under these circumstances a gap is formed between the platform and the train. At many of the older stations the gap is quite large, for example, at Bank Station on the Central line the gap is 375mm (Horne, 2013). At newer stations in the Underground the platform and train are at the same height and the gap is minimized as much as possible.

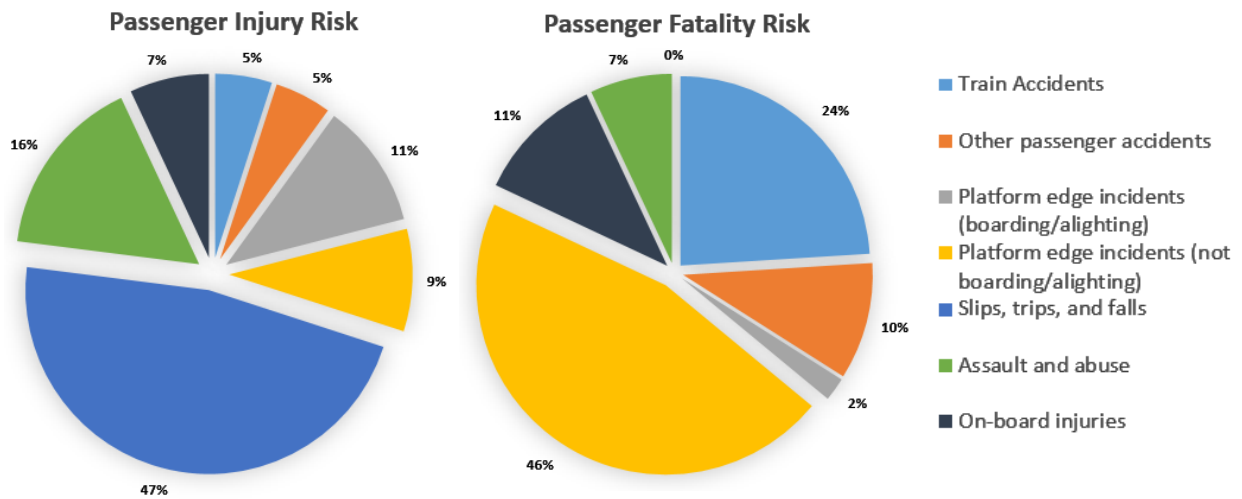


Figure 9. Passenger risk by accident type
Source: Adapted from Mind the Gap. 2015

With these various safety liabilities, London Underground has plenty of regulations and strategies to ensure that passengers travel safely. Overcrowding on the platform and inattentive riders that get too close to the train can lead to accidents. As a result, there are a series of precautions that are in place. The PTI is monitored by the train driver and control center through CCTV, and customer behavior is influenced by the “mind the gap” announcements, signs, and yellow line, as seen in Figure 10. There are also additional station staff present at the platforms during peak hours to direct passengers, provide organization, and prevent any potential track intrusions (Customer Standards & Experience Manager, 2014).



Figure 10. Mind the Gap

Source: (Howard, 2016), without permission

Platform staff are also required to ensure passenger safety, especially during peak hours. They are in charge of making announcements about when to board the train, when the doors are closing, and to encourage customers to let others off the train first. They also act as crowd control and signal the driver when the doors are clear to ensure that everything runs smoothly. The staff must also be knowledgeable of all emergency procedure and available to assist passengers with their needs (Customer Standards & Experience Manager, 2014).

2.4.2.3 The London Underground: Jubilee Line

One of the most recently constructed lines is the Jubilee Line. In 1932, the first part of what is now the Jubilee line was built to connect Baker Street and the Stanmore branch as a part of the Bakerloo Line. Since then, the line has been extended in two phases. In 1979, the branch was extended to connect with Charing Cross tube station in central London, and the section from Stanmore to Charing Cross became the Jubilee Line, separate from the Bakerloo line (see Appendix 4). In 1999, the Jubilee Line Extension (JLE) connected the line to Stratford Station in east London, as shown in Figure 11 (London Underground: Jubilee Line, 2017). This involved building 11 new stations, 8 of which are PED equipped. The Jubilee Line was commissioned 25

years after the Queen took office, in 1977, celebrating the Queen’s Silver Jubilee (Wright, personal communication, March 21st, 2017).

Figure 9a 1988, Olympia & York: Bakerloo Line Extension

1. Waterloo to Isle of Dogs via London Bridge.
2. Waterloo to Isle of Dogs via Bricklayers Arms.
3. Isle of Dogs to Stratford and Tottenham Hale.
4. Isle of Dogs to Beckton.



Figure 9b

1988, Olympia & York: Docklands Second Rail Line
Waterloo to Westcombe Park

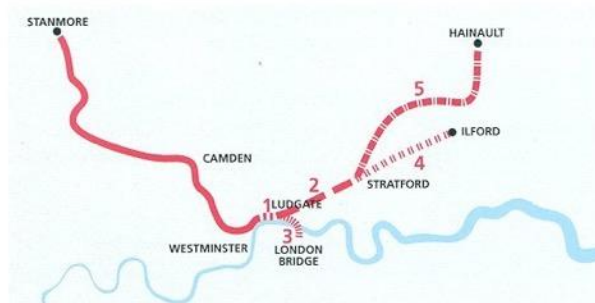
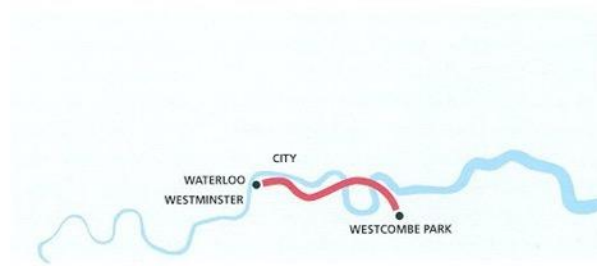


Figure 9c 1989, Central London Rail Study: Jubilee Line Extension

1. Aldwych to Ludgate.
2. Ludgate to Stratford.
3. Ludgate to London Bridge.
4. Stratford to Ilford.
5. Stratford to Hainault.



Figure 9d 1990, East London Rail Study: Jubilee Line Extension

- 1 Green Park to Stratford – now under construction
- 2 Aldwych to London Bridge via City
- 3 Canary Wharf to Canning Town via Leamouth
- 4 North Greenwich to Thamesmead

Figure 11. History of the Jubilee Line

Source: Adapted from (Omega Centre, 2008)

Today, the Jubilee Line accommodates 213 million passengers per year throughout its 27 stations (Jubilee Line, 2017). The line is 35 km long and is partly tunnel and partly above ground. The Jubilee line serves some of the most important destinations including the O2 concert venue, the Westfield shopping center and Olympic Park at Stratford, The Houses of Parliament, Westminster Bridge at Westminster, and Wembley Park for Wembley Stadium. Back in the 1980s, the East End of London was mainly occupied by warehouses and shipment houses and was in desperate need of a transportation system to and from central London. The JLE was initiated and built to connect Canary Wharf with central London. Since then, there was a huge regeneration project where new buildings and offices were constructed. The area continued to develop to become one of London’s biggest business district (Walling, personal communication,

March 20th, 2017).

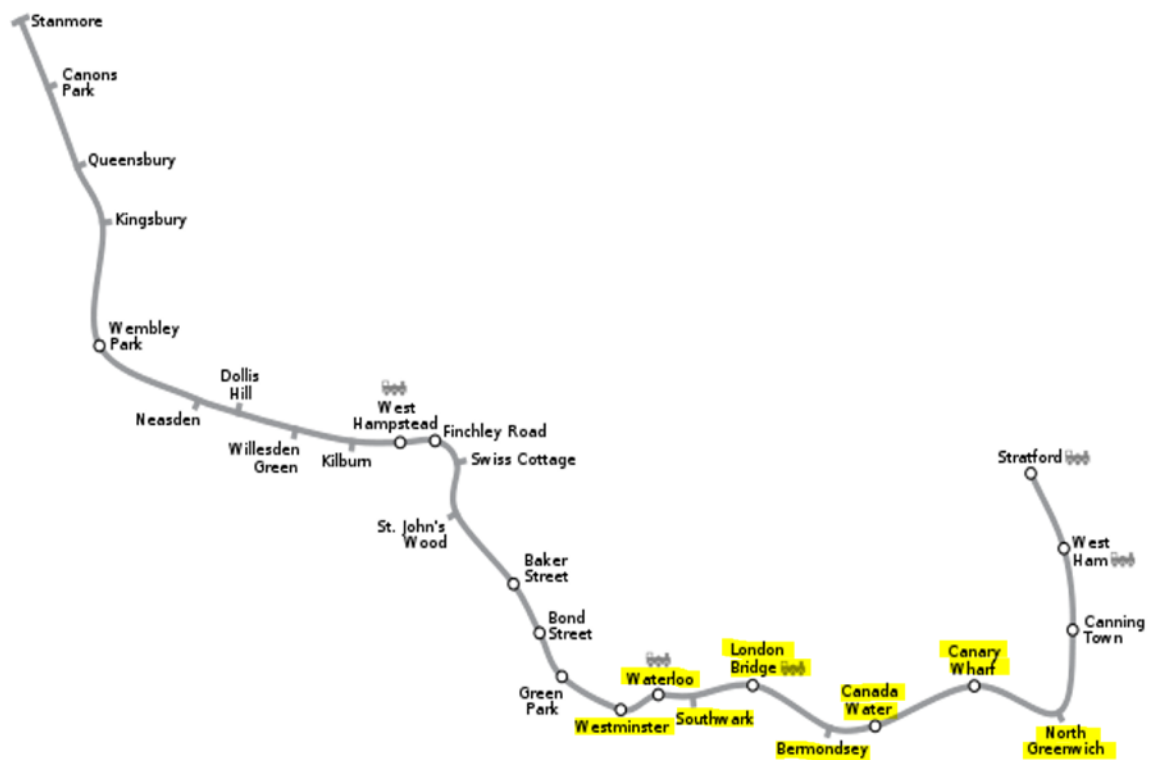


Figure 12. Geographical Path of Jubilee Line with Highlighted Stations with PEDs

Source: Adapted from J.D. Forrester, 2005.

Work on the Jubilee line did not stop in 1999. Starting in January 2006, a seventh car was added to all the Jubilee line trains and four new trains were incorporated to the line, bringing the total number of trains to 63, all of which are driven by TBTC (Major Boost for Jubilee Line, 2005). This means that a person is not needed to drive the train, although drivers are needed to open and close doors once they have arrived at the platforms. (Lo, 2012).

The Jubilee Line is unique because it is the only line in the London Underground network that uses Platform Edge Doors (PEDs). There are eight stations equipped with PEDs, from Westminster to North Greenwich, highlighted in yellow in Figure 12. The doors were installed as part of the JLE in May 1999. The PEDs provide a safer place for riders on the platform because they act as a barrier between the platform and the train. Since the installation of the doors no accidents have been recorded that involve an intrusion on the track (Transport for London, 2014). The PEDs also allow for more people to fit on the platform without putting them in

danger. At other stations, there is a serious risk of overcrowded platforms forcing people to get too close to the oncoming train. Because of this risk attendants have people wait in the hallways of the station as a result, causing a backup for other passengers using the station. PED equipped platforms not only provide a safer experience but also a quicker board time.

During the JLE the trains were also updated with the TBTC system, which includes the Automatic Train Protection (ATP). This protection system ensures that the drivers do not go past a danger signal when they are operating the train. The ATP supervises the train when it is being driven in protected manual. In the case the driver goes above the specified speed limit (i.e. is going too fast or not braking hard enough), the ATP takes over the control of the train. (“Metro Signaling”, 2016)

Compared to other lines, the Jubilee Line is the most accessible to anyone who wants to ride. Of the 27 stations on the line, 15 have step-free access. This is a result of the JLE in 1999. By this time the Disability Discrimination Act had been implemented and it had become a social norm to make transportation accessible to everyone. During the JLE in the 1990’s, six new stations were added to the line and five stations were refurbished. These refurbishments included 34 lifts and 118 escalators to ensure step-free access for all 11 stations.

In quantifying the benefits of rail transportation equipped with modern technologies, David Banister and Mark Thurstain-Goodwin studied the JLE. In the two years after the JLE first opened, it drove its passengers a total of 1.6 million km’s, saving 14.4 million hours in travel time (Banister & Thurstain-Goodwin, 2011). The TBTC system and the PEDs have long term benefits, despite the initial costs of implementation. Tables 1a and 1b depict how after only four years the benefits of the JLE outweigh the initial investment into the railway system by £4.66 billion. The Jubilee Line trains are equipped with improved technologies and currently have more predictable run times that save time and optimize energy consumption. (Banister & Thurstain-Goodwin, 2011).

Table 1a. Adapted from Funds Invested into Jubilee Line

	Investment into Jubilee Line (£ billion)
Capital Costs	5.18
Operating and Maintenance Costs	2.90
Net Rail Revenue	(1.87)
Total	6.21

Table 1b. Adapted from Benefits from Jubilee Line

	Benefits from Jubilee Line (£ billion)
Time Saving	7.06
Congestion Relief	2.59
Highway Benefits	1.22
Total	10.87

Source: Adapted from Banister & Thurstain-Goodwin, 2011

Through our research of the technologies described above and how they apply to the London Underground and the Jubilee Line, we have been able to thoroughly cover major areas related to our project and understand why these technologies are used. We believe that this information will enable us to develop a plan to gather the necessary data to form a recommendation for CPC and TfL regarding the reliability of the Jubilee Line. CPC Project Services, a consulting agency working on behalf of TfL, is looking to further reduce delays, increase safety, and improve accessibility on the Jubilee Line and throughout the London Underground. There are many positives and negatives to these technologies found during our background research, along with costs and benefits in implementing them on existing rail lines. In particular, CPC Project Services is looking to demonstrate to TfL whether or not a second stopping accuracy validation system is necessary. In doing so, train capacity on the line can be increased, simultaneously improving safety and reducing delay times.

