Improving the estimation of platform wait time at the London Underground

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Bachelor of Arts, Mathematics
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Abstract

In recent years, the proliferation of automatically collected data has allowed many transit agencies to complete more frequent and thorough analyses of service quality. However, while the types and quality of automatically collected data are sure to improve in the future, many transit agencies will be limited to using their current automatically collected data until they have the time and resources to implement new data collection systems. This thesis focuses on improving the analyses undertaken with the currently available data.

The primary objective of this thesis is to improve the accuracy of the estimation of platform wait time (PWT) at the London Underground (LU) by determining the methodology that provides the most accurate and robust estimates of PWT. Three methodologies are tested: (1) LU's current PWT methodology using train tracking data that has been made more complete and robust through the use of automated processes; (2) a variant of LU's current PWT methodology; and (3) an improved PWT methodology that avoids the deficiencies of LU's train tracking data. Specifically, this improved PWT methodology relies on the count of trains recorded at stations in order to eliminate the need to use train identification data to verify that a specific train reached a specific destination station and to minimize the effect of data recording errors on the estimation of PWT.

The PWT methodologies presented in this thesis are applied to a four-week period on the Bakerloo and Piccadilly lines. For a specific time period and day, it is found that the differences between the PWT estimates from a new PWT methodology and LU's PWT methodology are usually less than 5%. It is concluded that higher quality NetMIS data and improved PWT estimation methods are a worthwhile investment, even if they lead to small changes in estimated PWT, because they ensure that variations in PWT reflect actual operations and are not due to poor NetMIS data or PWT estimation errors. Further, a hybrid approach that combines the best of LU's current PWT methodology and the train-count-based PWT methodology is recommended as one way to improve PWT estimates.

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Chapter 1

Introduction

Measuring the performance of a metro system[1] is an integral aspect of delivering the highest quality service possible. In the beginning, agencies relied on manually collected data, which are expensive to collect and generally yield small sample sizes, to conduct service performance analyses. Additionally, transit agencies have historically focused on measuring their system's performance from the supply side, taking an agency-centric point of view. For example, agencies may measure trains per hour at a specific location or the number of missed trips. While these measures are certainly worthwhile and provide an idea about how passengers see the service, agencies would benefit from including metrics that are more clearly passenger-centric.

In recent years, the proliferation of automatically collected data, including data from track circuits and smart cards used by passengers to pay fares, has allowed many agencies to complete more frequent and thorough analyses of service quality. This increase in automatically collected data availability has also allowed agencies to develop more passenger-centric performance metrics. These metrics may include measures such as excess journey time and reliability buffer time[2], which measures how much extra time passengers must allow for their journey to arrive on-time at their destination a high percentage (e.g., 95%) of the time. These passenger-centric

[1] Other colloquial terms for a metro system include subway, underground, and tube.

[2] See Uniman et al. (2010) for a more detailed description of reliability buffer time.

metrics complement agency-centric metrics to provide a more comprehensive picture of how customers view the service being provided.

While the types and quality of automatically collected data are sure to improve in the future, many transit agencies will be limited to using their current automatically collected data until they have the time and resources to implement new data collection systems. This thesis focuses on improving the analyses undertaken with the currently available data. How can the methods for calculating service quality metrics be perfected given the currently available data? Is there a way to improve the available automatically collected data? Additionally, by considering service quality from the passengers' perspective instead of just from the agency's perspective, this thesis focuses on service quality analyses that have not traditionally been considered by transit agencies.

Before presenting the motivation for this research, it is important to note that, although all of the processes and applications presented in this thesis are specific to the London Underground (LU), the ideas and methods presented in this thesis should apply to any metro that archives its train tracking data.

1.1 Motivation

LU places an emphasis on measuring performance from the passenger's perspective, accomplishing this task largely through the use of the Journey Time Metric (JTM).[3] LU's JTM, which measures the time passengers spend in the transit system, is used throughout the agency to quantify the passenger experience. Passengers' journey time is broken into five components: Access, Egress, and Interchange time; Ticket Purchase Time; Platform Wait Time (PWT); On-Train Time (OTT); and Closures. The closures component measures the journey time that results from planned and unplanned service disruptions and closures. LU has "baseline" or "expected" values for each of these components. As a result, comparing the amount of time actually

[3]London Underground (2009) and London Transport (1999) provide more details about JTM.

spent on each component of journey time to the baseline value allows LU to estimate excess journey time.

The automatically collected data used to calculate PWT and OTT are stored in LU's Network Management Information System (NetMIS) database. While the NetMIS data are certainly an improvement over the manually collected data used in the past, these data still have some important deficiencies. The NetMIS database should contain information, including train identification, arrival time, and departure time, for every train at every station in the LU network. However, for a variety of reasons to be explained in Section 3.3, there are instances where some or all of these data are missing at certain stations. Additionally, train identifications sometimes change mid-trip, making it difficult to determine where a train ended a trip.

These data deficiencies can affect the accuracy of PWT estimates. PWT is calculated based on the departure headways between trains serving a given origin-destination pair; the train headways are determined by the data in NetMIS for a representative station within a line segment. Because NetMIS data are incomplete and not completely robust, situations exist where it is not possible to know with certainty that a train recorded at an origin station eventually arrived at a given destination station. This occasional inability to match trains between origin and destination stations and the existence of missing arrival and departure time data can lead to errors when estimating PWT. It should be noted that the NetMIS data deficiencies do not cause problems with the calculation of OTT because there is very little variation in running times on the LU network. As a result, a less than 100% sample of all running times can still be used to accurately measure running times experienced by passengers.

The focus of this thesis is to improve the accuracy of estimating the PWT component of JTM by developing an improved PWT methodology that avoids the deficiencies of NetMIS data and by developing automated processes that make this automatically collected data more robust. The new PWT methodology proposed in this thesis will avoid the need to match trains at origins and destinations while the automated processes proposed in this thesis will decrease the number of instances

where (1) trains cannot be matched between origin and destination stations and (2) trains are missing arrival and/or departure times at a specific station.

These improvements to the PWT calculation process should increase the accuracy of the estimation of the PWT component of JTM. However, it is unclear which combination of PWT methodology and data source will provide the most accurate estimate of PWT. Therefore, a comparison of the results obtained from different combinations of PWT methodology and data source will be completed to help determine the best combination of methodology and data.

In addition to increasing the accuracy of the PWT component of JTM, more complete and robust NetMIS data will be useful for LU staff and for improving the assignment of passengers to individual LU trains as proposed by Paul (2010). Several hundred staff within LU use NetMIS data. The majority of NetMIS data users work in operations and use the data to analyze line performance. However, an important minority of staff, including those in Transport Planning, Service Performance Information, and Operations Support, also use NetMIS data. This group of users is important because they publish performance analyses for the entire LU organization.

Paul (2010) proposed methods for determining loads on individual LU trains by using data from NetMIS and the Oyster card system, which is used by approximately 80% of LU customers and must be "tapped" to enter and exit the LU system. Paul's goal was to assign passengers to specific trains in order to estimate train loads and the number of passengers left behind by each train at each station. While Paul developed a sound framework for estimating train loads, her results were not completely satisfying. Specifically, Paul's model appears to overstate the numbers of left behind passengers. For example, her model estimated that 26% of passengers were left behind even when there should have been no congestion on the trains.

Improving the robustness of NetMIS data should improve the accuracy of Paul's model by reducing the reliance on three of Paul's assumptions relating to NetMIS data. These three assumptions are as follows:

1. When a train erroneously receives a new Train ID, which is a seven digit number that identifies a unique piece of rolling stock, passengers who boarded the train

before the Train ID changed but alighted after the Train ID changed are assumed to have on-train times within two minutes of the expected running time given by LU's Route Choice Model (RCM).

2. Inferred running times match those given by LU's RCM when passengers board or alight at a station for which there are no NetMIS data.

3. Train departure time is set to train arrival time for trains that have only the arrival time recorded in NetMIS.

Because the processes proposed in this thesis are not expected to correct all errors in the NetMIS data, these assumptions will not be completely eliminated. Instead, the number of instances where the first two assumptions are required during the assignment of passengers to trains will decrease; the quality of the final assumption can also be easily improved by assuming 20 second dwell times in all cases where departure time is missing.

1.2 Objectives

The primary objective of this thesis is to determine the combination of methodology and data that provides the most accurate and robust estimates of PWT. Secondary objectives that will be accomplished while working towards the primary objective include the following:

1. Develop, test, and demonstrate a new methodology for calculating PWT at LU;

2. Develop, test, and demonstrate procedures through which LU can complete *ex post facto* data processing to make their collection of train tracking data more complete and robust;

3. Determine if a new PWT estimation methodology or incremental improvements to the quality of data used to estimate PWT produce large enough improvements in the accuracy and robustness of PWT estimates to justify the cost of

time and infrastructure needed to implement these changes to the methodology and data.

1.3 Research approach

The objectives listed in Section 1.2 will be pursued by using two distinct, but related, approaches. The first set of methodologies involves different processes for estimating PWT; processes that make NetMIS data more complete and robust make up the second set of methodologies. The processes for calculating PWT and the more complete and robust NetMIS data will then be used along with the original NetMIS data to achieve the primary objective of determining the best combination of PWT methodology and data. An overview of these methodologies will be provided in the remainder of this section while more details about these methodologies are presented in Chapters 4 and 5.