3 Methods

3.1 Goals and Objectives

Our project goal was to investigate the reliability of the modern train technologies implemented during the Jubilee Line Extension. For this project, reliability was defined as the benefits and limitations of the modern technologies, their effect on dwell time and safety, and their accessibility for all train riders. This was evaluated by validating the stopping accuracy of the trains to ensure the Transmission Based Train Control (TBTC) and the Platform Edge Doors (PEDs) were functioning correctly, determining the dwell time at stations along the line (both with and without PEDs), interviewing drivers, duty reliability managers (DRMs) and senior Transport for London (TfL) staff, surveying passengers about the modern technologies, and observing disabled accessibility, behavior of passengers on platforms with PEDs, as well as overall train performance patterns. Our definition of reliability can be broken down into five objectives from both a human perspective and a technical perspective. First, we investigated the safety measures on Jubilee line. This includes how passengers behave at stations with and without PEDs and the precautions taken at each platform. Second, we evaluated the accessibility of the trains and stations for all passengers, and how the PEDs affect the accessibility. Third, we assessed how the modern technologies affect the punctuality of the Jubilee line trains, particularly in relation to changes in the dwell time. Fourth, we validated the TBTC system that currently measures the stopping accuracy of trains on stations that are PED equipped. This work was done with CPC Project Services, a private consultancy firm that is working with TfL to improve the reliability of the Jubilee Line. Once the objectives were fulfilled we provided our recommendations on how to improve the reliability of the line. To achieve our objectives, we broke them down into more detailed and focused steps:

1. Conducted a survey to understand how passengers feel about reliability of the Jubilee Line. The survey included questions on safety, train punctuality, and accessibility of Jubilee Line in comparison to other lines in the London Underground (LU).
2. Conducted interviews with train operators and DRMs to understand how they work with the current technologies, and how these systems affect them.

3. Conducted interviews with higher-ranked staff to understand how the system-wide network of operations works, and what TfL's long-term objectives are.
4. Performed station observations at stations to gauge passenger behavior on various platforms throughout the Jubilee Line.
5. Measured actual stopping position of the train by setting up an external, low-tech, train-based measurement system that is independent of and more accurate than the TBTC.
6. Compared data from our measurements with data from the currently installed sensors (readings from the tachometers and inductive loops of the TBTC) to verify that the train stops within the projected tolerance and is reporting its position correctly.

3.2 Data Collection

To approach and analyze the social implications of improving the reliability of the Jubilee Line, we collected different kinds of “human” data. This involved communicating with passengers, drivers, DRMs, and LU employees. We surveyed passengers to obtain their opinions on safety precautions, accessibility, and train performance compared to other lines. We interviewed drivers and DRMs to learn about experiences with ATC, PEDs, and working on the Jubilee Line. We interviewed the GM and SCM of Jubilee Line to gather insights from the point of view of higher ranking employees. We also observed passenger behavior at the stations along the line. During the same time period, we collected data regarding the actual stopping of the trains and the dwell time at all platforms on the line. This data was used to validate the accuracy of the reported stopping location of the trains.

3.2.1 Passenger Surveys

In order to gather information regarding riders' opinions on the reliability and accessibility of trains in the Jubilee Line, an in-person and online survey was conducted. This survey was performed over a two-week period, and over one hundred responses were collected.

Various demographics of riders were targeted; commuters, students, tourists, shoppers, old, young, male, female, etc. This was done to elicit as many riders' opinions as possible, which vary depending on demographics. Since improving reliability and accessibility is meant to improve all riders' experiences, it was important to get feedback from as wide of a range of

customers as possible. We managed to collect responses from all the groups listed above.

This diverse response was achieved by conducting the surveys during various time frames, stations, and social media platforms. The survey was conducted during different times of the day; one during the evening peak hour (4-5 pm) and one during a non-peak hour (2-3 pm). The peak hour survey targeted commuters or routine riders of the Underground. This was a period of time when we were informed by staff that the majority of the passengers would be working age people going home from work. The non-peak hour targeted tourists, students, or other casual riders (18 and older), as it was observed they mainly use the Underground during these hours. The survey was conducted at different stations namely Green Park, Westminster, Southwark, London Bridge, Canada Water, Canary Wharf, and Stratford.

Both the online and in-person survey started by asking riders whether they are willing to complete a quick verbal survey regarding reliability of the Jubilee Line. We then introduced who we are, who we are working with, and what our project aims to achieve. We then summarized the consent form (Appendix F) and asked if they agree to partake in the study. Once they agreed, we proceeded with the 15 questions (see Appendix G). This number of questions was chosen so that the survey took less than three minutes to complete, while still gaining a lot of useful information.

The survey included an information handout to help passengers visualize and understand what PEDs are (see Appendix H). This was to make sure every single passenger is at the same level of knowledge when completing the survey. Riders were also encouraged to ask any questions they have regarding the train technologies described.

All the surveys were conducted using Qualtrics, a web-based survey software tool. The verbal surveys were conducted using an offline version of this tool. This method was chosen because it was more effective than distributing paper surveys, and also more environmentally friendly.

In order to obtain more responses, we distributed the survey through various online platforms, namely several London Facebook pages, District Dave's Forum, Rail UK Forum, and Reddit (in the r/London and r/LondonUnderground subreddits). This online version of the survey was conducted through the online version of Qualtrics. Similar to the offline version, we presented a consent form in the beginning of the survey, outlining who we are and what the purpose of the survey is. A simplified version of the information handout was included in the

question to aid the questions regarding PEDs. The questions are the same as the ones listed in Appendix G.

3.2.2 Driver Interviews

To understand more about the how the drivers interact with the TBTC, we interviewed Underground train drivers that work on the Jubilee Line. These interviews are valuable to us because drivers are directly affected by the performance of the system. We spoke with six drivers and asked them a series of questions pertaining to TBTC and PEDs, and their experience with them. Verbal interviews led to the best results because of the personal nature of some of the questions. We conducted the interviews with two interviewers, as to not overwhelm the drivers. We also recorded some of the conversations and took detailed notes on all of them. We provided a consent form, shown in Appendix I, which described who we are and what our project is. We began the interview with general introductory questions and allowed them to guide the conversation. We asked more specific questions relating to our project depending on their responses. The pre-planned questions can be found in Appendix J.

We took many considerations into account regarding the content of our interview questions, as they are employees of LU. In order to make them feel comfortable answering the questions, we disconnected ourselves from CPC and TfL, so they did not feel they were getting interviewed by their bosses. We also kept the drivers' identities confidential to allow them to open up honestly without the fear of getting exposed.

We needed to find a suitable time to interview them without causing any inconvenience or taking time away from their breaks. For this reason, all the interviews lasted less than six minutes, except for the one performed at the Stratford fleet house, where the drivers are stationed. We performed one interview inside the cab of a train while the driver was working. This gave us valuable visual insight into how the drivers' answers translate into their hands-on work.

The responses of the drivers gave us a different point of view regarding the stopping of the trains, the door opening, passenger interaction with Platform Train Interface (PTI), and their interaction with the on-board train technology. This information from the drivers complements the technical parameters that need to be considered by the ATO system. In addition, it supplemented our data when forming recommendations.

3.2.3 Senior Jubilee Line Manager Interviews

We had two informative interviews with senior Jubilee Line employees. The first interview was with Phil O’Hare, the General Manager of the Jubilee Line, and the second was with the Service Control Manager (SCM) of the Jubilee Line. These interviews were very important because both positions work day to day ensuring the Jubilee Line is running reliably. The General Manager is responsible for the overall performance of the Jubilee Line. This includes station service, service control and train operations. The SCM is responsible for the control of the entire Jubilee Line, the Duty Reliability Managers (DRMs), and ensuring that the timetable runs well. DRMs provide support to trains and stations staff and by monitoring service and performance on the line.

We conducted the interviews with the whole group present because these two interviews were very important to the findings of our project. We also asked to record conversations and took detailed notes. We began the interview with general introductory questions and allowed them to guide the conversation. We asked more specific questions relating to reliability depending on their responses. The pre-planned questions can be found in Appendix K.

In both interviews we discussed the topic of reliability. We asked about our four objectives, safety, accessibility, train punctuality, and stopping accuracy. The most important question we asked them was if there was one thing they would change about the line to improve reliability, what would it be. This question aimed to bring up long term plans for the Jubilee Line, issues surrounding those plans, and differing opinions between senior employees of LU.

3.2.4 Platform Train Interface Observation

We observed the PTI to understand more about how the PTI poses the greatest safety threat for the passengers. This included specific safety precautions regarding the PTI, rider accessibility, train performance, and observations of passenger behavior at platforms with PEDs and without PEDs. These observations took place in person at the stations.

There are some widespread safety precautions that are taken to prevent PTI intrusions. These include signs around the platforms, public announcements, and door closing alarms. During peak hours, there are LU staff members on the platform directing passengers and communicating with the train operator. They are responsible for keeping the platform safe and organized. We observed the distribution of signs around the platforms and stations and their

effect on passengers, the frequency of the announcements “mind the gap” or “mind the closing doors”, effectiveness of platform staffs, door closing alarms, and station delays caused by passengers.

We also observed the accessibility at stations through the line. During these observations we looked for factors that affect platform and train accessibility. This includes: lifts from the street level to the platform, how large the gap is to board the train, the step up or down to board the train, presence of a platform hump, staff availability, and the provision of information. A checklist of observations we performed at the stations are shown in Appendix K.

To assess the effectiveness of PEDs, we measured the dwell time and safety perception of all stations on the line. This was done by using a stopwatch to measure the length of time between when the train arrives and when it leaves. The total dwell time can be affected by a variety of external factors that may lead to skewed results, such as passengers trying to catch the train at the last second. To isolate these factors, we also measured the time between the train stopping and the doors opening at all stations. Through this observation, we were able to determine if PEDs are causing any significant delays. To evaluate the perception of safety of PEDs, we looked for patterns that might correlate with the presence of PEDs, for example how far people stand from the platform edge. If people stand close to the platform edge, it shows that they feel more secure. If people stand far, this shows that people are more cautious.

3.2.5. Stopping Accuracy

As previously discussed in this paper, stopping accuracy is one of the most significant measurements of an ATO system’s efficiency (Ma & Zeng, 2014, p. 1237). By determining if a train is stopping accurately or whether the measurement system is accurate, a wide range of systematic problems can be revealed. A problem with either of these functions translates to problems with mechanical systems like the brakes, problems with the reporting or connectivity of the TBTC system, or a variety of other issues. Through the use of an external train-based system, we determined if the stopping accuracy recorded by the on-board system was valid.

To measure the stopping accuracy of the train we used two simple systems on board the train. We set up duct tape along the line of the train doors, accurately marking every centimeter and the appropriate direction on the tape, and then capturing an image at each PED station of where the train stopped. These images were then carefully analyzed to record the actual stopping

position with an accuracy of ± 1 cm. The positive and negative depended on which direction the train was going that journey, and this was marked accordingly on the tape, as shown in Figure 13.

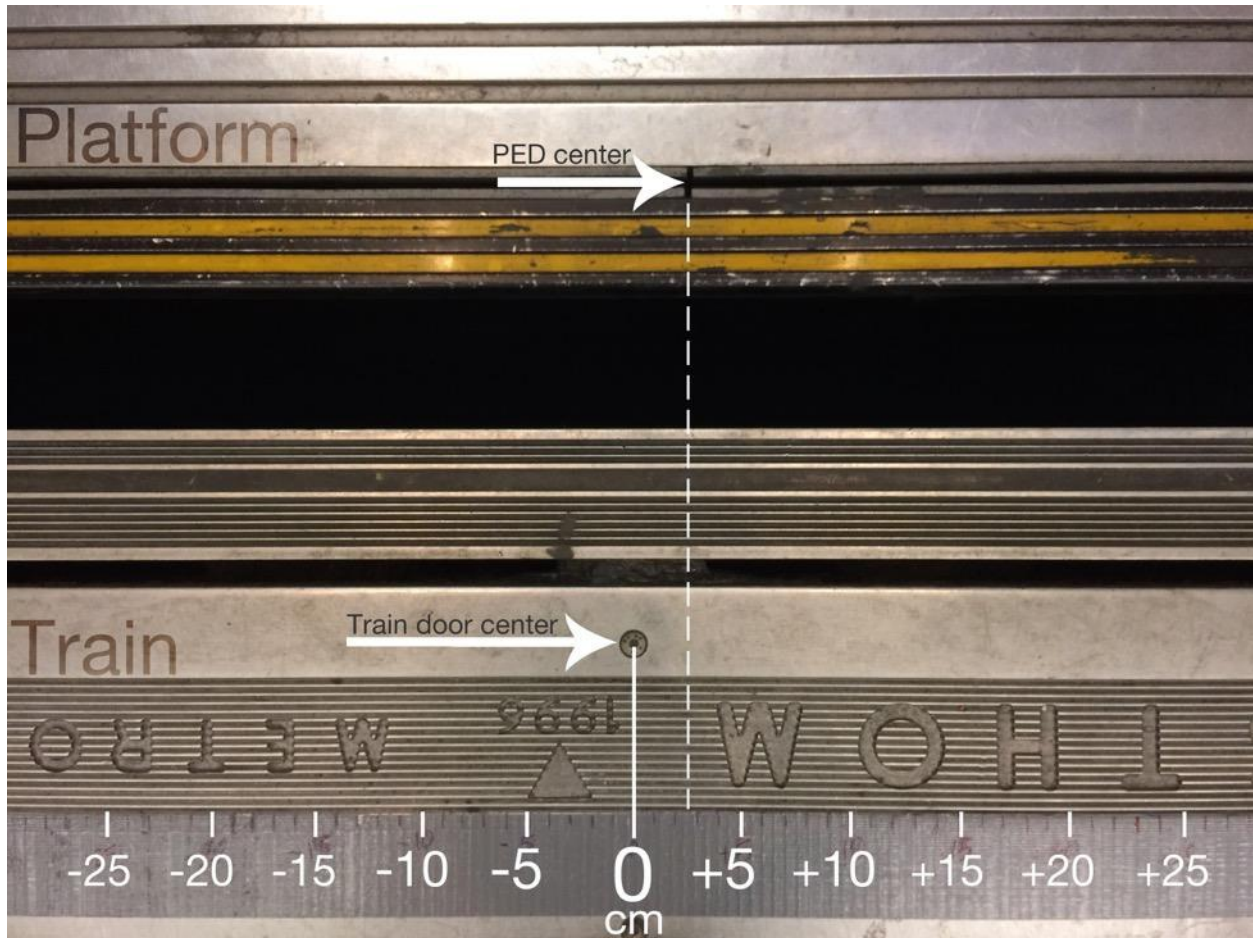


Figure 13. Picture of the stopping accuracy measurements

We developed a second method as an alternative measurement method in case of any obstructions for the first method; i.e. a crowded train with passengers obstructing our ability to capture the image, non-legible markings on the tape after extended use, or not enough time before the doors close to capture an image. This was simply using a measuring tape to measure the position and whether or not it overshoot or undershot. This measurement was not preferable because it involved crouching down at every stop, making extensive data collection more tiring and prone to human error. We performed these methods on nine trains during peak and nonpeak hours. A picture of this method being used is shown in Figure 14.



Figure 14. Performing a manual measurement of the stopping accuracy, second method

Once we collected data for two weeks, we compared our measurements to the data supplied by the VCC and VOBC that was provided by CPC Project Services. The VCC has a resolution of 20 centimeters, while the VOBC has a tighter resolution of 5 centimeters. Comparing these data involved examining if our manual measurements, with a 1 centimeter resolution, align with the measurements of the VOBC. For example, a measurement of +8 cm would be reported as 0 from VCC (since it is within 20cm) and +5 from VOBC (between 5 cm to 10 cm). Moreover, we looked at whether the stopping accuracy affected the door opening time and the total dwell time. Door opening time for non-PED stations was measured starting from when the train comes to a complete stop to when the train doors are fully open. For PED stations, it was measured to when the PEDs were fully open. This was done to measure the time required to board or alight the train

4 Findings

Our findings were based on a wide range of data that was collected throughout the project. First, we have human data, which consisted of passenger surveys and interviews with London Underground Jubilee Line staff, our sponsor, former London project sponsors, and several senior Transport for London (TfL) employees. Second, we have data obtained from the train-based manual stopping accuracy measurement system we created, which was analyzed and compared with data from the Vehicle On Board Control (VOBC) and Vehicle Control Center (VCC) of the TBTC system. Third, we have data obtained from TfL intranet and previous studies on the Jubilee Line and the London Underground.

4.1 Safety

To investigate the safety of the Jubilee line we performed a series of passenger surveys, driver and duty reliability manager (DRM) interviews, and on site analyses of stations. These analyses consisted of observations of passenger behavior on platforms, as well as observations on the structure and layout of the platforms themselves. We found that overall, Platform Edge Doors (PEDs) and Automatic Train Control (ATC) have positive effects on safety experienced by passengers and drivers. There are, however, some areas where safety could be improved.

The survey sought passengers' perspectives on safety at different stations along the Jubilee Line. We collected 104 survey responses from a diverse group of riders, with 35% of riders being between ages 18 and 24, 37% between the ages of 25 and 39, and 26% between the ages of 40 and 65. Of those 104 responses, 74% of passengers feel somewhat safe or more safe at platforms equipped with PEDs. In addition, only 15% have had a bad experience with PEDs. When asked to elaborate on their bad experience, the common response we got was that the doors have shut on them or the doors have malfunctioned causing a delay in their journey. In an analysis of incidents with PEDs, Dobell analyzed 11 years of data (from 2003 to 2014) and found that the most common incident was people getting stuck in the doors. During the study period, 326 incidents occurred with people being caught in the doors, although the number of incidents over time normalized per number of passengers is decreasing (Dobell, 2014).

Of the passengers that took our survey, 29% said that Jubilee was their favorite line, making it the most popular line, as shown on Figure 15¹.

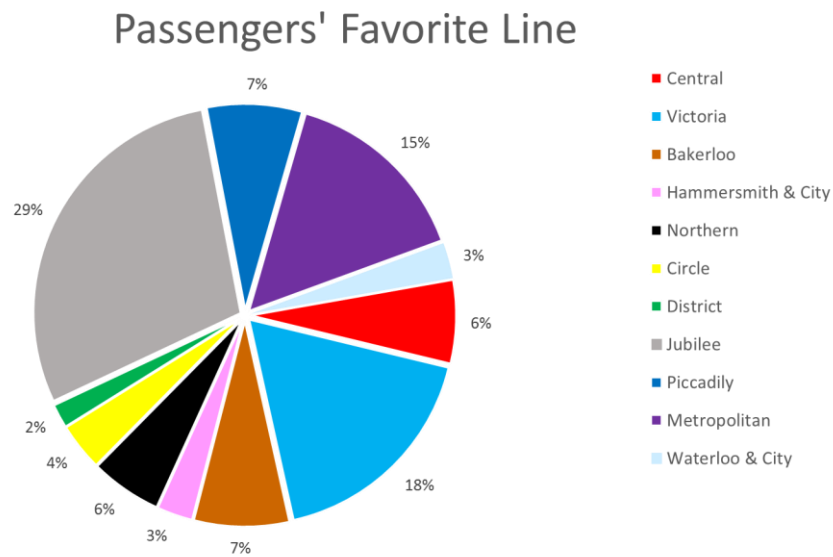


Figure 15. Passengers Favorite Line

When asked to explain why it was their favorite line, 32% said it was because they like the clean and modern look of the line (25% said it was because of the train cars, and 7% because of the stations). The responses were also grouped into several categories, as shown in Figure 16.

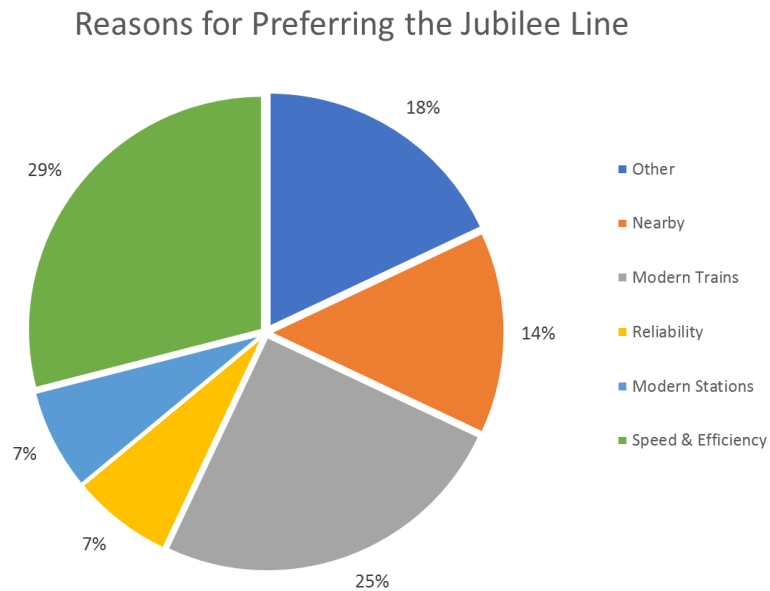


Figure 16. Reasons for Preferring the Jubilee Line

¹ There may be a selection bias as the in-person surveys were performed at Jubilee Line station.

According to The Station Presentation Handbook by Transport for London, the presentation of a station may give passengers a sense of security (Tfl, 2017). We found this to be true through our observations of the layout and infrastructure of the stations. The newer and larger stations, like Canary Wharf and Westminster, looked clean and sharp, while the other older stations, like Neasden and Wembley Park, looked worn down because of faded signs and an aging station structure. This difference in appearance could have an effect on how passengers feel about their perceived safety.

The survey also asked passengers if they are satisfied with the provision of signs throughout the stations. Roughly 72% of passengers answered that they are satisfied; however, after interviews with senior management on the Jubilee Line, we learned that the biggest threat to safety is unaware and disconnected passengers. The senior management believes that passengers are not reading the signs that have been provided for their safety, therefore causing a threat to the line and themselves.

Based on interviews with train drivers, all of whom have had several years of experience driving on the Jubilee Line, the unanimous consensus was that all six felt safer and more relaxed driving trains on the Jubilee Line, especially at stations equipped with PEDs. They feel reassured knowing that there will not be a track intrusion at those stations. Ideally, they stated they would like to see PEDs installed at all stations. Moreover, the drivers prefer their working environment with the ATC systems, primarily because of Automatic Train Protection (ATP). ATP allows manual driving, but can take over control of the train if the driver does not brake in time or goes over the specified speed limit. Drivers also feel more comfortable driving in this mode because they can avoid a Signals Passed at Danger (SPAD), which could potentially cause delays or accidents. According to drivers, this sense of increased safety and reduced stress allow them to do their job better. Driver five said for PED-equipped stations that “when the platforms are more secure, you are more relaxed.”

During our discussion with the Service Control Manager (SCM), he said it was not a matter of liking PEDs or not; it is about whether the doors solved the problem they were trying to fix. The doors were installed to reduce the wind generated by the trains within stations. PEDs achieved the goal of reducing the strong winds created and had significant collateral benefits. The PEDs drastically diminish the risk of PTI incidents and increase platform organization. On platforms with PEDs, riders form queues outside the doors because they know where to board,

but at other stations riders are scattered about the platform. This can cause issues when the train arrives because they rush to board and push into people. When asked if there is the potential to install them on other stations, the SCM said that the “benefits to safety are second to none”, but they are a system that will only be installed on new builds because the cost to retrofit is too expensive.

An additional safety benefit of PEDs is that they prevent any objects from falling in the tracks as revealed during the driver interviews. This keeps the tracks cleaner, which has a multitude of positive effects on safety. Objects falling on the tracks can get caught between the tracks and the train wheels, causing increased wear to the trains, therefore increasing the danger of malfunction and accidents. Accumulating trash in the track area can potentially be a fire hazard. Finally, PEDs make it practically impossible for passengers to intentionally or unintentionally fall into the track.

4.2 Accessibility

In order to evaluate the accessibility of Jubilee Line in comparison to other lines in the London Underground, we conducted passenger surveys and station observations. We found that the Jubilee Line is more accessible to all riders as compared to other lines in the Underground, due to the physical systems and organizational policies that are in place.

Based on our survey responses, 67% of the passengers feel that Jubilee Line is somewhat or much more accessible than other lines in the Underground. Of the survey responses that said they have required assistance from the London Underground staff, 45% said that Jubilee Line was their favorite line (as shown in Figure 17). In addition, all of these responses said that the Jubilee Line is somewhat or much more accessible than other lines in the Underground. Out of these same responses, only 11% have had bad experience with the PED.

Favorite Line of Passengers Who Require Assistance

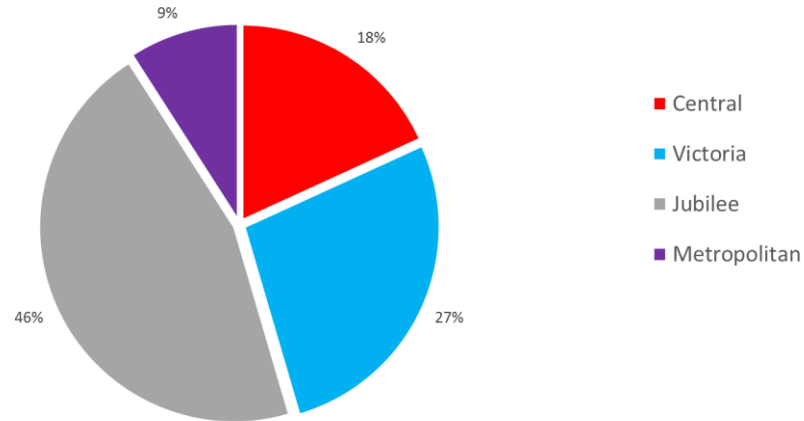


Figure 17. Favorite Line of Passengers who require assistance

Our observations also demonstrated the increased accessibility of the Jubilee Line. First, we observed that the Jubilee Line has more stations providing step-free access, meaning that riders can go from the station entrance to the train without taking a step, than any other line. Most stations in the Jubilee Line have lifts, platform humps, and level boarding and alighting to achieve this, as shown in Figure 18.

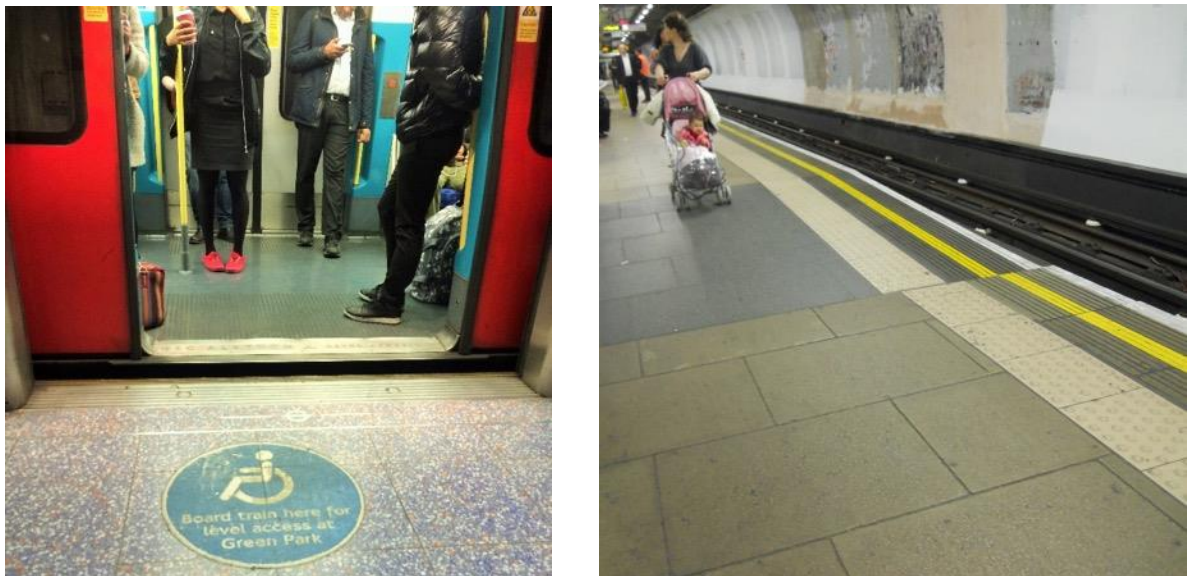


Figure 18. Left: Level boarding. Right: Platform hump.

Platform humps specifically allow people using wheelchairs to board and alight the train easily, because the platform is raised to be level with the train at certain sections. We also

observed that stations in the Jubilee Line provide more instructions for disabled passengers. This includes signs showing where to board to get level access at stations further down the line, where the lifts are, and instructions for disabled boarding and alighting. Finally, every single car in Jubilee Line trains provide a designated area for passengers with wheelchairs or baby buggies as shown in Figure 19.