1.3.1 Calculating platform wait time

Three methodologies for calculating PWT will be used in this thesis. The first methodology will be that currently used by LU. One important aspect of this methodology is that, because PWT is based on passengers' origin *and* destination, train identification data are used on six of LU's 11 lines to match trains seen at representative origin and destination stations; NetMIS data on the other five lines are too unreliable to allow accurate matching of trains, so LU makes assumptions about the stations served by trains observed at representative stations on these lines. Because LU's current methodology assumes that all passengers traveling from any station in the same origin line segment to any station in a specific destination line segment experience the same PWT, the second methodology for calculating PWT will increase the number of segments on each line to reflect the belief that PWT may vary within segments that contain a large number of stations. The third methodology used in this thesis relies on the count of trains recorded at stations to determine origin-destination-based PWT. The train-count-based PWT methodology aims to eliminate the need to use

train identification data to verify that a specific train reached a specific destination station and to minimize the effect of data recording errors on the estimation of PWT.

1.3.2 Making NetMIS data more complete and robust

The two main goals related to making NetMIS data more complete and robust are to (1) fill in missing arrival and/or departure times and (2) revise Train IDs associated with a specific trip when the Train ID changes during that trip. Methodologies will be developed and implemented for finding instances where a Train Event, which corresponds to the arrival and departure of a train at a specific station, is missing the departure time. Additionally, methodologies will be developed and tested to find cases where an entire Train Event is (erroneously) not recorded at a specific station. In both cases, missing data will be filled in based on the data available for Train Events during the same trip.

A "sandwich" method will be used to correct instances where a train received a new Train ID in the middle of a trip. The details of this method will be described in detail in Section 5.1.2. However, the general idea is that the sandwich method looks at the Train IDs of the trains before and after the train in question. If the leading and following Train IDs remain the same from one station to the next but the middle Train ID changes between the two stations, then the two Train Events recorded in NetMIS for the middle train can be assigned the same Train ID.

1.3.3 Determining the best combination of methodology and data

The primary objective of this thesis involves comparing the results produced by using various combinations of methodologies and data to calculate PWT. The combinations of methodology and data that will be considered are as follows:

1. LU's current PWT methodology and current NetMIS data
2. LU's current PWT methodology and revised NetMIS data

3. LU's current PWT methodology with more line segments and current NetMIS data

4. Train-count-based PWT methodology and current NetMIS data

1.4 Thesis organization

Previous work on performance measurement strategies for metros is summarized in Chapter 2. Chapter 3 provides an overview of the Bakerloo and Piccadilly lines, the two LU lines that are the focus of this thesis. Additionally, Chapter 3 introduces LU's train tracking data, including details about how the train tracking data move through several systems as they migrate from track circuits into the NetMIS database, and describes causes of data recording errors and how NetMIS data are used in LU's JTM.

LU's PWT methodology is explained in Chapter 4 while Chapter 5 presents the new PWT methodologies. Specifically, Section 5.1 explains the processes used to revise NetMIS data, Section 5.2 describes the methodology for using more line segments with LU's PWT methodology, and Section 5.3 explains the train-count-based PWT methodology. The effectiveness and results of using these methodologies to estimate PWT are presented in their respective sections. In the case of making NetMIS data more complete and robust, results are presented to quantify the degree to which problems, including missing arrival and departure times and incorrect Train IDs, were fixed by the automated processes that revise the NetMIS data.

Chapter 6 provides a summary of this thesis. This chapter will include final conclusions and suggestions for future work.

Chapter 2

Literature review

Authors including Furth et al. (2006), Kittelson & Associates et al. (2003b), Uniman (2009), and Wilson et al. (1992) have emphasized the benefits of using automatically collected data to generate service performance metrics. These metrics allow transit agencies to analyze past performance in a manner that helps inform decisions in the present and future. As Kittelson & Associates et al. (2003b) write, "Agencies use performance measures to help provide service as efficiently as possible, monitor whether agency and community goals are being met, and – over time – improve service so that it attracts new riders." While there are a large number of metrics that can be used to quantify service performance (see Kittelson & Associates et al. (2003a)), this chapter focuses on those metrics that relate to service regularity and reliability.

The data used to calculate these two types of service performance metrics is gradually shifting from manually to automatically collected data. As Furth et al. (2006) note, "AVL technology holds substantial promise for improving service planning, scheduling, and performance analysis practices." Indeed, AVL systems provide a great source of data for analyzing service regularity and reliability. However, it is important to note that AVL data on their own do not allow for analyses at the disaggregate level of individual passengers. Instead, as Wilson et al. (1992) point out, AVL data allow agencies to "measure average service quality" and "compare actual service quality with an ideal standard." Nonetheless, it is reasonable to expect these measures to quantify service performance from the passenger's perspective. Authors

including Furth & Muller (2006) and Uniman (2009) advocate measuring performance from the passenger's perspective, and Uniman notes that AVL-derived measures such as average and excess platform (or passenger) wait time (PWT), both of which will be discussed in detail later in this chapter, "are not unreasonable proxies for quantifying the passenger experience." Be that as it may, Uniman argues that data from Automatic Fare Collection (AFC) systems provide a better view of the actual passenger experience. A hybrid approach is proposed by Paul (2010), whose work was referred to in Section 1.1 and is also discussed in more detail later in this chapter, as she shows that combining AVL and AFC data may provide a rich source of information about passenger travel times experienced on some metro systems.

The rest of this chapter focuses on service regularity metrics, with an overview of these metrics provided in Section 2.1. Various ways to estimate PWT, which is a passenger-centric service regularity metric, are discussed in Section 2.2. The final section describes the use of smart card data to measure journey time (Section 2.3.1), the quantification of reliability (Section 2.3.2), and the use of AVL and AFC data to assign individual passengers to specific trains in a metro system (Section 2.3.3).

2.1 Service regularity metrics

TCRP Report 88 (Kittelson & Associates et al. (2003b)) outlines five ways to measure headway regularity. The first metric, the coefficient of variation of headway deviations, is introduced in the Transit Capacity and Quality of Service Manual (2nd edition) (Kittelson & Associates et al. (2003a)). This metric is defined as the standard deviation of headway deviations divided by the mean scheduled headway, where headway deviation is the difference between actual and scheduled headways. The second and third headway regularity metrics, termed service regularity and wait assessment, give "the percentage of headways that deviate no more than a specified amount from the scheduled interval." The "specified amount" is a percentage of the headway in the service regularity metric and a number of minutes in the wait assessment metric. The fourth metric, the headway ratio, "is the observed headway divided by the scheduled

headway, multiplied by 100." Finally, the fifth metric, which was initially presented by Henderson et al. (1991), uses Gini's ratio to calculate a headway regularity index that is standardized so all values are between zero and one.

Trompet et al. (2010) use data from 13 transit agencies to analyze the pros and cons of four service regularity metrics. Two of these metrics, service regularity and wait assessment, are among those discussed by Kittelson & Associates et al. (2003b). The other two metrics they investigate are excess wait time, which is the difference between the actual average PWT and the scheduled average PWT, and "standard deviation of the difference between the actual and the scheduled headway." The 13 transit agencies included in this report are all members of the International Bus Benchmarking Group (IBBG), which includes agencies in Europe and North America, plus the bus agencies in Singapore and Sydney. Although Trompet et al. (2010) focus solely on bus systems, their work is certainly applicable to rail systems.

Seven of the 13 agencies included in Trompet et al. (2010) use the wait assessment approach to measuring service regularity while two use the service regularity approach. The values used to define a regular headway vary by agency; the smallest range used is that in Brussels where headways are regular if they are between the scheduled headway and the scheduled headway plus two minutes while the largest range is in Singapore where headways are regular if they are within five minutes of the scheduled headway. London Buses uses excess wait time to measure service regularity while the other four transit agencies included in this study do not have a formal measure of service regularity.[1]

Trompet et al. (2010) emphasize the need to choose a service regularity metric that is "clear, easily understandable, and useful to the audience." This goal for the interpretability of a service regularity metric makes it difficult to advocate the use of the coefficient of variation of headway deviations as proposed by Kittelson & Associates et al. (2003a). The headway regularity index and the standard deviation metric proposed by Trompet et al. also fall into this group of metrics that are more

[1]It appears that service regularity approaches of 14 agencies have been listed in this paragraph, but this is because the Vancouver Coast Mountain Bus Company uses both wait assessment and service regularity.

difficult to explain to some stakeholders. Trompet et al. oberve that analyzing headways to determine if they fall within a specified range around the scheduled headway offers an easy-to-communicate service regularity metric. However, one of the drawbacks of this type of metric is the subjective nature of the specified range around the scheduled headway. That is, each transit agency can define its own range, where a larger range naturally makes service appear more regular. Another drawback of this type of service regularity metric, as Trompet et al. (2010) note, is that it does not quantify or even indicate the extent to which service is irregular. For example, if a headway is defined as regular if it is between 4 and 8 minutes, a 9 minute headway will look just as bad as a 19 minute headway.