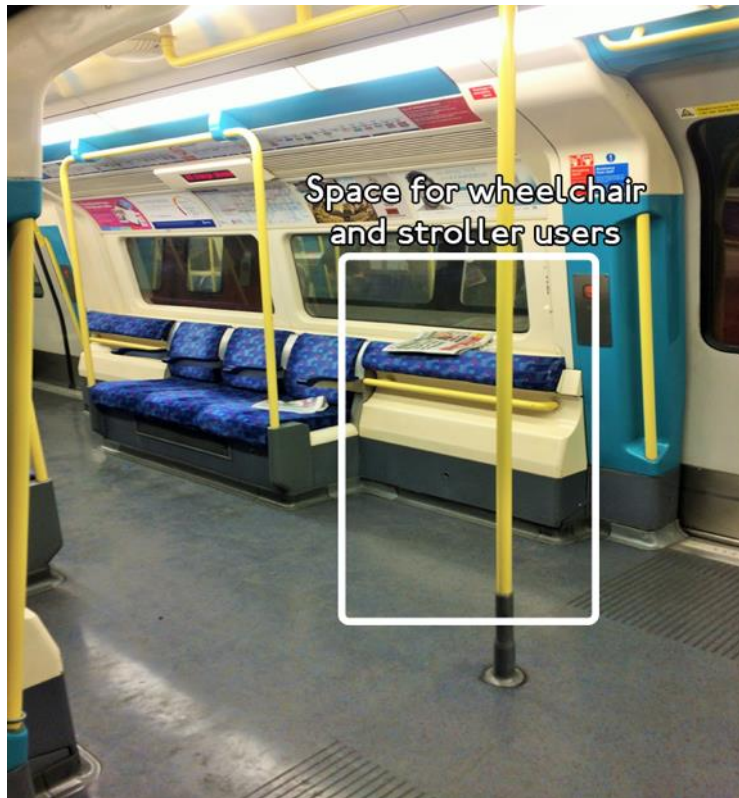


Figure 19. Wheelchair and Baby Buggy Space on Jubilee Line Train

4.3 Train Punctuality

We found that passengers generally felt the Jubilee Line was more punctual than other lines, with fewer delays and fewer train shortages. Based on our survey, 53% of passengers felt that the Jubilee Line has somewhat fewer or much fewer delays compared to other lines in the Underground. Only 8% of passengers felt that the Jubilee Line had significantly more delays. We also found that 51% of passengers felt that the Jubilee Line had somewhat fewer or significantly fewer train shortages than other lines. Only 10% of passengers felt that Jubilee Line had

somewhat more train shortages, while none said that Jubilee Line had significantly more train shortages.

Based on our analysis, we found that when functioning properly, PEDs do not increase dwell time or cause delays to any significant degree. We found that at PED stations, the doors take on average less than half of a second longer to open compared to non-PED stations. Moreover, the PED-equipped stations showed more consistency with regards to the door opening time.

When looking at the total dwell times, the PEDs did not show any significant contributions to delays. When looking at the data from all the stations, on average the PED stations show less total dwell time. From Figure 20, which shows the dwell times for non-PED and PED stations, we can see that most data points are concentrated between the 20s and 40s range, with a few outliers. The reason for this is that the total dwell time can be, and often is, affected by a variety of external factors. One example is Wembley Park station, where there is almost always a driver change, which results in a total dwell time of well over a minute (often more than 2). In order to eliminate such factors, we performed an analysis using only the data points that fell within 1.5 standard deviations from the average dwell times for non-PED and PED stations respectively. A graph of the total dwell times for non-PED and PED stations, excluding the outliers, is shown in Figure 21. This analysis shows that the PED stations had an average dwell time 0.33 seconds longer than the non-PED stations, which is a very small difference, especially given the size of the two data sets. Moreover, the PED-equipped stations had a lot more consistent dwell times (significantly lower standard deviation). This is the exact same pattern that the door opening times showed.

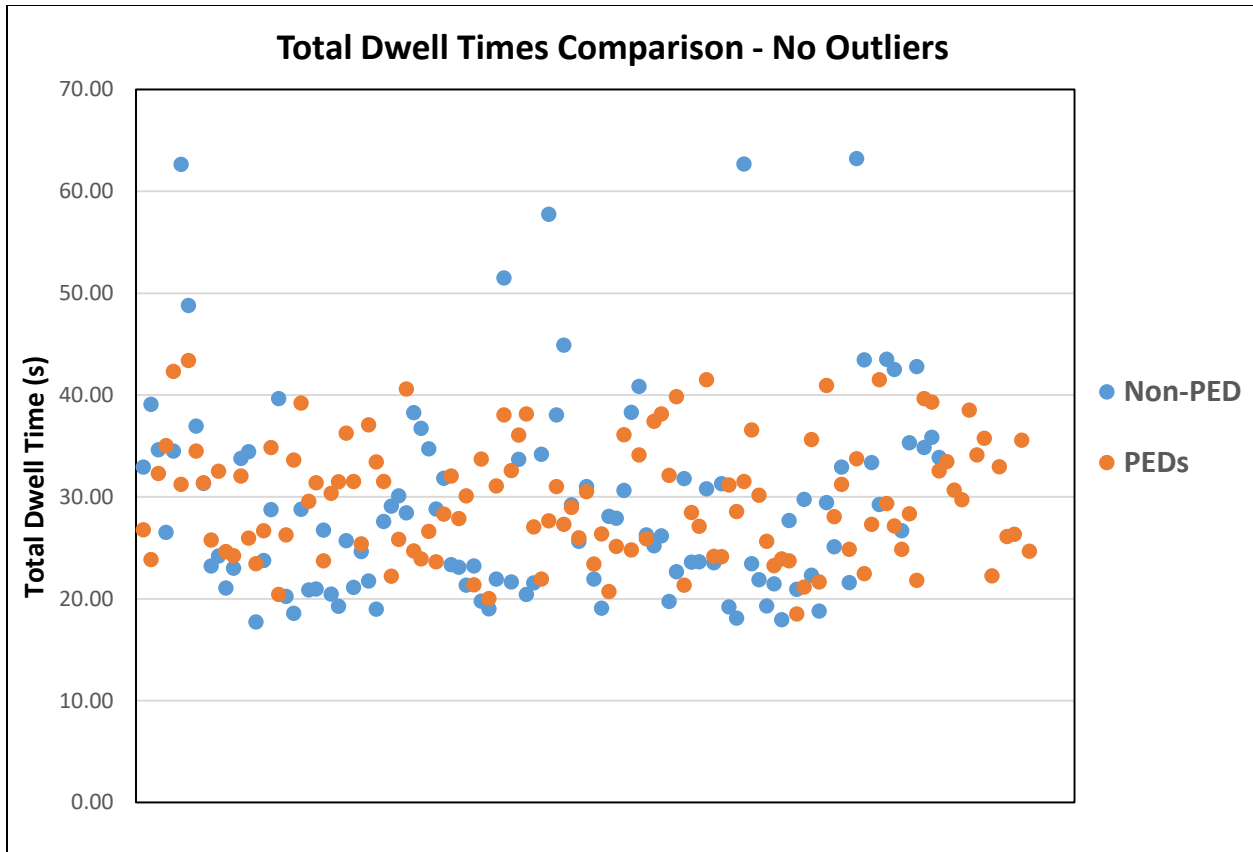


Figure 21. Total Dwell Times Comparison - No Outliers

Overall, the door opening and total dwell time for PED stations show a distribution that closely matches the one for non-PED stations. The extra dwell time added by the PEDs is less than 0.5 seconds. However, when something goes wrong at a PED station, the delays are much more significant. The SCM provided an example of an error where the doors open unexpectedly. LU has not determined the cause of this problem, and the only solution is to react to the fault in the system. This involves stopping the operation of at least the particular station where this happened, or even the entire line, causing major disruptions.

In both interviews with senior Jubilee Line employees they emphasized that customer behavior is the largest cause of delays. The SCM said 30-40% of delays are a result of customer's lack of "awareness and understanding of the system." O'Hare said that customer behavior needs to be improved before any further improvements are made on the line, because that will cause a serious reduction in delays. During the interviews with the SCM and O'Hare, other improvements on the line that could improve train punctuality and reduce delays were also discussed. Both focused on the poor ventilation inside the trains. In the summer the trains can

become very hot, especially during peak hours as more passengers are crowded close together in the trains. This can cause passengers to become ill and potentially pass out. Other passengers see this happen and pull the emergency brake instead of staying with the passenger and getting them off on the next stop. As a result there is a delay, potentially causing other trains behind to stop between stations. This can cause even more people to become ill, as stopped trains have even worse ventilation, causing a domino effect of delays. If the riders knew to wait until the next stop they will not only get help sooner, but also reduce the effect on the trains running around them.

4.4 Stopping Accuracy

For our stopping accuracy analysis, we performed manual measurements ourselves, which we compared to data obtained from the VCC and the VOBC through CPC Projects Services. We made this comparison to look for discrepancies between data sets. We also looked for the number of significantly inaccurate stops for the entire Jubilee line between March 1st and 26th (more than 500,000 stops).

Comparing our stopping accuracy measurements to the VCC data, we found that the VCC is very reliable in reporting the stopping accuracy correctly. Of all the stops at which we performed manual measurements, the VCC reported the stopping accuracy correctly for more than 96% of them.

Based on our analysis of the entirety of the VCC data, we found that the trains stop accurately in the vast majority of cases. More than 96% of the stops performed were within 20cm of the target (i.e. the train and platform doors perfectly aligned). Deviations from the target that are less than 20cm are within the required tolerance and cause no obstructions for passengers alighting and boarding at PED stations. Moreover, less than 2% of the stops missed the target by more than 40cm. A deviation of less than 40cm might result in some obstruction at PED stations, but not significant enough to prevent passengers from getting in or out of the trains. The distribution of this data set is shown in Figure 22. Our manual measurements showed the same pattern as well. The maximum deviation we measured was 29cm, and more than 97% of the measured stops were within 20cm of the target. The distribution of our manually obtained data is shown in Figure 23. Note that for both Figures 22 and 23, the vertical axis has a logarithmic scale.

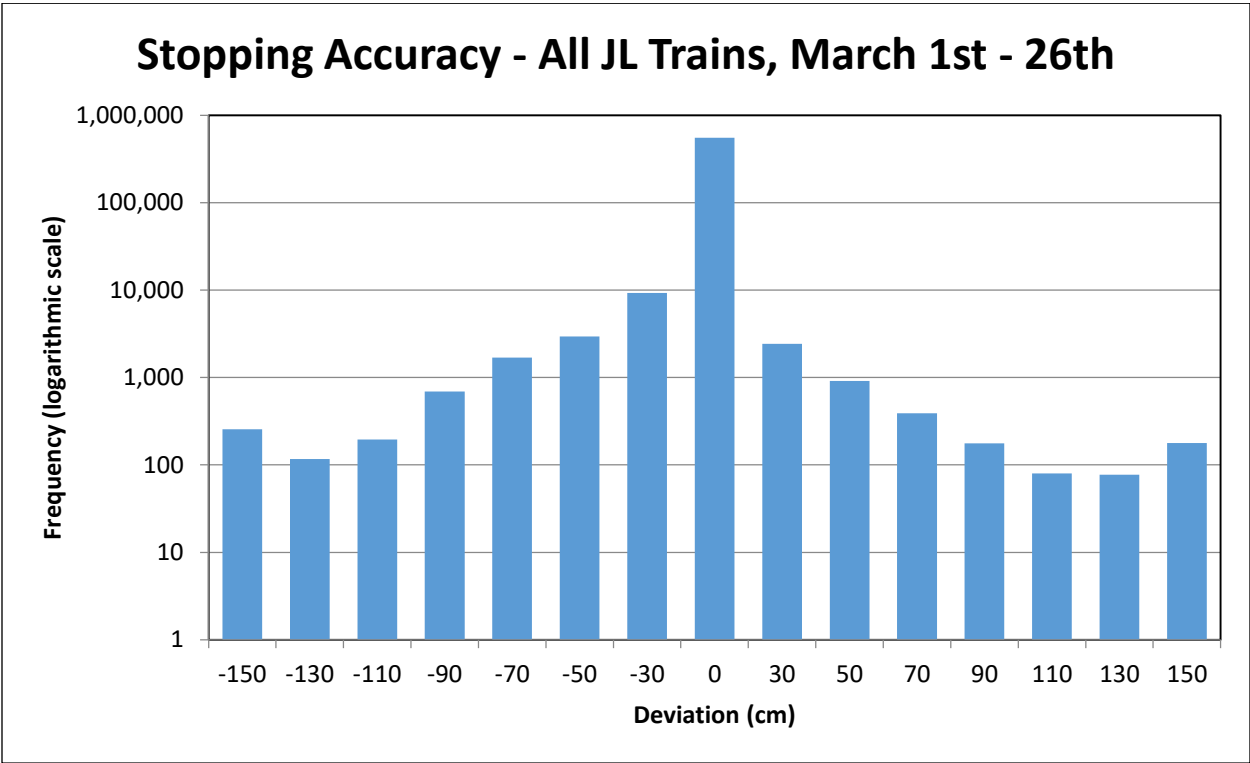


Figure 22. Stopping accuracy of the entire Jubilee Line fleet for March - Data obtained from VCC

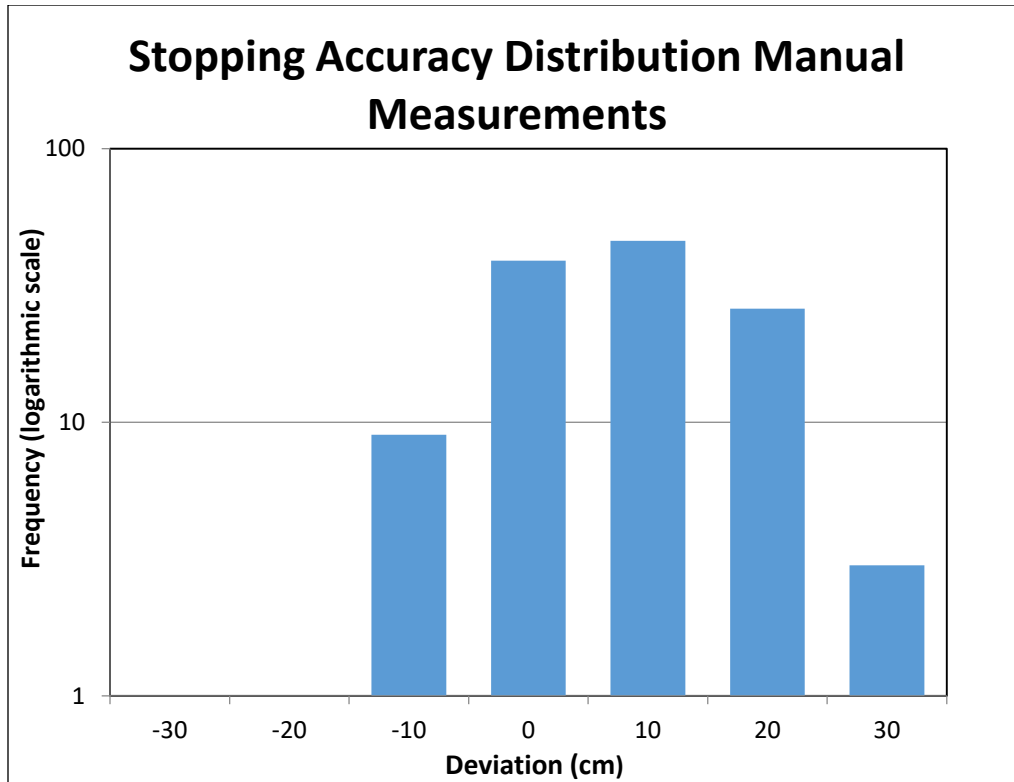


Figure 23. Stopping accuracy - Manual Measurements

One difference between these two distributions is the number of overshoots and undershoots. In our measurements, we found that there are notably more overshoots than undershoots. This distribution does not match the distribution for the VCC data for the entire month of March, which shows that there were more undershoots than overshoots. Given the vast amount of data obtained by the VCC, especially compared to the limited amount of our manual data, discrepancies like this are to be expected.

The train driver interviews also support these findings. All of them said that the trains almost always stop accurately at PED stations. When asked if the train has ever stopped outside the tolerance at a PED station, driver four said “No, not once”, and driver six said “most of the time they will stop accurately.”

Finally, we analyzed the VOBC data we obtained. We obtained VOBC data corresponding to eight measurements at PED stations to make the comparison across our manual measurements, the VCC-reported data, and the VOBC-reported data. From this comparison, we found three patterns. First, only in three cases did the VOBC values match our manual measurements. Second, the conversion from the VOBC 5-cm resolution values into the 20-cm

resolution VCC values was correct for all cases. Third, the VCC values matched the manual measurements in all cases.

5 Discussion

5.1 Brief Recap of Findings

In terms of our first objective, safety, we found that based on passengers' opinions reflected in our survey, as well as driver, staff, and senior TfL employees' opinions expressed during interviews, PEDs have had an overall positive contribution to safety. We also found that the majority of passengers have the Jubilee Line as their favorite line, due to the newer stations and improved safety features. Nonetheless, there are still some drawbacks to PEDs such as passengers getting caught in between the doors.

For accessibility, we found that Jubilee Line is more accessible compared to other lines in the Underground, based on passenger survey and observation data. This is due to most stations having level access, lifts, platform humps, as well as train cars with designated area for disabled passengers.

We then found that train punctuality is affected by various factors from our surveys, observations, and interviews. Passengers mostly believe the Jubilee Line has fewer train shortages and less delays than other lines. Passengers also said it was their favorite line, with some of the common reasons being the reliability, speed, and punctuality. From the interviews and observations, we learned that passenger behavior has the biggest effect on the punctuality of trains and that the smallest delay can cause a huge impact overall.

Lastly, our analysis of the manually obtained stopping accuracy data and the data from the VCC and the VOBC showed that the trains are very accurate in their stops, which is crucial for PED-equipped stations, since the train and platform doors need to be aligned, and that the VCC is also highly accurate in measuring the stopping deviation from the target. However, the VOBC measurements did not match our manual measurements in the majority of cases.²

² It should be noted that the VOBC analysis was done only with eight data points.

5.2 Significance of Findings

5.2.1. Safety

Assessing the impacts of PEDs on passenger safety is important because the doors cost a significant amount of money to install, and in most cases, are impractical to retrofit. From our findings, we found that PEDs significantly reduce incidents associated with London Underground's biggest safety threat, the PTI. At the same time, we found that there are more complications associated with operating them. This assessment is important to see whether the safety benefits of PEDs outweigh the costs and complications, and whether or not there are other factors that play a bigger role in improving safety. It will also help us evaluate the necessity and feasibility of installing PEDs on upcoming stations.

Starting with the more obvious effects, PEDs improve safety as they prevent people from intentionally or unintentionally falling into the track. This means that the train operation is not interrupted by track intrusion, and the number of accidents will significantly decrease. All riders will feel safer to stand closer to the PTI when waiting for the train to approach, as there is a barrier separating them from the track. During rush hours when the platform is very crowded, passengers will be able to stand near the platform edge while waiting for the train without having to worry about getting pushed over into the tracks. From the driver's perspective, PEDs serve as a guarantee that when approaching a station, no one can jump or fall to the track. This will make them feel more relaxed to drive the train. At the same time, PEDs will not prevent everyone from attempting suicide, as they can easily go to stations where PEDs are not installed. PEDs serve more as a barrier to prevent people from accidentally getting pushed over and to provide them with an increased sense of security.

PEDs have collateral positive effects such as providing psychological benefits of reducing staff and riders' trauma from witnessing accidents. The cost to society of a single incident of a person jumping into the track is estimated to be over one million pounds. With around 250 suicide cases in main railways per year, the costs associated with suicide become very significant (Dobell, Personal Communication, March 27, 2017). PEDs are good long term investments in that they reduce the costs associated with these incidents. Further, another benefit of PEDs is that they improve the appearance of train stations. PEDs make stations look more

modern and new, and we suspected that this was one of the reasons why the Jubilee Line is the most popular among our survey responses.

Unfortunately, PEDs also have various drawbacks. To begin with, they cost a substantial amount of money. A single PED costs about £100,000. This number is even higher when retrofitting it to older stations, as there are additional costs associated with adjusting the infrastructure. Most older platforms will not be able to sustain the weight of PEDs or do not have space for them. Some platforms are also curved and many are not level with the train, which makes implementation of PEDs even more complicated and costly. Retrofitting PEDs may not be feasible as it requires major changes to stations.

There are also additional costs associated with maintaining and repairing PEDs. According to the SCM, PEDs need to be maintained every day. PEDs are checked on a case by case basis, since the issue with one particular PED is always different from another. This makes maintenance more complicated and unpredictable. Furthermore, PEDs have issues such as random self-opening and unsynchronized closing. Since the current system that controls PEDs is independent of Transmission Based Train Control (TBTC), there are issues associated with the two systems not working in conjunction. At the same time, it is very complicated and costly to integrate the two systems together.

Further, it is important to reconsider other factors that may contribute to improving safety. The first one is consumer behavior. According to the SCM and GM of Jubilee Line, consumer behavior is very unpredictable and difficult to control. O'Hare mentioned that TfL has conducted different studies to understand consumer interaction with instructions, signs, announcements, etc. They found that even the smallest detail, such as size of the platform, can change the way people behave. They also noticed that human behavior may be altered in one particular station where relevant signs are in place, but once they move on to a different station, they switch back to their old habits. An interesting example from Malcolm Dobell to show the oddity of human behavior is the fact that more incidents happen in level PTIs than in non-level PTIs. This shows that human behavior is unpredictable, and in many cases even counter intuitive.

People tend to merely think about themselves. Especially during rush hours, riders are only concerned about getting on to the first train, ignoring the fact that their action might put others in a safety risk. People wear earphones and do not pay attention to signs and

announcements because they ride the tube every day, and thus think that they know everything. One explanation from the Service Control Manager (SCM) was that there are too many signs in the stations, leading to an information overload for the passengers who end up ignoring them. Another explanation could be that the design of current signs are too wordy and not eye-catching, which was observed on several stations on the line.

Even worse, people tend to resist change, which means that altering human behavior requires revamping the entire culture. People are comfortable with the way things are, and changing one seemingly simple behavior can be very difficult. One example to demonstrate this is the period of time when TfL decided that people should stand on both sides of the escalator, as opposed to having people stand on one side and walk on the other side. In TfL's mind, this would reduce incidents associated with escalators, thus moving forward with improving passenger safety. The response they got, however, was very negative as people claim that they have "rights" to walk through escalators. This just shows how hard it is to control and alter human behavior.

Human behavior is hard to predict and control, hence it is no surprise that riders are the biggest safety threat when it comes to train operation. If this is true, perhaps implementing PEDs will only shift passenger safety threats from PTI to something else. Perhaps the solution to improving safety is not only technology, but also studying and understanding human behavior. Perhaps improving safety can be done by simply educating people on the importance of safety or having effective safety precaution signs. Perhaps TfL have been focusing on the wrong things.

Our findings demonstrated that passengers are very much tied to technology. They showed that passengers' perceptions about their own safety and of the reliability of the transportation system is largely based on how modernized it is and what technologies are present. Looking at the top two favorite lines, the Jubilee and Victoria, both have ATC through TBTC. The difference between them, other than the route, is that the Victoria line has newer stock whilst the Jubilee has six completely new stations and five enlarged or rebuilt ones. So, with all else being the same, it logically appears that passengers value the larger and newer stations more than they do newer train stock. Building new stations or renovating old ones would of course be the most expensive option for improving reliability, but it should be noted that passengers appear to pay significant notice to the environment around them. We believe that the certain characteristics of the new stations, like the significantly larger platforms, the metallic

ceiling and wall designs, and of course the PEDs on eight of the stations, give passengers an increased sense of safety and reliability simply because of the modern technologies around them.

5.2.2. Accessibility

Our investigation found that the new stations on the Jubilee Line are more accessible than the older stations on the line and most of the Underground system. This is a result of the relatively new legislation that enforced regulations to ensure that public transportation is accessible to everyone that wishes to use it. The new Jubilee Line stations are equipped with lifts, escalators, level boarding areas, and signs denoting which cars are level at certain older stations, like Green Park, to allow for easy alighting. According to our conversations with senior Jubilee Line staff and our sponsor, all future Underground stations will be built to allow for step-free access.

Unfortunately, the previously mentioned features are only implemented on 26% of the stations. The most significant limiting factor in upgrading older stations is the lack of funds. In an ideal world, London Underground would have enough money to install lifts, ramps, and level access at all stations. Moreover, there are significant technical difficulties in upgrading older stations by installing accessibility features. Many of the old stations do not have room to easily install lifts to allow step-free access from the street to the platform. As a result, small fixes will have to be implemented to accommodate anyone who needs assistance getting to the platform.

Through talks with Malcolm, it came to our attention that TfL has a free, door-to-door van service for people with permanent or long term disabilities, called Dial-a-Ride, that operates independently from all the other TfL services. Dial-a-Ride is intended to be used for every-day short trips; users are encouraged to call a day ahead to arrange their trips. Our sponsor's view is that an expanded and improved service like this is easier to implement and more cost efficient than transforming all the old stations of the London Underground to have lifts and level-access platforms (M. Dobell, personal communication, March 27, 2017).

5.2.3. Train Punctuality

Our data analysis shows that many factors affect train punctuality. Despite passengers saying that they think the Jubilee Line runs with less delays overall, there are still areas that need to be improved to increase service reliability. From talking with senior Jubilee Line employees

and our sponsor we have heard different perspectives on what needs to be done to reduce delays. One potential solution that was discussed is improving the technology on the line. As of April 2017, the whole Jubilee Line system is not integrated; the PEDs are not controlled by TBTC. When there is an error, the staff has to fix that one then react to the next one. If the technology on the line is integrated, the PEDs and the TBTC could work in unison, decreasing delays and eventually leading to a fully automated system. A fully automated and fully integrated system has been implemented in Singapore and has shown to decrease delays and run efficiently (SMRT, 2016), as discussed in more detail in Chapter 2.

The other opinion we have encountered has to do with the customer behavior on the line. Both of the senior Jubilee Line employees we have interviewed said that passenger behavior is the most significant factor of delays. Therefore, before any further technological improvements are made, they have to reach out to the customers. Both interviews said that the reason behind this is that passengers are not aware of the system around them and the effect their actions can have on it. Customers are frequently distracted by their phones and are not paying attention to announcements, signs, and the other people around them. This inattentive and careless behavior causes delays on the line when passenger try to rush onto the trains at the last moment and end up running into the doors, drop items down on the track, and miss major announcements. The SCM we spoke to said that reaching out to customers to improve their behavior is an “untapped territory” with great potential and something needs to be done to correct this before the increase in trains per hour on the line in 2020.

The interviews also discussed the major impact of a single, small delay on the line. Phil O’Hare emphasized that if there is a delay in the morning peak, it will ruin the time table for the remainder of the day. As mentioned earlier, the delay can be caused by many factors from customer illness to a system malfunction, or even a passenger holding the doors open for a friend to get in the train. It is very important that the staff does their best to minimize the threat of delays. An example O’Hare gave was that passengers rush to board the train when they see the doors closing. They run into the door causing it to reopen, causing the train to be delayed by more than 10 seconds. Although this may seem like a small effect, the seconds build up and by the end of peak hours, there are major delays. The smallest delay causes a domino effect on the trains behind it. This behavior was something we have observed ourselves on a regular basis, at various locations and times of day. One survey respondent even said that their bad experience

with PEDs is that it makes it harder for them to run and get on the train as the doors are closing, since there are 2 sets of doors, highlighting the bad passenger habits.

Our dwell time analysis showed that the PEDs add very small amounts of time in the total dwell time. The increase in the average dwell time was small enough that the total effect in delays is negligible, even over a full day of operation. Moreover, the stations with PEDs showed more consistency regarding the dwell time. This is very important because the consistency allows for better scheduling, since the dwell times are more predictable. However, it should be noted that all the PED station stops we witnessed were fairly accurate. We suspect that a very inaccurate stop, where the train door opening is not fully contained within the PED opening, might result to increased dwell times. A more significant negative trait of PEDs is that they can cause major delays when repairs are needed, because at least one station will need to shut down. This problem can be partially addressed by fully integrating the PEDs with the rest of the TBTC, but not fully.

5.2.4 Stopping Accuracy

Our stopping accuracy data analysis revealed three important results. First, the VCC was found to be measuring the stopping accuracy correctly. Second, the VCC data for all the trains on the Jubilee Line for March 1st to 26th showed that the trains are consistently stopping accurately.

Validating if the VCC is measuring the stopping accuracy correctly was crucial for our project. First of all, this was one of the main objectives set by our sponsor when we received the first project description. It is also very important for the operation of the Jubilee Line, and by extension other lines using very similar TBTC systems, since the stopping accuracy measurement is one of the major indicators of the system's day-to-day operation. Moreover, knowing that the VCC-derived data are indeed correct allowed us to perform further meaningful analysis on the very large data set covering the month of March for the entire Jubilee Line fleet.

Both the data set covering all the trains of the Jubilee Line for the month of March and our manually obtained data showed that the trains of the Jubilee Line stop very accurately, especially at stations with PEDs. This result is important, as it affects everyone involved in the Jubilee Line: passengers, train operators, platform and station staff, as well as senior management staff. On the passenger level, it means that it is extremely rare that a passenger will

be obstructed while boarding or alighting the trains (at stations with PEDs). This means that more passengers will be able to get in and out of the trains and get to their destination without any disturbances. Moreover, the reliability of the stopping location of the trains at stations both with and without PEDs allows for the passengers on the platform to queue in an orderly fashion around the locations where the train doors will be, resulting in much more efficient alighting-boarding process; as a result, the passenger-carrying capacity of the line can be maximized, and delays will be positively impacted as well. From the perspective of the train drivers, very accurate, consistent stopping allows them to operate the train doors quickly, keeping the dwell times to a minimum. For the platform staff, accurate stopping is welcome because the reduced customer disturbances mean that the staff members will not have to intervene with passenger behavior as often. Finally, accurate stopping is important for senior staff of the line because it means that the investments on the modernization of the Underground have positive effects on the daily operation, and should therefore continue.