The headway ratio presented by Kittelson & Associates et al. (2003b) does not offer a completely satisfactory view of service regularity. While the ratio does provide a fairly intuitive way of thinking about service regularity as values greater (less) than 100 indicate service is less (more) frequent than scheduled, the results produced by this metric could misrepresent reality when aggregated over a time period. Kittelson & Associates et al. (2003b) do not say exactly how headway ratios should be aggregated over a time period, but it is possible that any aggregation could cause short headways to cancel long headways to make it appear that regular service was provided. One way to get around this problem is to use a metric such as excess wait time that recognizes that more passengers will be affected by longer headways while fewer passengers will benefit from shorter headways assuming a uniform passenger arrival rate. Indeed, Trompet et al. (2010), along with the 13 members of the IBBG, chose the excess wait time metric as their preferred service regularity metric. The next section presents the theory behind excess wait time while also presenting other passenger wait time-related metrics.

2.2 Passenger wait time

The motivation to analyze PWT comes from the belief that people strongly dislike waiting. According to Osuna (1985), Loehlin (1959) proposes that time spent waiting

is perceived as lasting longer than it did in reality. Psarros et al. (2010) conducted a field survey of bus passengers in Athens, Greece, and found that perceived waiting time was usually at least 50% greater than actual waiting time. Additionally, Psarros et al. (2010) found that passengers who have larger actual waiting times tend to produce "a larger overestimation of their corresponding perceived times." Osuna (1985) writes that Bruzelius (1979) found that passengers find waiting about three times more onerous than in-vehicle travel time. In a similar fashion, London Underground estimates that passengers find PWT twice as onerous as traveling on an uncrowded train.

Why do passengers feel so strongly about waiting time? Osuna (1985) offers this rationale: "Anxiety and stress start to build up in an individual due both to a sense of waste and to the uncertainty in the time he will still have to wait." Osuna investigates the anxiety and stress associated with waiting, which he terms the psychological cost of waiting, and proves that this cost "is a marginal increasing function of waiting time." Further, Osuna shows that real-time information decreases the psychological cost of waiting but argues that each person perceives waiting differently depending on their "chronic propensity to anxiety" and external factors such as the conditions of the waiting area.

The works of Furth & Muller (2006), Osuna & Newell (1972), Wilson et al. (1992), Bowman & Turnquist (1981), and Furth et al. (2006) offer summaries of the use of transit vehicle departure headways to calculate PWT. In the case of a metro system, the departure headway between two trains that depart Station n at times t_{i-1} and t_i, where $t_i > t_{i-1} + K$, is given by $H_i = t_i - t_{i-1}$, where K is the sum of the minimum reoccupation time[2] at Station n and the minimum dwell time at Station n. Before presenting the ideas put forth by these researchers, it is important to note two critical assumptions used in the work of all of these authors except Bowman & Turnquist (1981). First, passengers using high frequency transit services, which are generally defined as those with headways no greater than 10 minutes, are assumed

[2]Reoccupation time is the amount of time it takes for Train i-1 to exit Station n and Train i to come to a complete stop at the Station n platform.

to arrive at a stop randomly and independent of actual and scheduled vehicle arrival and departure times. Second, all passengers are assumed to be able to board the next vehicle that arrives at their station.

Furth & Muller (2006) present the most basic way of calculating average PWT given these assumptions. They call this version of average PWT "nominal waiting time" and define it as follows:

$$W_{nominal} = 0.5 \cdot H_{schedule} \tag{2.1}$$

Thus, the nominal waiting time is based on scheduled departure headways. In reality, however, headways vary from those given in the schedule. As Furth & Muller note, "Passengers arriving during long headways will, on average, have longer waits than those arriving during short headways." Furthermore, more passengers will be waiting for a train that has a longer headway. For example, for headways of 2, 4, and 6 minutes and assuming passengers arrive randomly and at a constant average rate, more passengers will be waiting for the train that arrives at the end of the 6 minute headway than the trains that arrive at the end of the 2 or 4 minute headways. Thus, the nominal waiting time understates the average PWT experienced by passengers.

Although the nominal waiting time provides an easy-to-calculate first order approximation of average PWT, a more accurate calculation of average PWT can be obtained by using the approach developed in Osuna & Newell (1972). Osuna & Newell assume that passenger arrivals are "uniformly distributed over time." Based on this assumption and those assumptions stated at the beginning of this section, it is known that a passenger will arrive during headway H_k with probability $H_k / \left(\sum_1^n H_i\right)$, where there are n headways observed during the time period of interest. Further, a passenger that arrives during H_k will have an expected PWT of $H_k/2$. The average PWT for all n headways can then be found as:

$$E\left(w|H_1, \ldots, H_n\right) = \sum_{k=1}^{k=n} \left(\frac{H_k}{\sum_{i=1}^{i=n} H_i} \cdot \frac{H_k}{2} \right) = \frac{\sum_1^n H^2}{2 \cdot \sum_1^n H} \tag{2.2}$$

It will be seen in Section 4.1 that LU uses (2.2) to calculate average PWT.

By assuming that the sample of headways is large and that the sample average converges to the expected value, (2.2) can be rewritten as:

$$E\left(w|H_1,\ldots,H_n\right) \rightarrow \frac{E[H^2]}{2E[H]} = E(w) \tag{2.3}$$

Further, based on the definition of variance, it is known that $E[H^2] = (E[H])^2 + var(H)$, which gives the following:

$$\begin{aligned} E(w) = \frac{E[H^2]}{2E[H]} &= \frac{(E[H])^2 + var(H)}{2E[H]} \\ &= \frac{E[H]}{2}\left(\frac{(E[H])^2 + var(H)}{(E[H])^2}\right) \\ &= \frac{E[H]}{2}\left(1 + \frac{var(H)}{(E[H])^2}\right) \end{aligned} \tag{2.4}$$

Wilson et al. (1992) define the coefficient of variation of headway as "standard deviation divided by mean headway." That is, $cov(H) = [var(H)]^{\frac{1}{2}}/E[H]$. This allows (2.4) to be rewritten in a form commonly seen in the literature:

$$E(w) = \frac{E[H]}{2}\left(1 + cov^2(H)\right) \tag{2.5}$$

As Wilson et al. (1992) point out, when there is no variation in headways, the average PWT from (2.5) becomes the nominal waiting time given in (2.1).

In an effort to standardize the average PWT metric over routes that have different scheduled headways, Wilson et al. (1992) introduce the idea of excess PWT, which they define as "the difference between the actual expected wait time and the expected wait time that would result if there were perfect schedule adherence." This is shown mathematically in (2.6), where $E_s[H]$ is the average scheduled headway and $cov^2(H_s)$ is the square of the coefficient of variation of scheduled headway.

$$\text{Excess PWT} = E(w) - \frac{E_s[H]}{2}\left(1 + cov^2(H_s)\right) \tag{2.6}$$

As Trompet et al. (2010) note, Excess PWT can be negative if the schedule calls for irregular headways and the actual service delivered provides constant headways.

Furth & Muller (2006) argue that the equation for average PWT given in (2.5) undervalues the actual cost of waiting by not capturing the complete passenger experience. Specifically, (2.5) does not account for what the authors call "potential waiting time." The importance of potential waiting time stems from the belief, as Furth & Muller write, that "passengers' perceptions tend to be based on extreme values."

Furth & Muller argue that passengers must plan to have a PWT equal to the 95th percentile of the PWT distribution to ensure that, assuming a fixed amount of in-vehicle travel time, they arrive on-time at their destination an acceptable percentage of time. By using the 95th percentile to set budgeted waiting time, passengers will arrive late 5% of the time, which corresponds with two one-way trips per month for a typical commuter. Furth & Muller define the difference between budgeted waiting time and average waiting time as potential waiting time. This is given mathematically in (2.7).

$$W_{potential} = W_{0.95} - E(w) \tag{2.7}$$

Although passengers will not generally experience all of the potential waiting time as actual waiting time because the full amount of potential waiting time is only realized when actual waiting time is the 95th percentile of the waiting time distribution, passengers still find potential waiting time onerous because they must include it in their budgeted travel time. Therefore, Furth & Muller propose weighting potential waiting time by 0.75 and average waiting time by 1.5, where both values are given as minutes of in-vehicle travel time per minute of waiting time. Although the magnitudes of these values are chosen somewhat arbitrarily instead of being determined through a rigorous study of passenger perceptions, these values are less than and greater than one, respectively, because the former is not always realized whereas the latter is, on average, realized.

Furth & Muller then use these proposed weights to write an equation for waiting cost:

$$\text{waiting cost} = 1.5 \cdot E(w) + 0.75 \cdot W_{potential} \tag{2.8}$$

By dividing (2.8) by the weight on the average PWT term, an equation giving what the authors call equivalent waiting time is created, where the results are in terms of minutes of PWT:

$$W_{equivalent} = E(w) + 0.5 \cdot W_{potential} \tag{2.9}$$

Furth & Muller define excess equivalent waiting time as the difference between actual and scheduled equivalent waiting time and argue that "because it accounts for the hidden waiting costs of potential waiting time, excess equivalent waiting time more accurately reflects the impact of operations on customer service than does excess mean waiting time." This is an important distinction to make because although excess average PWT captures the variability of service in comparison to the schedule, it does not capture trip-to-trip variability, which is what some passengers may consider when deciding their trip start time.