Finally, we analyzed the VOBC data we obtained. We received VOBC data corresponding to eight measurements at PED stations to make the comparison across our manual measurements, the VCC-reported data, and the VOBC-reported data. From this comparison, we found three patterns. First, only in three cases did the VOBC values match our manual measurements. Second, the conversion from the VOBC 5-cm resolution values into the 20-cm resolution VCC values was correct for all cases. Third, the VCC values matched the manual measurements in all cases. This analysis shows that the VOBC is not very accurate at its measurements. A definite conclusion cannot be made at this stage, however, since we only had a very small data set available to work with. Even though the VOBC was not very accurate, the VCC data, at a 20-cm resolution, was still perfectly accurate.

Regardless of the inaccurate measurements of the VOBC, the stopping accuracy of the trains at PED stations (where the tolerance is $\pm 50\text{cm}$) is not affected. The train stopping does not need to be accurately measured down to 5cm for the doors to operate normally. In addition, the dwell time will not be affected in any way as long as the trains stop within the tolerance. As previously discussed, the trains do stop within the tolerance in the overwhelming majority of cases.

5.3 Recommendations to the Sponsor

To address some of the problems we discussed during our data analysis, we have formed the following recommendations to improve reliability on the Jubilee Line.

5.3.1. Triple Pole

Triple poles, as visualized in Figure 24, can replace the current single vertical pole. They consist of three bars protruding from the central pole, spaced equally from one another. These would allow passengers to more safely and easily stand near the center of the car, as our observations have shown it sometimes is difficult for many passengers to stand near the center and grip the same pole. These have also been implemented in various metro systems around the world, specifically in the Paris Metro and the Singapore Mass Transit that were discussed in the Background section of this report (see Chapter 2).



Figure 24. Visualization of Triple pole in a Jubilee train car

5.3.2. Platform Markings

Platform markings, as shown in Figure 25, will allow more effective boarding and alighting. These markings will give passengers an idea of where the train doors are going to open, allowing passenger to wait and queue in the right area. The markings will also encourage passengers on the platform to stand on the side of the door opening area, to avoid obstructing passengers exiting the train, a problem we have noticed daily. We believe that this will improve passenger flow in and out of the train, and therefore reduce dwell time. A similar system is in place in the Singapore Mass Rapid Transit, and has been working effectively.



Figure 25. Visualization of Markings demonstrated on the non-PED Jubilee Line platform at Stratford.

5.3.3. Metal Railings

Metal railings, shown in Figure 26, work as a cheaper and easier to implement alternative to PEDs. Retrofitting PEDs can be very costly, and impossible in some stations, due to their size, weight, and complexity. Metal railings serve a similar purpose to PEDs, in that they prevent passengers from falling onto the track. These metal railings would be placed along the platforms in the areas between the train doors, and serve as both a safety barrier, as well as a marking of

where the doors will open. This will work in conjunction with the platform markings previously described. According to Eric Wright, a retired London Underground engineer, this will account for $\frac{2}{3}$ of the area along the platform. This metal railing barrier will help reduce accidents or unintentional track intrusion.



Figure 26. Metal Railing in Shanghai

Source: (Bricole Urbanism, 2010), without permission

5.3.4. Connected Cars

Connected train cars, like ones that are already implemented in the Metropolitan, Circle, District, and Hammersmith & City lines, allow better distribution of passengers along train cars. Connected cars also allow passengers to move along the whole train, finding space in less packed cars. From our observations, it is apparent that some cars are always more crowded than the others, and thus boarding and alighting in that specific car takes longer. This contributes to increased dwell time. We believe that having connected cars can reduce this issue, as passengers will be more evenly distributed along the train. These connected cars will also benefit people with wheelchairs and baby buggies because it allows them to board at a level entrance and travel through the train to an exit that has a platform hump. Figure 27 shows a computer render for new

trains to be used in the future in the London underground, and Figure 28 shows a picture of the connected car trains currently in use in the Underground.



Figure 27. New Tube for London train stock.
Source: (London Underground, 2014), with permission



Figure 28. In-Train picture of the trains used currently in the Metropolitan, Circle, District, and Hammersmith & City lines

5.3.5. Mechanical Gap Fillers

Mechanical gap fillers, as shown in Figure 29, bridge the gap at the PTI. These mechanical gap fillers are extended from the train upon stopping at stations, and prevent people from falling into or getting trapped in the PTI. Some stations have large gaps between train and platform, especially stations with curved platforms, which makes it challenging for some

passengers to go over the gap. Mechanical gap fillers will make it easier for people in wheelchairs or baby buggies to board and alight the train, thus reducing dwell time and improving customer experience. Overall, we believe that mechanical gap fillers would significantly reduce the risk associated with PTI and improve boarding and alighting for all passengers.



Figure 29. Mechanical Gap Fillers on a German Train
Source: (Danza, 2013), without permission

5.3.6. Door Obstructing Fee

A fee is proposed for when any passengers prohibit the train doors (or PEDs) from closing. Based on our interview with the general manager, a single incident can propagate delays throughout the entire line. The delay is caused by forcing the doors to reopen and then waiting for the driver to investigate the issue and close them again. This can delay the trains that are behind as well, and thus affect the timetable for the entire line. Fees have been used commonly in the past to influence customer behavior, although the problem lies in how to determine when a misdemeanor occurs and linking it to the passenger. Our recommendation is to apply this to only those with registered Oyster cards and implementing software to recognize the face of the person committing the act. With current CCTV camera placement this could be difficult, so a cost-effective camera could be implemented inside the trains on each door, facing the opposite side,

such that whenever the train detects the doors being blocked, the camera will capture a photo and send the image to software written for this purpose. With the current ATO system installed, we believe that establishing the interconnectivity and interoperability of a system like this one should be much more feasible than on a non-ATO line. Another means of identifying could be by having a sensor on the doors, such that when the doors are closing it detects if an Oyster card is passing through at that specific moment. The problem with this method, however, is that it would only be able to identify passengers with registered Oyster cards, and passengers could easily avoid the sensor. See Figure 30 below for a visual demonstration.



Figure 30. Demonstration of camera detection for fee.

5.3.7. Accessibility Card

An accessibility card is proposed that would be available for riders with disabilities (visible or invisible) that require assistance to navigate around the Underground. A template for it is shown in Figure 31. Passengers would apply for this card online, providing a doctor recommendation. This card is just like the regular Oyster card, but upon tapping in it would send a notification to the station staff that a particular passenger requires assistance. This is more efficient and less difficult than the current system of requesting assistance, which involves calling ahead of time for help or requesting help at the station. It also could help the dignity of passengers with disabilities, since it saves them the potential embarrassment of having to constantly ask for assistance.



Figure 31. Mockup of an accessibility Oyster card to identify persons that require accessibility accommodations.

5.3.8. Investigation of the Effectiveness of Signs

As discussed earlier, we found that there are different perspectives on the provision of signs throughout stations. From our survey, we learned that a majority of passengers are satisfied with the provision of information. However, from the interviews with senior Jubilee Line staff we learned that there are conflicting opinions on whether the Underground needs more signs or less signs. In order to determine which opinion is valid, we suggest a study be performed on the distribution and optimization of signs across the Underground network. This study could include the design and placement of signs in comparison with the time it takes people to travel through the station.

5.4 Limitations and Future Research

During the data collection process, we came across limitations and areas that can be further investigated. Due primarily to the time constraints and the limited scope of our project, we were unable to investigate these areas.

Ideally, we would have preferred more data samples to further validate the stopping accuracy. During the first three weeks, we collected about 150 measurements at platforms with

PEDs, and a total of around 300 dwell time measurements. This was a good sample size given the time constraints, but before drawing solid conclusions regarding validation, more samples are needed.

We would like to have gained significantly more Real-Time Data (RTD) measurements from the VOBC. The VOBC provides a stopping accuracy measurement with a resolution of 5 cm, and is the primary data source for the VCC. This data allows a more accurate comparison between our collected measurements and the measurements from the train. Based on the very small sample we received, it appears that these measurements might not be correct. Because of this, a more extensive study will yield useful results. This study could also be extended to platforms without PEDs. With this further research, we could implement a more accurate platform marking system.

Another limitation we encountered was the sample size and diversity of our survey. We reached our goal of collecting over 100 responses, but a higher number of responses would make our findings more valid. One of the problems we encountered while collecting survey responses was getting people to take the in-person survey. We tried standing outside of stations to get responses; however, most people were in a rush and were not willing to stop and take the survey. The diversity of the respondents to our survey was satisfying, but could be further improved. We conducted our in-person portion of the survey outside stations along the Jubilee Line, which we believe resulted to some selection bias, as it was very likely that the people that answered our survey also rode the Jubilee often. To gain a more diverse response pool, we recommend that the survey be conducted at other stations throughout the Underground. More responses would give us access to a more diverse group of passengers and allow us to form more definitive conclusions about how passengers feel about the reliability of the Jubilee Line.

During the various interviews we performed, we talked about the accessibility of the Underground. As of April 2017, most of the stations on the Underground do not have step-free access. When we talked to the senior employees about the expansions of step-free access, they said it is a goal of the Underground to achieve step-free access, but it is limited by cost. A topic of future research could be a cost-benefit analysis of transforming all stations to have step-free access from street to train on an entire line or even throughout the whole Underground network. This future investigation could also include reaching out to accessibility advocacy groups to gain more insight into the issues surrounding the topic.

5.5 Conclusion

Our data analysis has led us to two overarching factors that can improve the reliability of the Jubilee Line. We learned that both ends of the Jubilee Line management believe that positively influencing customer behavior is currently the best way to improve service reliability. Based on our findings, we believe that any future modernization plans will be more effective if the customer behavior is dealt with beforehand. By ensuring that customers are aware of the signs and announcements, and that they understand how the entire system operates, their behavior can be influenced more effectively. Through improving customer behavior and implementing the recommendations listed previously, namely implementing triple poles, platform markings, metal railings, connected cars, mechanical gap fillers, door obstructing fee, and accessibility card, delays and safety risks caused by customers can be mitigated significantly at very little comparative cost.

As a long-term means of improving reliability, further modernization of the Jubilee Line would be the best course of action, for many of the reasons previously described in this section. This would of course be the costliest approach, as long-term and consistent improvements across the entire line to accessibility, safety, punctuality, and stopping accuracy would require new train stock and new or renovated stations. In terms of new stock, full ATC operation would improve punctuality by ensuring consistently accurate stops and reducing delays and dwell time, connected cars would enable accessibility and easy access to all sections of the train, and the clean and modern appearance of the trains would improve customer satisfaction. It could also be possible that customers would be influenced more easily through signs and announcements if they are highly satisfied with the system they are currently in.

We believe it is imperative for London Underground to continue the improvements and modernization being made on the Jubilee Line, and to do so across the entire network in order to further the growth of London as a global metropolis.

5.6 Reflections

Jack Arnis Agolli

This project was a great learning experience. We began with a team of people from different disciplines that had never met before, and managed to determine how to work well together as a team and produce a great end result. In the beginning of ID 2050 we were given only a short few sentences describing our project that we were supposed to turn into a final project. It seemed so overwhelming at the start, yet as the process went on and the team got to know each other, things started to wrap together very well. In all my project experience, I have never worked in a better functioning team before.

Working with CPC and TfL was also truly an amazing and unique experience. I learned so much from working our sponsor. Not only about the rail transport system in London (which is one of the most important and most complex engineering systems in the city) but about working with people in general. The project was also not in my discipline of aerospace engineering, and doing this research in a different area and in a different country was challenging and very helpful. Being focused only on IQP during the term also allowed me to really push the limits of my work. By only working on this project and not having to take classes at the same time, I feel that I was able to be more creative and dedicate more time to it. In conclusion, I think the challenges faced in this project helped me grow to become not only a better engineer, but also a better person.

Marianna Bailey

On the first day of ID2050, I had no idea what to expect. We were immediately told to sit with our groups and try to find some things we have in common. I had never met any of them before and finding something we all had in common was surprisingly difficult. Despite coming from very different backgrounds we all knew we were united by one goal. Looking back, I never expected our team to work together as well as it did. Everyone contributed equally to the team and each person played multiple key roles. We listened to each other's ideas, took turns being leaders, and looked past small disagreements to produce a rewarding IQP. Throughout the semester, we faced a series of setbacks on our project, however we did not get discouraged. We

saw each issue we encountered as an opportunity to improve and I think this mentality will stay with me as I continue my career.

This project gave me an opportunity to get out of my comfort zone. I had become so used to with being at school and I dreaded life after graduation. Living in London gave me a chance to experience the real world before college is over. I had a great seven weeks and this experience has had a huge impact on how I will live the rest of my life.

Errando Berwin Jayapurna

IQP has been one of the best experience I have in WPI. Whether it is being in one of the greatest city in the world, working with some of the most competent people I have met, or just taking time off from the bizarre chemical engineering classes; I am very grateful for every single day of these last seven weeks in London. In retrospect, I never expected that my team could work together to accomplish such an amazing outcome. Things were not always as easy. I remember being very nervous about how technical this project is, and how my little to no experience with trains would hinder my performance as a team member. I had no idea who I was working with. I was also never a big fan of reading nor writing.

Things got better as we hit the ground running. The reading, writing, and research was not as bad as I imagined, especially since it was shared among four people. We did not have the best teamwork going through ID2050, but we still made sure things were done well. Once we arrived in London and got to spend more time together outside doing IQP work, we got to know each other better personally. This significantly improved the team dynamic and the quality of our work. This team turned out to be one of the best I have ever worked with.

I learn from this IQP that a team could accomplish things that I, individually, could never imagine achieving. We complemented each other in a lot of different ways, and we strived through the different challenges and circumstances that came in the way because we worked together as a team. I also found that working on things outside chemical engineering can be very exciting. And for all this, I am very grateful.

Yiannis Kaparos

The IQP process, starting 15 weeks ago, has been the most complete project cycle I have ever been a part of. It started with very preliminary background research and early talks with our sponsor, progressed with analysis and understanding of the background information we gathered and developing data collection methods, then adjusting those methods based on new information and changed circumstances on-site, going through with extensive data collection, and finally analyzing a variety of different types of data, understanding the patterns behind the data, and forming conclusions and recommendations. It included physical measurements, talking to strangers on the street, talking with high-ranked officials, talking with train drivers, and observing masses of people. This variety of information we gathered was eye-opening; I had never realized how important non-technical data are for even the most rigorous, technical projects. Moreover, the relationship between us, CPC, and TfL, which created some inefficiencies regarding access to specific data, as well as the nature of a government-funded public transportation network that is TfL added a political flair to our project. We came across issues that were deeply connected to the politics of TfL, the allocation of the available funds (which are often not enough), and handling the public's reaction. This IQP truly was an all-inclusive experience; research, data collection and analysis, interviews with very high-ranked executives, talking to the public, politics, and great teamwork – nothing was missing.

The level of collaborative teamwork we achieved in this project was truly unique for me. I have never before blindly trusted anyone other than my parents to do anything. My teammates for this project, however, proved to me that I can completely trust others without having to double-check their work. This allowed us to get more things done faster, and then come together and refine everything to a very high standard. I never really had bad teammates before, but none were as great a team as this one.

Finally, I really enjoyed living in London for 7 weeks. Living abroad was not really a new experience for me, but every place in the world is different in its own way, and experiencing these differences was one of the most exciting aspects of being involved in this project.

References

- A Brief History of the Underground. (n.d.). Retrieved January 16, 2017, from <https://tfl.gov.uk/corporate/about-tfl/culture-and-heritage/londons-transport-a-history/london-underground/a-brief-history-of-the-underground>
- American Public Transportation Association. (n.d.). Public Transportation Benefits. Retrieved February 26, 2017, from <http://www.apta.com/mediacenter/ptbenefits/Pages/default.aspx>
- Balant, P., Borup, M., & Ogunsola, A. (2007, May). Achieving Transmission Based Train Control in London-1995 Tube Stock System Compatibility. *Institution of Railway Signal Engineers*, 30, 1-2. Retrieved January 31, 2017, from <http://irse.org.hk/newsletter/Issue%2030%20May%202007.pdf>
- Banister, D., & Thustain-Goodwin, M. (2011). Quantification of the non-transport benefits resulting from rail investment. *Journal of Transport Geography*, 19(2), 212-223. Retrieved from <http://www.sciencedirect.com/science/article/pii/S0966692310000712>
- Bentley, J (February, 2007). An introduction to train brakes. TARO - the Traffic Accident Reconstruction Origin, Retrieved from <http://www.tarorigin.com/art/Jbentley/>
- Bin, N. (1970). Analysis of train braking accuracy and safe protection distance in automatic train protection (ATP) systems. *WIT Transactions on The Built Environment*, 20.
- Burke, M. *Proposals for new safety regulations for railways and other guided transport systems*. (n.d.).
- Connor, P. (2015). *London underground electric train*. Marlborough: The Crowood Press. Retrieved from <http://lib.myilibrary.com?ID=841912>
- Copenhagen Metro (N.d). Retrieved February 19, 2017, from <http://intl.m.dk/#/>
- Donohue, P., & Feiden, D. (2012, Mar 26.). Terror on the tracks: More passengers struck by trains Daily News Retrieved from <http://www.nydailynews.com/new-york/terror-tracks-passengers-struck-trains-article-1.1050724>
- Donoso G, Ladera CL, Martín P. Damped fall of magnets inside a conducting pipe. *American Journal of Physics*. 2011;79(2):193-200. <http://dx.doi.org/10.1119/1.3531964>. doi: 10.1119/1.3531964.
- Eagling, J., & Ryley, T. (2015). An investigation into the feasibility of increasing rail use as an alternative to the car. *Transportation Planning and Technology*, 38(5), 552-568. doi:10.1080/03081060.2015.1039234

- Eddy-current braking: A long road to success. Railway Gazette News Web site.
<http://www.railwaygazette.com/news/single-view/view/eddy-current-braking-a-long-road-to-success.html>. Updated 2008. Accessed Feb 02, 2017.
- Facts and Figures. (n.d.). Retrieved February 19, 2017, from <http://web.mta.info/nyct/facts/>
- Fishbein, R. (2014, Mar 12). Report: NYC infrastructure is crumbling. *Gothamist* Retrieved from http://gothamist.com/2014/03/12/nyc_infrastructure_rip.php
- Forrester, J. D. (2005, September). Geographical Path of Jubilee Line [Digital image]. Retrieved January 15, 2017, from <http://www.londontubemap.org.uk/>
- Frigola Almar, J. (2006). Planning system of metro networks. Comparison between Copenhagen and Barcelona.
- Georgescu, M. P. (Jun 22, 2006). Driverless CBTC – specific requirements for CBTC systems to overcome operation challenges. *Computers in Railways, Mind the Gap*. (2009, February 10). Retrieved January 31, 2017, from <http://www.railway-technology.com/features/feature49489/>
- Health and safety at work etc act 1974. Retrieved from <http://www.hse.gov.uk/legislation/hswa.htm>
- Herkewitz, W. (2013, Jul 10,). Understanding a runaway train: How do air brakes work? *Popular Mechanics*, Retrieved from <http://www.popularmechanics.com/technology/a9176/understanding-a-runaway-train-how-do-air-brakes-work-15678938/>
- HollySys Asia Pacific Subsidiary of HollySys Automatic Technologies Announced Contract Win of Thomson Line Integrated Supervisory Control System in Singapore. (2014). Retrieved Jan 31, 2017, from <http://hollsys.investorroom.com/2014-06-05-HollySys-Asia-Pacific-Subsidiary-of-Hollsys-Automation-Technologies-Announced-Contract-Win-of-Thomson-Line-Integrated-Supervisory-Control-System-in-Singapore>
- Horne, M. (2013). Mind the Gap. *Metadyne*. Retrieved March 31, 2017, from http://www.metadyne.co.uk/mind_the_gap.htm
- International Association of Public Transport. (2016). Statistics Brief - World Report on Metro Automation (pp. 1-6, Rep.). Brussels, Belgium: UITP. Retrieved from http://www.uitp.org/sites/default/files/cck-focus-papers-files/UITP_Statistic%20Brief_World%20Metro%20Automation%202016_Final02.pdf
- Jubilee Line.(n.d.). Retrieved January 18, 2017, from <http://www.london-tube-map.info/jubilee-line/>

- Jun Wei Du, & Ya Dong Fang. (2013). Integrated supervisory control system based on distributed component management. *Applied Mechanics and Materials*, 340, 744. doi:10.4028/www.scientific.net/AMM.340.744
- Kabak, B. (2012) Another Year, Another Push for Platforms Doors. Retrieved from <http://secondavenuesagas.com/2012/03/27/another-year-another-push-for-platform-doors/>
- Kelley, J. , Ko, D.H. , Mazza, L. , & Robinson, S.E. (2016). Reducing Dwell Time: London Underground. Unpublished Interactive Qualifying Project. Worcester Polytechnic Institute.
- Knorr-Bremse.(2013). Magnetic track brakes. Retrieved from [http://www.knorr-bremse.com/media/documents/railvehicles/product_broschures/brake_systems/Magnetic Track Brake_P_1269_EN.pdf](http://www.knorr-bremse.com/media/documents/railvehicles/product_broschures/brake_systems/Magnetic_Track_Brake_P_1269_EN.pdf)
- Kyriakidis, M., Hirsch, R., & Majumdar, A. (2012). *Metro railway safety: An analysis of accident precursors*. Amsterdam [u.a.]: Elsevier.
- Lo, C. (2012, May 31). Driverless Train Technology and the London Underground: The Great Debate
- London Underground Intranet. (n.d.). Assisting your disabled customers. Retrieved April 10, 2017, from <http://luintranet.tfl/>
- LTA awards 6 downtown line contracts totaling \$1.13 billion. (2008). Retrieved from <https://www.lta.gov.sg/apps/news/page.aspx?c=2&id=2040>
- Ma, L., & Zeng, X. (2014). Analysis on Train Stopping Accuracy based on Regression Algorithms. *JSW*, 9(5), 1237-1244.
- Martinez, J. (2016, May 23). MTA Statistics Show Subway Overcrowding and Delays Worse than Last Year. Retrieved March 31, 2017, from <http://www.nyl.com/nyc/all-boroughs/transit/2016/05/23/mta-statistics-show-subway-overcrowding-and-delays-worse-than-last-year.html>
- Mathew, T. V., & Rao, K. (2007). Role of transportation in society. Introduction to transport engineering (pp. 3.5) NPTEL.
- Mind the gap. (2015). RSSB.
- Mohammed, T. S., Al-Azzo, W. F., Akaak, M. A., & Suroor, M. L. (2014). Full automation in driverless trains: A microcontroller-based prototype. *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, 3(7), 10417-10422. doi:10.15662/ijareeie.2014.0307003

- MRT. (2013). Paris Metro - Line 14. Retrieved from https://www.systra.com/IMG/pdf/metro_meteor_en-3.pdf
- Myhre, M., & Rosso, F. (1996). Designing for security in meteor: A projected new metro line in Paris. Preventing mass transit crime, 199-216.
- Narin, M. (2017). In Agolli J. A., Bailey M., Davies G., Dobell M., Jayapurna E. B. and Kaparos Y.(Eds.), *Mehmet narin's email on how the trains measure their position and data collection*
- National Travel Survey: England 2015 (2016).
- NFPA130 Standard for Fixed Guideway Transit and Passenger Rail systems (2010 ed.). (2010). National Fire Protection Association.
- North east line. Retrieved January 31, 2017, from <https://www.lta.gov.sg/content/ltaweb/en/public-transport/projects/north-east-line.html>
- Omega Centre. (2008). *Project Profile: UK Jubilee Line Extension (JLE)* (Rep.). Retrieved April 4, 2017, from University College of London website: http://www.omegacentre.bartlett.ucl.ac.uk/wp-content/uploads/2014/12/UK_JLE_PROFILE.pdf
- Platform Screen Doors (PSD) |. (2015). Retrieved January 18, 2017, from <http://www.railsystem.net/platform-screen-doors-psd/>
- Qu, L. and W. K. Chow. 2012. "Platform Screen Doors on Emergency Evacuation in Underground Railway Stations." *Tunnelling and Underground Space Technology* 30: 1-9.
- Railway Technical Web Pages. (n.d.). Retrieved February 13, 2017, from <http://www.railway-technical.com/>
- Rodríguez, G. d. A., Seriani, S., & Holloway, C. (2016). Impact of platform edge doors on passengers' boarding and alighting time and platform behavior. *Transportation Research Record: Journal of the Transportation Research Board*, 2540, 102-110. doi:10.3141/2540-12
- Siemens. (2012). Paris (France) Line 14. Retrieved from https://w5.siemens.com/france/web/fr/sts/en/france/Documents/Fiche_Paris_Line_14_2_12_en.pdf
- Singapore Country Profile. (2016). Retrieved Jan 31, 2017, from <http://www.bbc.com/news/world-asia-15961759>
- Soendergaard, M. (1996). How Copenhagen chose an automated minimetro system- a comparative analysis of 3 mass transit systems; *5th International Conference on Automated*

People Movers, APMs: Toward the 21st Century,

South China Morning Post, “Taegu’s subway line has been beset by disaster”, Main Section, p. 10, Hong Kong, 19 February (2003).

ST Electronics. (1997). *Integrated Supervisory Control System for Singapore MRT - North East Line.*

Standard Tube Map (2016). Transport for London.

Statistics Brief Local Public Transport in the European Union (Rep.). (2016, September).

Retrieved February 26, 2017, from International Organisation for Public Transportation website: [http://www.uitp.org/sites/default/files/cck-focus-papers-files/UITP_Statistics_PT_in_EU_DEF_0.pdf](http://www UITP.org/sites/default/files/cck-focus-papers-files/UITP_Statistics_PT_in_EU_DEF_0.pdf)

Statistics Denmark. Retrieved from <http://www.statbank.dk/BY1>

Transport for all, Accessible Transport in London. (2017). Retrieved March 31, 2017, from <http://www.transportforall.org.uk/>

Transport for London. (2014). *New Tube for London: Feasibility Report.* (No. 170). Transport for London.

Transport for London. (2016). *Travel in London.* London: Transport for London.

Transport for London. (n.d.). How we are governed. Retrieved January 24, 2017, from <https://tfl.gov.uk/corporate/about-tfl/how-we-work/how-we-are-governed>

United States. Congress. Office of Technology Assessment. (1976). Automatic train control in rapid transit. the University of Michigan: Office of Technology Assessment.

























































































































Visiting Paris. (n.d.). Retrieved March 28, 2017, from http://www.ratp.fr/en/ratp/c_21879/visiting-paris/


Westinghouse Platform Screen Doors. (2017). London underground: Jubilee Line. http://www.westinghouse-brakes.com/en/archive/jubileeline_1/jubileelinelondon.jsp?print=1

World's population increasingly urban with more than half living in urban areas. (2014). Retrieved January 31, 2017, from <http://www.un.org/en/development/desa/news/population/world-urbanization-prospects-2014.html>

Wortman, M. (2005). *Public transportation: Benefits for the 21st century.* New York: Visual Reference Publ.