Furth et al. (2006) offer a slightly different way of quantifying the difference between actual and scheduled waiting times. Their method aims to quantify the percentage of passengers who experience excessive waiting times, where "excessive" is defined subjectively. The best way to understand this proposed metric is to consider the example presented by Furth et al. (2006). Consider a service with an 8 minute scheduled headway and 6 observed headways of 4, 5, 7, 9, 10, and 13 minutes. Normal headways are defined as those up to 9 minutes, excessive headways are those between 9 and 11 minutes, and unacceptable headways are those greater than 11 minutes. Because passengers are assumed to arrive uniformly over time and board the first vehicle that arrives, the percentage of passengers experiencing excessive and unacceptable headways is given by the proportion of all "headway minutes" that fall into each category.

Table 2-1 shows how the minutes in each of the actual headways are distributed between the three categories. As an example, consider the 10 minute headway. All

Headway	Waiting Time			Total
	Normal 0 to 9 min	Excessive >9 to 11 min	Unacceptable >11 min	
4	4			4
5	5			5
7	7			7
9	9			9
10	9	1		10
13	9	2	2	13
Total	43	3	2	48
Percentage	89.5%	6.3%	4.2%	100%

Table 2-1: Example of excessive waiting time (Adapted from Furth et al. (2006))

passengers who arrive during this headway will experience a normal headway except those arriving during the first minute of the headway; these passengers will wait between 9 and 10 minutes and will experience an excessive headway. As this table shows, 6.3% of passengers experience an excessive headway while 4.2% of passengers experience an unacceptable headway.

The equivalent waiting time metric proposed by Furth & Muller (2006) and the excessive waiting time metric proposed by Furth et al. (2006) provide two worthwhile, but different, ways of quantifying the impact of inconsistent headways. On the one hand, the former metric quantifies the effect of inconsistent headways on how much time passengers must *budget* for trips. On the other hand, the excessive waiting time metric provides transit agencies with a way to analyze how many passengers were *actually* affected by unacceptable headways. While the equivalent waiting time metric has the advantage that values of time can be used to quantify the monetary cost of irregular service, the excessive waiting time metric has the advantage that it quantifies the proportion of passengers actually experiencing excessive waiting time. It should be noted that these two metrics are both subject to some level of subjectivity. With the equivalent waiting time metric, an agency must set the budgeted waiting time percentile along with the weights on potential and average waiting time; in order

to use the excessive waiting time metric, an agency must set the sizes of the headway bin.

One final model for estimating average PWT is worth mentioning because it aims to eliminate the assumption that all passengers arrive randomly and independent of the timetable. This is especially important because, as real-time vehicle arrival information becomes more widely available to passengers before they arrive at a stop or station, the assumption of randomly arriving passengers will become a poorer approximation of reality even for high frequency services. The model presented by Bowman & Turnquist (1981), which focuses on bus users but is also applicable to rail, divides passengers into two groups – "aware" passengers and "unaware" passengers. The unaware passengers are assumed to arrive at stops randomly while aware passengers are assumed to arrive at stops during some time interval before a scheduled vehicle arrival based on the utility of arriving the given amount of time before a scheduled vehicle arrival. A logit model is used to generate the probability that aware passengers will arrive in a given time interval before a scheduled vehicle arrival.

Bowman & Turnquist implemented their model with data collected on bus and passenger arrivals during the morning peak period at seven bus stops in Chicago and the neighboring city of Evanston. They found that at almost every stop all passengers fell into the aware passenger category and hypothesize that this is the case due to most morning peak travelers being regular users of their bus route. Thus, it is not surprising that Bowman & Turnquist (1981) found that their average PWT estimates demonstrate "a much greater sensitivity to schedule deviation, and a much lower sensitivity to frequency, than does the random arrival model" because all of their passengers were assumed to arrive at the stop based on the timetable.

2.3 Relevant research completed for the London Underground

Parts of the work of Chan (2007), Uniman (2009), and Paul (2010) relate to the topic of this thesis. Two focuses of Chan (2007) are using Oyster smart card data to measure excess journey time and developing a reliability metric. Both of these are important to this thesis because the first directly relates to LU's Journey Time Metric (JTM), of which PWT is one component, and the second forms the foundation for the work by Uniman (2009) that proposes the addition of a sixth, reliability-based component to JTM. The work by Paul (2010) also provides part of the motivation for this thesis. Therefore, it is important to review her work and discuss how the methods developed in this thesis can improve the methods she proposed.

2.3.1 Oyster-based Journey Time Metric

Chan's Oyster-based method for calculating journey time relies on two components – actual journey time and scheduled journey time. The actual journey time is determined for individual passengers by using the tap-in and tap-out times recorded for each passenger in the Oyster database. The difference between each passenger's actual and scheduled journey times, the calculation of which is explained shortly, gives that passenger's excess journey time. Weighted averages of excess journey time are then calculated at the OD and line levels.

The methodology used by Chan to calculate scheduled journey time differs from the scheduled journey time methodology used for LU's JTM, and Chan acknowledges that the scheduled journey times obtained with these methodologies are not directly comparable. JTM calculates scheduled PWT from all stations in an origin segment to all stations in a destination segment; scheduled on-train time (OTT) is also calculated by line segment. In comparison, Chan's Oyster-based method calculates scheduled PWT by origin station and does not base PWT on only those trains serving a specific origin and destination; excess PWT is defined as the time spent waiting beyond a

full headway, instead of beyond a half headway as used in LU's JTM; and scheduled OTT is calculated for each OD pair instead of by line section. Additionally, scheduled access and egress times in JTM include walk time from a station's entrance through the fare gates to the platform and vice versa for egressing passengers. However, Chan's Oyster-based method eliminates the time spent walking between a station's entrance and the fare gates by using as scheduled access and egress times 85% of the JTM scheduled access and egress times.

In the end, Chan found that three of the five LU lines she studied exhibited a higher Oyster-based excess journey time than JTM-based excess journey time. While Chan's Oyster-based approach to calculating excess journey time offers the advantage of calculating actual journey time based on very disaggregate passenger-level data instead of relying on the more aggregate data used with JTM, Chan's results are difficult to interpret because of the significant differences between the two methods for calculating scheduled journey time. Another weakness of using Oyster data to calculate journey time is that the results produced do not naturally disaggregate journey time into components such as PWT, OTT, and access, egress, and interchange (AEI) times. However, it is possible to estimate each passenger's OTT from NetMIS data and AEI times from the amount of station crowding, with PWT making up the remainder of a passenger's Oyster journey time. Because LU's JTM also uses NetMIS data to calculate OTT and station crowding levels to calculate AEI times, the main advantage that Oyster-based journey time offers over LU's JTM is that the former determines PWT based on passenger data instead of train data.

2.3.2 Quantifying reliability

The second part of Chan (2007) that is relevant to this thesis is her focus on quantifying reliability. Uniman (2009) also reports extensively on quantifying reliability and provides strong motivation for this focus. For the transit agency, improvements in reliability translate into a more efficient service that may include less scheduled slack time and fewer bunched vehicles. Previous researchers have consistently found that passengers consider reliability to be "of substantial importance" (de Jong et al.

(2004)), so improved reliability translates directly into an improved customer experience.

Uniman divides factors that impact reliability into two groups. The first group includes factors that are intrinsic to the agency, such as those that relate to the network (e.g., automatic or manual train control), schedule (e.g., amount of slack time included in the timetable), maintenance, and human actions (e.g., variation in driving technique across train operators). The second group includes factors that are exogenous to the agency, such as weather and medical emergencies. Further, each of these groups of factors can be classified as either persistent or unpredictable.

The development of reliability metrics began with the Journey Time Reliability Factor (JTRF) proposed by Chan (2007). In a manner quite akin to Furth & Muller (2006), Chan develops the JTRF to reflect the idea that passengers are most affected by events in the upper tail of the journey time distribution. Chan defines the JTRF as "the difference between an upper threshold, the Nth percentile journey time, and the median journey time," where the Nth percentile is defined such that passengers view journey times above the Nth percentile as "highly undesirable." Chan proposes $N = 95$.

Uniman (2009) builds on the work of Chan (2007) after concluding that LU's use of PWT to capture the effect of unreliability on passengers does not reflect the full impact of unreliability on passengers. This belief was influenced by Furth & Muller (2006) and motivated Uniman to propose a way to directly incorporate reliability into LU's JTM. To do this, Uniman defines the reliability buffer time (RBT), which "represents the amount of 'buffer' time that needs to be budgeted into one's schedule above the typical travel time," as the "difference between the 95th and 50th percentile travel time." Uniman applies the RBT to three OD pairs on the LU network by deriving journey times from Oyster data from 20 consecutive weekdays in February 2007.

Uniman proposes adding RBT to JTM as its sixth component. RBT would be measured by segment-to-segment OD pair like the other components of JTM, and these results would be aggregated to the line and system levels. The baseline or "scheduled" RBT used to calculate excess RBT would be based on the RBT experi-

enced when a line is operating under consistent, recurrent conditions. Uniman shows the impact of including RBT in the calculation of JTM on LU's Victoria line during the AM peak in February 2007. It is important to note that the JTM components presented by Uniman are based on the component proportions determined by JTM and the median Oyster total travel time instead of the total travel time calculated by JTM. This choice of total travel time source was made to ensure the compatibility of RBT and JTM because JTM is based on different data sources than RBT. It should also be noted that the impact of ticket purchase time (TPT) is normalized out of the JTM results presented by Uniman because TPT is not included in the total travel time derived from Oyster.

Uniman found that passengers on the Victoria line during the AM peak in February 2007 experienced a median total travel time of 16.71 minutes and an RBT of 8.55 minutes, or a perceived journey time of $16.71 + 8.55 = 25.26$ minutes. Further, as the left half of Figure 2-1 shows, 34% of the unweighted journey time was accounted for by RBT. Uniman then produced weighted JTM values by using a value of time weighting for RBT of 0.6, which presents a lower bound for the impact of reliability on perceived journey time and is based on the work of Furth & Muller (2006), while using the JTM-prescribed value of time weightings for all other components. The contribution of RBT to JTM, as shown in the right half of Figure 2-1, decreases to 16% in the weighted version of JTM, reflecting the fact that passengers do not always experience their budgeted travel time as actual travel time.

2.3.3 Assigning passengers to trains

Paul's goal "is to assess the feasibility of identifying which trains individual passengers take to get from their origin to destination while traveling in a high frequency urban rail transportation system." Paul's model, which is created for the specific case of the London Underground, produces estimates of "passenger loads, walk times, and the number of left behind passengers." Paul's work was partially motivated by the assumption in LU's Train Service Model, which is a tool that simulates service on the LU network, that passengers are left behind when the density of passengers on

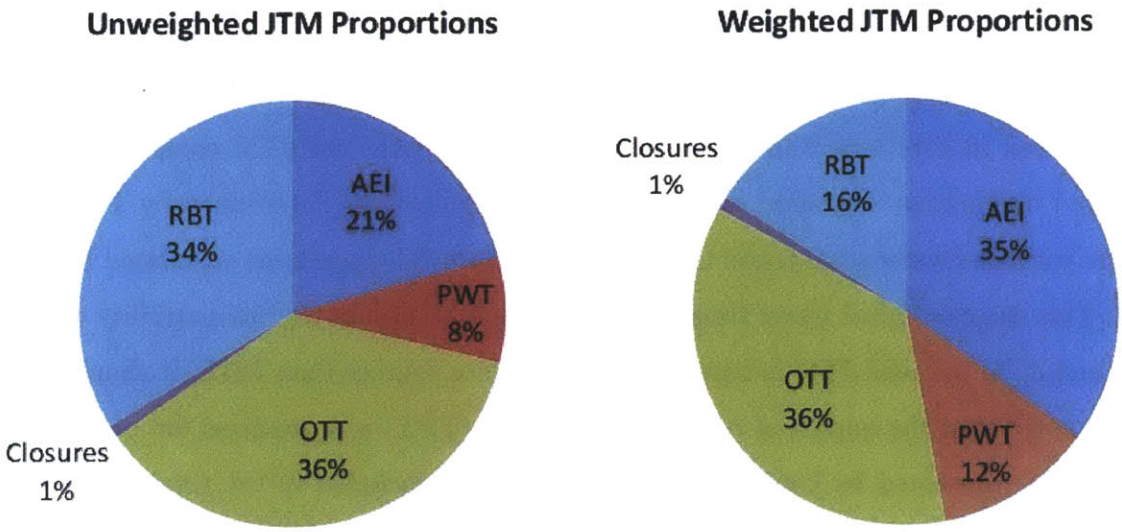


Figure 2-1: Contribution of JTM components and reliability buffer time to perceived journey time (Adapted from Uniman (2009))

a particular train is five passengers per square meter or greater. Paul expects the relationship between train load and left behind passengers "to be a more continuous function" due to passengers' varying willingnesses to board a crowded train.

The model developed by Paul primarily relies on passenger entry and exit information from LU's Oyster smart card database and train tracking data from LU's NetMIS database. Knowing when a passenger entered and exited the system, the model uses train tracking data to determine which trains that passenger feasibly could have taken to get from their origin to destination. When a passenger has more than one possible itinerary, AEI times estimated for each itinerary are used to assign a passenger to a specific train. Once this assignment has been made, walk times and PWT can be estimated for each passenger. Additionally, train loads and the number of left behind passengers at each station can be estimated.

Despite the significant strides Paul made in developing methods for assigning passengers to individual trains based on automatically collected data, Paul's methods suffer from some weaknesses that are usually due to flaws in the data. For example, the Oyster database truncates the seconds associated with timestamps and reports time at the level of minutes; Oyster smart card clocks and the NetMIS train location

clocks are not aligned; NetMIS train tracking data are imperfect due to Train IDs, which are supposed to identify one unique train, that erroneously change mid-trip and Train Events at stations that are not recorded or are missing the departure time; and, due to the complexity of LU's network, multiple route choices often exist between given origin station and destination stations, making it difficult to know a passenger's actual route. Additionally, Oyster data indicating through which gate at a station a passenger entered or exited was not available to Paul. Because many stations have more than one location where passengers can access the station, this lack of data makes it harder to determine AEI times, thus also making it difficult to calculate PWT for individual passengers.

Due to these issues, Paul was forced to make some significant assumptions. As noted in Section 1.1, when a train erroneously receives a new Train ID, passengers who boarded the train before the Train ID changed but alighted after the Train ID changed are assumed to have an on-train time within two minutes of the expected running time given by LU's Route Choice Model (RCM). In cases where NetMIS data are not available at a given station, passengers traveling to or from that station are assumed to experience running times equal to the running times given by RCM. Finally, when a train's arrival time, but not its departure time, is recorded in NetMIS, that train's departure time is set equal to its arrival time. While Paul made some other assumptions, they are not relevant to this research and will not be discussed here. In the end, Paul's model suggested that 26% of passengers were left behind even when there should have been no congestion on the trains. This percentage is much higher than expected and indicates the unreliability of some of the assumptions in Paul's model and that the data integrity issues discussed earlier compromise the model's usefulness.

Paul concludes that her model "does not conclusively indicate" that passengers can be accurately assigned to trains based on her methodology. However, Paul is optimistic that additional research can improve her methods to make the model sufficiently accurate. On another optimistic note, Paul finds that the average egress times calculated from her model match those directly measured by LU staff. This is good

news if a reliable method can be developed for calculating a passenger's access time based on egress time because knowledge about a passenger's access time allows for the calculation of a passenger's PWT.

As it stands now, Paul's method for determining access time is to assume that a passenger's access time is in the same percentile of the access time distribution for all passengers assigned to trains at the access station as the passenger's percentile of the egress time distribution at the destination station. However, this assumption may not be valid due to passengers rushing to catch a train at the origin station but being more relaxed when leaving the destination platform. It should be noted, however, that even if this method for determining access time remains unchanged, using non-truncated Oyster timestamps, the truncated versions of which lack an important level of detail for accurately determining a passenger's AEI times but are expected to be replaced by timestamps reported at the second-level by mid-2011, may improve the accuracy of access time estimation.

Chapter 3

Overview of London Underground

The London Underground (LU) is one of several operating units of Transport for London (TfL), the integrated body responsible for transportation in Greater London. Other units under the TfL umbrella include London Buses, Docklands Light Railway (DLR), London Overground, and the groups in charge of London's taxis, paratransit, congestion charging, and main roads and traffic lights. The Mayor of London serves as the Chairman of the Board of TfL.

An average of more than 28 million journey stages[1] were completed in Greater London daily in 2009. (Transport for London (2010)) More of these journey stages were made on public transport, which includes bus, Underground, DLR, tram, rail, taxis, and private hire vehicles, than any other sector. Figure 3-1[2], which provides a disaggregate view of the mode shares in London in 2009, shows that approximately 10% of journey stages in London are made on the Underground.

More than one billion journeys are made each year across LU's network of 11 lines, 400 km of tracks, and 260 stations.[3] As Figure 3-2 shows, weekday journeys are overwhelmingly concentrated in the morning and evening rush hours while weekend trips are more evenly spread throughout the day. Each of these time periods is

[1]Each one-way trip is composed of one or more journey stages; a new journey stage begins when a traveler changes transport mode.

[2]Percentages presented throughout this chapter may not sum to 100 due to rounding.

[3]The general network and line statistics and histories presented in this chapter come from Transport for London (2011).