Appendix A: Paris Metro map

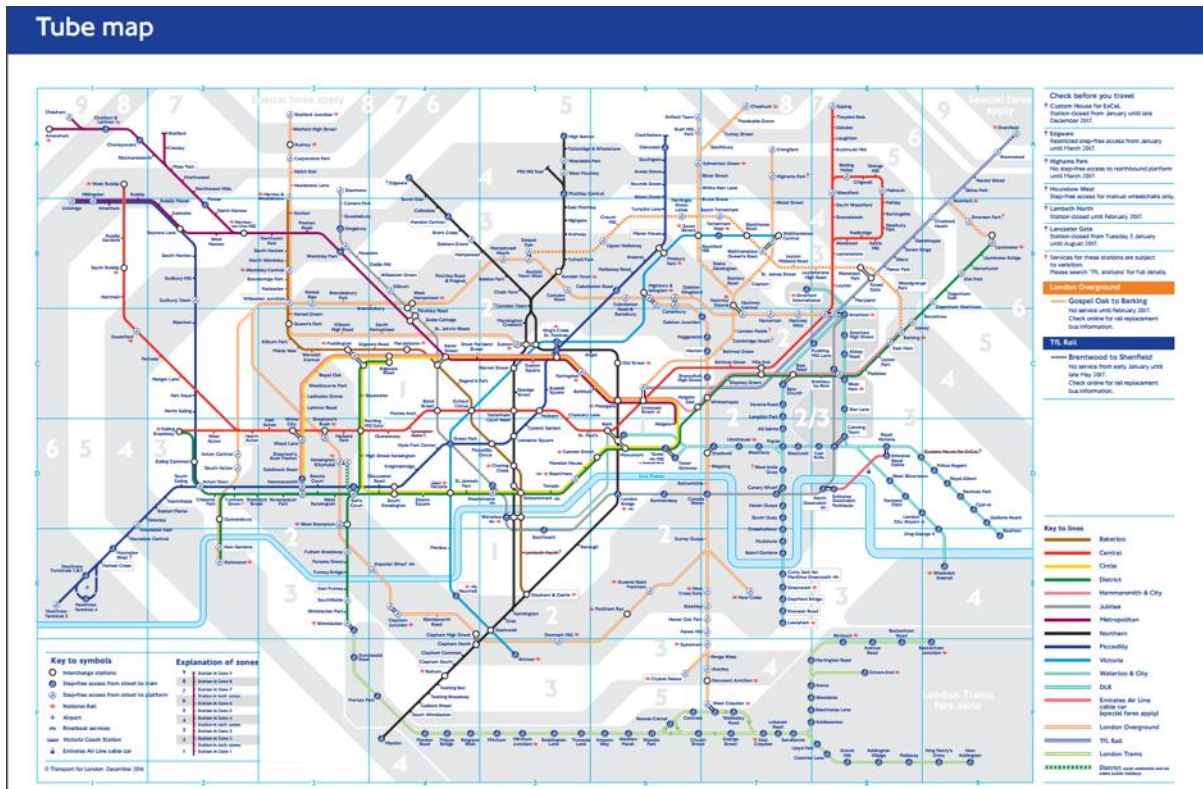
 Index des gares et stations accessibles	
Asnières-sur-Seine  *	B1
Auber   *	D3
Avenue du Pdt Kennedy	
Maison de Radio France    *	B4
Avenue Foch   *	A3
Avenue Henri Martin   *	A3
Barbès – Rochechouart    *	E2
Bercy   	F5
Bibliothèque Fr. Mitterrand    *   	F5
Boulaivilliers   *	A4
Boulevard Victor   *	A5
Ch. de Gaulle – Étoile   *	B3
Châtelet   	D3
Châtelet – Les Halles     *	D3
Cité Universitaire   *	D6
Clichy – Levallois  *	B1
Cour St-Émilion   	F5
Denfert-Rochereau   *	D5
Esplanade de La Défense    *	
Gare d'Austerlitz   *	E4
Gare de l'Est  *	E2
Gare de Lyon    *     *	E4
Gare du Nord    	E2
Gare Montparnasse  *	C5
Gare St-Lazare  *	C2
Gentilly   *	D6
Hausmann – St-Lazare   	D3
Invalides   *	C3
Issy – Val de Seine   *	A5
Jaurès   *	E2
La Défense      *	
La Garenne – Colombes  *	
La Plaine-Stade de France    *	
Madeleine   	C3
Magenta   	E2
Olympiades   	E5
Nation   *	F4
Neuilly – Pte Maillot    *	B3
Pereire-Levallois   *	C2
Port-Royal   *	D5
Pte de Clichy   *	C2
Pyramides   	D3
Saint-Denis – Pte de Paris    *	
Saint-Denis – Université    *	
Saint-Lazare   	D3
Saint-Ouen   *	D1
Stade de France – St-Denis    *	

* Gares ou stations dont l'accès au train nécessite un accompagnateur

Source: (RATP, 2017)

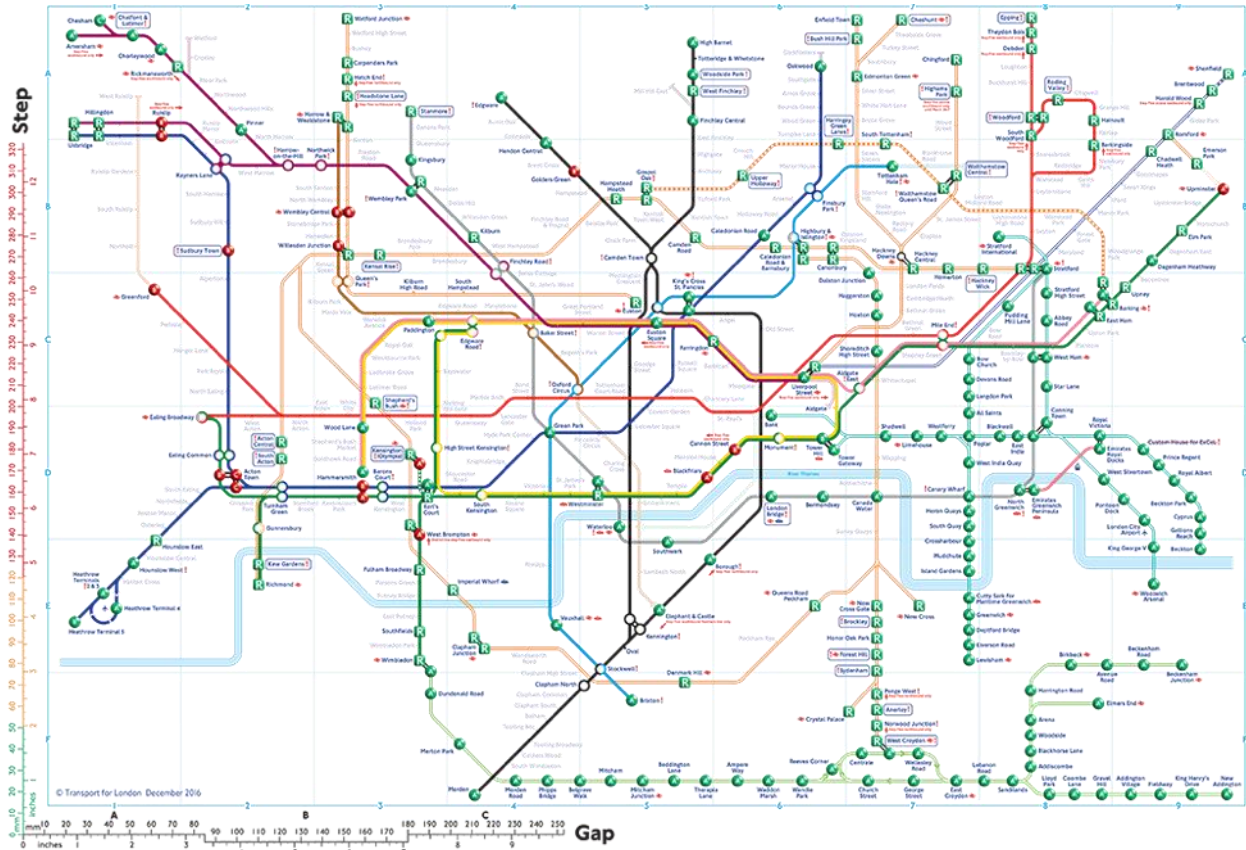
Appendix B: London Underground map

Standard Tube Map



Source: Transport for London, 2016

Appendix C: Step-Free Tube Map



Source: Transport for London, 2016

Appendix D: Methods Schedule

Project Timeline

Objective	Task	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
Observe Current State	Train Observation	█	█	█	█			
	Employee Interviews		█	█	█			
	Passenger Surveys		█	█	█			
Validate Stopping Accuracy	Analyze available data	█	█					
	Implement train and platform based validation system		█	█				
	Observe results			█	█	█		
Propose Recommendations	Analyze results of both objectives					█	█	
	Form recommendations						█	█
	Finalize report							█

Appendix E: Jubilee Line before 1979



Appendix F: Survey Consent Form

Thank you for agreeing to participate in this study conducted by students of Worcester Polytechnic Institute. The aim of this survey is to understand how riders feel about the modern technologies used on the London Underground. Your participation in this study is voluntary and you may stop at any time. Results of this survey will be kept confidential and will not be attributed to you in any way. Results of this survey will only be released in aggregate and with no personal identifying information. This survey will take approximately 5 minutes.

For questions regarding the research study, please contact our advisors, Prof. Adrienne Hall-Phillips (ahphillips@wpi.edu) or Prof. Josh Rosenstock (jrosenstock@wpi.edu). For questions regarding your rights as a research participant, contact the Human Research Protection Program at Worcester Polytechnic Institute, Worcester, Massachusetts, USA (irb@wpi.edu).

If you agree and are ready to participate in this survey, please click "Yes, I agree to the terms above" to start the survey and indicate your consent to participate. By agreeing you are verifying that you are over the age of 18.

Appendix G: Survey Questions

1. How often do you use the Underground?
 - Once or twice a month
 - Less than four times a week
 - More than four times a week
2. How old are you?
 - 18-25
 - 25-40
 - 40-64
 - 65 or above
3. Have you ever ridden on the Jubilee Line?
 - Yes
 - No
4. What lines do you use the most often?
 - Bakerloo
 - Central
 - Circle
 - District
 - Hammersmith & City
 - Jubilee
 - Metropolitan
 - Northern
 - Piccadily
 - Victoria
 - Waterloo & City
5. Compared to other lines on the Underground, the Jubilee line has ____
 - Many more delays
 - Somewhat more delays
 - Same amount of delays
 - Somewhat fewer delays
 - Much fewer delays
6. Compared to other lines on the Underground, the train shortage in the Jubilee line is ____
 - Much more
 - Somewhat more
 - The same
 - Somewhat fewer
 - Much fewer
7. Compared to stations without PEDs, PEDs make you feel ____
 - More safe

- Somewhat safe
- The same
- Somewhat less safe
- Much less safe

8. Have you ever had a bad experience with PED?

- No
- Yes

If yes, please explain: _____

9. Have you required assistance from London Underground's staff to use the Underground? For example, wheelchair assistance, assistance with a baby or small child in a baby buggy, any hearing or sight impairment, or less able to stand.

- Yes
- No

10. Do you find the Jubilee Line more accessible than other lines for people with disabilities?

- Much more accessible
- Somewhat accessible
- The same
- Somewhat less accessible
- Much less accessible

11. In your opinion, what more can be done on the London Underground to improve rider accessibility?

12. What is your opinion on the provision of information such as announcements and signs?

- Satisfied
- Neutral
- Dissatisfied

13. What is your favorite line?

- Bakerloo
- Central
- Circle
- District
- Hammersmith & City
- Jubilee
- Metropolitan
- Northern
- Piccadilly
- Victoria
- Waterloo & City

14. Please explain why: _____

Appendix H: Informational Handout

What are Platform Edge Doors (PED)?

In the most basic sense, they are doors that serve as a barrier between the platform and the train.

Figure 1. Train with PEDs (left). Train without PEDs (right).



What does the Jubilee Line have?

The pictures shown above are from the Jubilee Line. Currently, eight stations are equipped with PEDs.

Why is this important?

PEDs significantly reduce the wind generated by the movement of the trains in the tunnels, and they also make the stations significantly safer for the passengers. They prevent people falling on the tracks either by accident, on purpose, or by getting pushed on the tracks.

Appendix I: Interview Consent Form

Informed Consent Agreement for Participation in a Research Study

Investigator: Jack Agolli, Marianna Bailey, Errando Berwin Jayapurna, Yiannis Kaparos

Contact Information: cpc17@wpi.edu

Title of Research Study: Investigation of Reliability and Accessibility: London Underground Jubilee Line

Sponsor: CPC Project Services

Introduction

You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation.

Purpose of the study:

We will verify the stopping accuracy of the Jubilee Line through some experimentation and observations in order to determine any problems the line may have. In addition to this, we wish to examine the implications modern train technologies have on both train drivers and passengers, which is why this study is necessary.

Procedures to be followed:

We will try and have one-on-one interviews with train drivers in order to learn how they work with the technologies on the Jubilee Line. This should be a short interview that will last a maximum of 10 minutes.

Risks to study participants:

There is a potential risk that drivers could face litigation issues if they are found to be speaking negatively of their position or employer. This is a theorized risk and not entirely known, and if their identities are kept anonymous then there is no foreseeable risk. Therefore we will not be revealing any identities in our report. Any data that will be included (ie. quotes) will be stripped of all identifying characteristics.

Benefits to research participants and others:

The benefits of the driver interview would be that drivers are recognized for the work they put in everyday. We will also mention in our paper if they are exceeding expectations to ensure that the train runs on time and stops accurately. The benefits for the passengers that take the survey is that they can share their good and bad experiences with us and we will provide TFL and CPC on recommendations of how to address their concerns.

Record keeping and confidentiality:

We will keep the identities of the drivers confidential in our final paper. Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or it's designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you.

For more information about this research or about the rights of research participants, contact:

cpc17@wpi.edu or the IRB Chair (Professor Kent Rissmiller, Tel. +1 508-831-5019, Email: kjr@wpi.edu) and the University Compliance Officer (Jon Bartelson, Tel. +1 508-831- 5725, Email: jonb@wpi.edu).

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

_____ Date: _____
Study Participant Signature

_____ Date: _____
Study Participant Name (please print)

_____ Date: _____
Signature of person who explained this study

Should a participant wish to withdraw from the study after it has begun, the following procedures should be followed: please email us at cpc17@wpi.edu and we will promptly discard your responses.

Special Exceptions: Under certain circumstances, an IRB may approve a consent procedure which differs from some of the elements of informed consent set forth above. Before doing so, however, the IRB must make findings regarding the research justification for different procedures (i.e. a waiver of some of the informed consent requirements must be necessary for the research is to be “practicably carried out.”) The IRB must also find that the research involves “no more than minimal risk to the subjects.” Other requirements are found at 45 C.F.R. §46.116.

Appendix J: Driver Interview Questions

1. How long have you been working as a tube driver?
2. Have you ever worked on any other lines?
3. How do you feel about the Platform Edge Doors? What are some positives and negatives you have experienced?
4. Describe the steps you go through when approaching the stop to opening the doors.
5. What do you do if the train does not stop within the tolerance?
 - a. Have you noticed at this happens often?
 - b. Can you tell us why you think this may happen?
6. How do you think PEDs have affected the Jubilee Line?

Appendix K: Senior Jubilee Line Manager

Interview Questions

1. What are your primary responsibilities as (General Manager/Service Control Manager)?
2. How do you feel about Platform Edge Doors?
3. Safety
4. Accessibility
5. Train Punctuality
6. Stopping Accuracy
7. If you could do anything to improve reliability on the Jubilee Line, what would it be?

Appendix L: Observation Checklist

Are the PEDs and train doors opening and closing at the same time?

Yes

No

- Is there a delay? If so, how significant is it?

How long does it take passengers to get on and off (the dwell time)?

- Do the doors decrease the dwell time or add to it?

Do the passengers crowd near the doors?

Yes

No

- Why do they crowd around the doors?

- Do people get stuck in the doors?

Is the PTI level?

Yes

No

Are the stations accessible?

Yes

No

- Are there level access?

Do trains have enough space for disabled passengers?

Yes

No

Are there signs to inform passengers about the location of lifts?

Yes

No