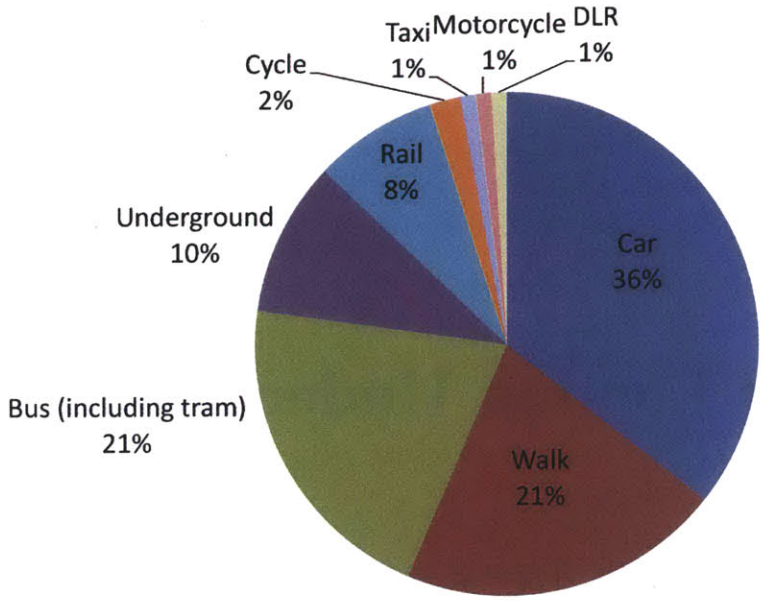


Figure 3-1: Disaggregate mode shares in London (Adapted from Transport for London (2010))

numbered by LU to assist in analysis. For example, the weekday morning peak is timeband 2 and the weekday evening peak is timeband 4. All 13 timebands used by LU are shown in Table 3-1.

For the purposes of this research, LU's lines can be classified based on the quality of their NetMIS data. Lines with good (poor) NetMIS data are those where NetMIS data (do not) allow a reliable reconstruction of the entirety of one trip for a specific train through the use of train identification data and time records at each station served during the trip. For example, departure times recorded at Queen's Park and Waterloo on the Bakerloo line may have been, in reality, associated with the same train, but NetMIS data may not indicate that these departure times belonged to the same train. The classification of LU's lines based on NetMIS data quality is shown in Table 3-2. As discussed in Chapter 4, a slightly different methodology is used to estimate PWT on lines with good and poor NetMIS data.

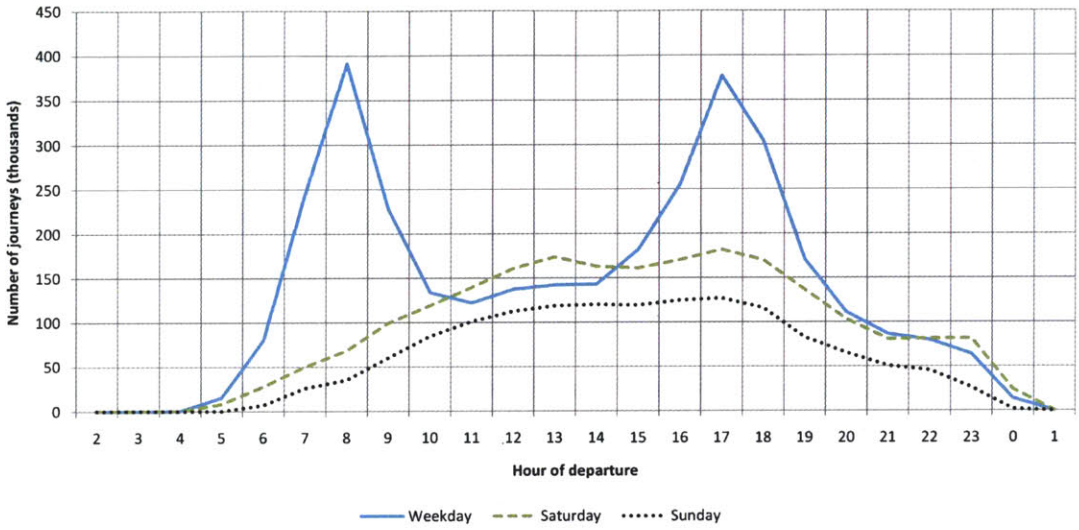


Figure 3-2: Entries on the LU network by hour of departure (Adapted from Transport for London (2007))

Timeband	Day of Week	Time Period	Explanation
1	Monday – Friday	05:30 – 07:00	Early
2	Monday – Friday	07:00 – 10:00	AM Peak
3	Monday – Friday	10:00 – 16:00	Inter-Peak
4	Monday – Friday	16:00 – 19:00	PM Peak
5	Monday – Friday	19:00 – 22:00	Evening
6	Monday – Friday	22:00 – 00:30	Late Evening
7	Saturday	05:30 – 10:00	Morning
8	Saturday	10:00 – 19:00	Midday
9	Saturday	19:00 – 22:00	Evening
10	Saturday	22:00 – 00:30	Late Evening
11	Sunday	07:00 – 10:00	Morning
12	Sunday	10:00 – 19:00	Midday
13	Sunday	19:00 – 00:00	Evening

Table 3-1: Timebands used by London Underground (Adapted from London Underground (2009))

Good NetMIS data	Poor NetMIS data
Bakerloo	Circle
Central	District
Jubilee	Hammersmith & City
Northern	Metropolitan
Victoria	Piccadilly
Waterloo & City	

Table 3-2: Classification of London Underground lines by NetMIS data quality

The two LU lines that are the focus of this thesis are the Bakerloo and Piccadilly lines, which are highlighted in Figure 3-3. The Bakerloo line runs northwest-southeast and the Piccadilly line runs northeast-southwest with two branches in the west. These lines were chosen for analysis because one has good NetMIS data while the other has poor NetMIS data. Additionally, although the planning for signal upgrades on these lines has begun, these upgrades are not expected to happen in the next five years. Therefore, the quality of the train tracking data produced by both lines is not expected to improve in the short run, and the ideas presented in this thesis for completing *ex post facto* data processing of train tracking data to make it more robust will have a longer useful life. It is important to note that, although this research focuses exclusively on the Bakerloo and Piccadilly lines, the methods proposed in this thesis are applicable to all LU lines.

The remainder of this chapter is split into three sections. The first two sections describe the two LU lines – the Bakerloo and Piccadilly lines – that are the focus of this thesis in terms of their scheduled operations and actual ridership. The final section discusses LU's train tracking data and how the train tracking data contribute to the calculation of LU's Journey Time Metric.

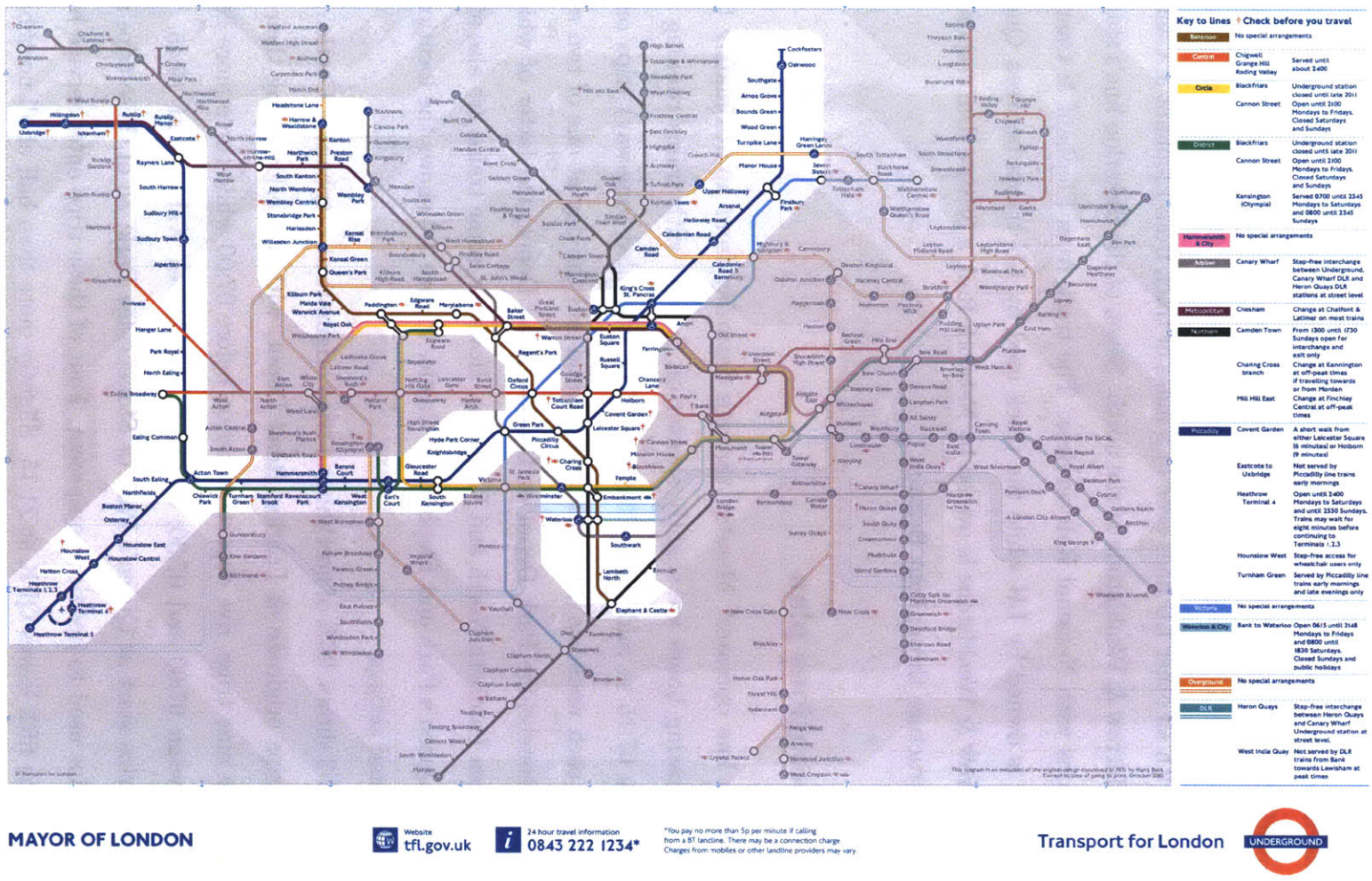


Figure 3-3: London Underground network

3.1 Bakerloo line

The Bakerloo line opened on March 10, 1906, initially running from Baker Street to Lambeth North. The line was extended to Elephant & Castle in 1906 and to Queen's Park in 1915. The Bakerloo line currently serves 25 stations and provides connections with all other LU lines over 14.5 miles of track from Elephant & Castle in the south to Harrow & Wealdstone in the north. Seven of the Bakerloo line's stations offer connections with National Rail services. The track from Elephant & Castle to Queen's Park is owned by LU while the track used by LU trains between Queen's Park and Harrow & Wealdstone is owned by Network Rail, a private firm responsible for rail infrastructure throughout Britain.

3.1.1 Operations plan

The Bakerloo line operates[4] Monday through Saturday from approximately 05:30 to 00:30; operating hours are slightly shorter on Sunday with trains running from approximately 07:15 to midnight. There are 712 scheduled (one-way) trips on the Bakerloo line each weekday. Most trains start and end the day at one of two major depots, the Stonebridge Park Depot or London Road Depot, the latter of which is located between Lambeth North and Waterloo. However, some trains are also stored overnight at Queen's Park and Elephant & Castle. Figure 3-4 shows the locations of these depots and sidings.

As Table 3-3 shows, 96% of northbound trips originate at Elephant & Castle. Nine northbound trips originate at London Road Depot, with Waterloo being their first stop. Of these nine trips, five depart Waterloo before 07:00 while three more depart Waterloo between 07:00 and 07:30; the ninth trip leaves Waterloo at 19:45. Five northbound trips start at Queen's Park or Stonebridge Park; all of these trips serve as pull-out trips used to position equipment. Four of these trips enter service before 06:00 while the fifth leaves QPK at 21:15. Slightly more than half of all northbound

[4]The scheduled operations data presented in this section come from the timetable that was in effect from May 18, 2008 through December 12, 2010.

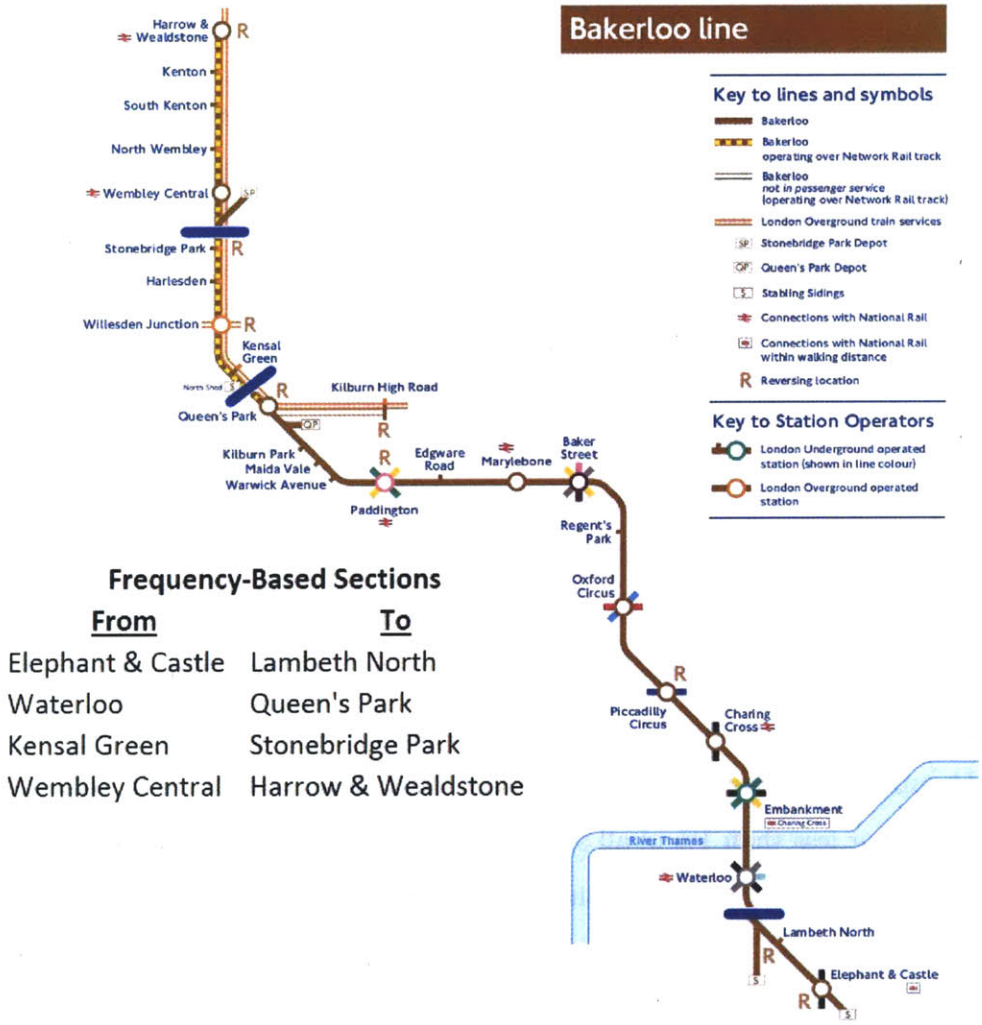


Figure 3-4: Depots, sidings, and frequency-based segments on the Bakerloo line

		Destination					
		ELE	LRDD	QPK	SPK	HAW	Total
Origin	ELE		5 (1%)	183 (51%)	53 (15%)	102 (29%)	343
	LRDD	2 (1%)		4 (1%)	2 (1%)	3 (1%)	11
	QPK	184 (52%)	4 (1%)		2 (1%)	2 (1%)	192
	SPK	54 (15%)	1 (0%)	2 (1%)		1 (0%)	58
	HAW	103 (29%)	1 (0%)	3 (1%)	1 (0%)		108
	Total	343	11	192	58	108	712

See Appendix A.1 for station code definitions

Table 3-3: Scheduled origins and destinations of weekday trips on the Bakerloo line (values in parentheses give the OD pair's percentage of trips in the direction of the OD pair)

trips end at Queen's Park while 17% and 31% of northbound trips end at Stonebridge Park and Harrow & Wealdstone, respectively. The rest of the northbound trips, a total of five trips or 1% of northbound trips, end at Lambeth North before going into the London Road Depot. All five of these trips are pull-in trips that leave Elephant & Castle after midnight.

Table 3-3 also presents similar data for the 355 weekday southbound trips on the Bakerloo line, a (small) majority of which originate at Queen's Park. Another 16% of southbound trips originate at Stonebridge Park, 30% at Harrow & Wealdstone, and two trips, or less than 1% of all southbound trips, at London Road Depot. Both the southbound trips starting at London Road Depot are pull-out trips that begin before 06:00 and enter service at Lambeth North. Nearly 97% of all southbound trips end at Elephant & Castle. Waterloo is the last station served by southbound trips ending at London Road Depot; with the exception of one trip terminating at London Road Depot after leaving Stonebridge Park at 15:30, all southbound trips that end at London Road Depot leave their origin after 23:00. Similarly, five of the six southbound trips ending at Queen's Park or Stonebridge Park leave their origin after midnight.

The Bakerloo line can be split into four segments that receive different frequencies of service. As Figure 3-4 shows, the stations listed in Table 3-3 serve as the segment

Segment	Avg Hdwy
Elephant & Castle to Lambeth North	3.0
Waterloo to Queen's Park	3.0
Kensal Green to Stonebridge Park	6.5
Wembley Central to Harrow & Wealdstone	10.0

Table 3-4: Scheduled weekday headways on the Bakerloo line

boundaries. Table 3-4 illustrates how average headways vary by segment. This data is based on weekday scheduled trips from 07:00 to 22:00; there is no significant variation in average headways within this time period.

3.1.2 Ridership

Table 3-5 illustrates how weekly demand is distributed over the weekday 07:00 to 22:00 time period. The timeband-level demand weightings (e.g., 0.21 during timeband 2) are calculated using passenger demand data from LU's 2002[5] Rolling Origin Destination Survey (RODS), which combines responses from a passenger survey with automatically collected gateline counts to produce an OD matrix for the entire LU network.[6] The RODS data are used to calculate the number of passenger entries on a specific line during any of LU's timebands, where entries during the weekday timebands are multiplied by five to allow for the calculation of weekly demand weightings. The timeband-level demand weighting is then the ratio of entries during a timeband to total weekly entries on the line. Table 3-5 shows that 77% of demand on the Bakerloo line occurs on weekdays from 07:00 to 22:00.

Table 3-5 also shows how demand is distributed along the Bakerloo line during the four timebands that make up the 07:00 to 22:00 time period. These four timebands are the four most heavily traveled timebands over the week. The demand weightings, which are again based on data from RODS, give the proportion of passengers who use the line during the given timeband and board in the *from* segment and alight in the

[5]Ridership data from 2002 are used because these data are being used by LU until April 2011 to weight the PWT experienced by passengers based on origin, destination, and timeband.

[6]See Chan (2007) and Paul (2010) for a more detailed description of RODS.

		Timeband			
From	**To**	**2**	**3**	**4**	**5**
Harrow & Wealdstone	Wembley Central	0.00	0.00	0.00	0.00
Harrow & Wealdstone	Kensal Green	0.01	0.01	0.02	0.01
Harrow & Wealdstone	Waterloo	0.02	0.01	0.01	0.01
Harrow & Wealdstone	Elephant & Castle	0.00	0.00	0.00	0.00
Stonebridge Park	Kensal Green	0.01	0.01	0.01	0.00
Stonebridge Park	Waterloo	0.08	0.03	0.01	0.01
Stonebridge Park	Elephant & Castle	0.00	0.02	0.00	0.00
Queen's Park	Waterloo	0.42	0.40	0.41	0.39
Queen's Park	Elephant & Castle	0.03	0.04	0.05	0.06
Lambeth North	Elephant & Castle	0.00	0.00	0.00	0.00
Elephant & Castle	Lambeth North	0.00	0.00	0.00	0.00
Elephant & Castle	Queen's Park	0.04	0.05	0.04	0.04
Elephant & Castle	Stonebridge Park	0.00	0.00	0.00	0.00
Elephant & Castle	Harrow & Wealdstone	0.00	0.00	0.00	0.00
Waterloo	Queen's Park	0.31	0.35	0.37	0.40
Waterloo	Stonebridge Park	0.03	0.04	0.04	0.03
Waterloo	Harrow & Wealdstone	0.01	0.02	0.02	0.01
Kensal Green	Stonebridge Park	0.00	0.00	0.00	0.02
Kensal Green	Harrow & Wealdstone	0.01	0.01	0.02	0.01
Wembley Central	Harrow & Wealdstone	0.00	0.01	0.00	0.00
	Timeband Weight	0.21	0.23	0.23	0.10

Table 3-5: Demand weightings for the Bakerloo line by origin, destination, and timeband

to segment; the segments are the same as those given in Table 3-4. As an example, 42% of passengers traveling during timeband 2 board *and* alight at a station between Queen's Park and Waterloo while 3% of passengers traveling during timeband 2 board at a station between Queen's Park and Waterloo and alight at Lambeth North or Elephant & Castle. In the northbound direction, 2% of timeband 4 passengers board between Kensal Green and Stonebridge Park and alight between Wembley Central and Harrow & Wealdstone while 4% of timeband 4 passengers board between Waterloo and Queen's Park and alight between Kensal Green and Stonebridge Park. Overall, a large majority of passengers board and/or alight in the central segment of the Bakerloo line from Waterloo to Queen's Park.

3.2 Piccadilly line

The Piccadilly line, which initially provided service from Finsbury Park to Hammersmith, opened on December 15, 1906. The line was extended to two of its three current termini, Uxbridge and Cockfosters, in 1933. Service to Heathrow Terminals 1, 2, 3 began in 1975 while stations opened at Heathrow Terminals 4 and 5 in 1986 and 2008, respectively. The 44.3 mile long Piccadilly line provides service to 52 stations, 27 of which lie on the trunk portion of the line between Cockfosters and Acton Town, and has direct connections with all LU lines except the Waterloo & City line. The Piccadilly line also provides connections with National Rail services at King's Cross St. Pancras and Finsbury Park.

3.2.1 Operations plan

The Piccadilly line operates[7] from approximately 05:30 to 00:30 on weekdays and Saturday and from approximately 07:00 to midnight on Sunday. Service consists of 894 scheduled (one-way) weekday trips. Figure 3-5 shows where depots and sidings are located on the Piccadilly line. The two main overnight train storage locations

[7]The scheduled operations data presented in this section come from the timetable that was in effect from December 13, 2009 through December 12, 2010.

Figure 3-5: Depots, sidings, and frequency-based segments on the Piccadilly line

for the Piccadilly line are Northfields Depot, which can be accessed from the Boston Manor and Northfields stations, and Cockfosters Depot, which can be accessed from the Oakwood and Cockfosters stations. Additional trains start and end service at the South Harrow Sidings and the Arnos Grove Sidings while one train is stored at each of the Acton Town Sidings and Uxbridge Sidings.

Table 3-6 presents the scheduled origins and destinations of the 894 scheduled weekday trips on the Piccadilly line. Because there are a large number of scheduled origins and destinations on the Piccadilly line, a few origins and destinations have been excluded from Table 3-6 to make it more readable. The timetable indicates that only one trip is scheduled to start and end at each of three stations – Green Park,

Hounslow Central, and Hatton Cross – that are excluded from the table; all of these trips are scheduled to occur after 23:30. Additionally, Hammersmith is excluded from this table because only 12 scheduled trips start or end at this station; all of these trips occur before 06:45 or after midnight. Finally, the three Heathrow stations have been combined into one category, abbreviated by HRA, to make the table easier to read.

As shown in Table 3-6, approximately 67% of scheduled westbound trips begin at Cockfosters while 17% begin at Arnos Grove. The remaining scheduled westbound trips begin at Acton Town, Oakwood, Northfields Depot, and South Harrow. Approximately 91% of scheduled westbound trips end at Heathrow (51%), Rayners Lane (14%), Uxbridge (14%), and Northfields Depot (12%). Eight of the 13 trips scheduled to end at Ruislip leave their origin between 07:00 and 22:00 while all seven westbound trips ending at Arnos Grove leave their origin before 06:00 or after midnight.

In the eastbound direction, 65% of scheduled trips begin at one of the western termini, with 51% beginning at Heathrow and 14% at Uxbridge. Another 16% begin at Rayners Lane and 11% begin at Northfields Depot. The origins of the remaining eastbound trips are allocated between Ruislip (13 trips, all beginning after 07:00 and before 22:00), Arnos Grove (five trips, all departing before 06:15), South Harrow (three trips, only one departing outside of the 07:00 – 22:00 window), and Acton Town (one trip departing at 22:10). The majority of scheduled eastbound trips end at Cockfosters (67%) while another 17%, 5%, and 3% end at Arnos Grove, Acton Town, and Northfields Depot, respectively. Two percent of the scheduled eastbound trips end at Oakwood and 1% at South Harrow, with most of these trips departing their origin before 05:30 or after 22:00.

All stations within each of the seven segments of the Piccadilly line receive the same service frequency in both directions. These segments, which are shown in Figure 3-5, vary in length from two to 24 stations. The average scheduled headways in each segment during the four weekday timebands from 07:00 to 22:00 are presented

		Destination										
		CFS	OAK	AGR	ACT	NFDD	HRA	SHR	RLN	RUI	UXB	Total
Origin	CFS		0 (0%)	6 (1%)	0 (0%)	33 (7%)	167 (38%)	0 (0%)	42 (9%)	5 (1%)	48 (11%)	301
	OAK	0 (0%)		1 (0%)	0 (0%)	0 (0%)	8 (2%)	0 (0%)	5 (1%)	1 (0%)	4 (1%)	19
	AGR	4 (1%)	1 (0%)		0 (0%)	13 (3%)	42 (9%)	0 (0%)	14 (3%)	3 (1%)	6 (1%)	83
	ACT	0 (0%)	1 (0%)	0 (0%)		9 (2%)	2 (0%)	0 (0%)	6 (1%)	2 (0%)	6 (1%)	26
	NFDD	11 (2%)	1 (0%)	29 (6%)	13 (3%)		10 (2%)					64
	HRA	180 (40%)	2 (0%)	35 (8%)	2 (0%)	12 (3%)						231
	SHR	0 (0%)	0 (0%)	1 (0%)	2 (0%)				0 (0%)	2 (0%)	1 (0%)	6
	RLN	48 (11%)	3 (1%)	7 (2%)	5 (1%)			6 (1%)		0 (0%)	0 (0%)	69
	RUI	11 (2%)	1 (0%)	1 (0%)	0 (0%)			0 (0%)	0 (0%)		0 (0%)	13
	UXB	51 (11%)	5 (1%)	4 (1%)	5 (1%)			0 (0%)	0 (0%)	0 (0%)		65
	Total	305	14	84	27	67	229	6	67	13	65	877

See Appendix A.2 for station code definitions

Table 3-6: Scheduled origins and destinations of weekday trips on the Piccadilly line (values in parentheses give the OD pair's percentage of trips in the direction of the OD pair)

	Average Headway			
Segment	**2**	**3**	**4**	**5**
Cockfosters to Southgate	4.0	3.5	3.5	3.5
Arnos Grove to Acton Town	2.5	3.0	2.5	3.0
South Ealing to Northfields	4.5	4.0	4.0	4.5
Boston Manor to Hatton Cross	5.0	5.0	5.0	5.0
Heathrow*	10.0	10.0	10.0	10.0
Ealing Common to Rayners Lane	5.5	9.0	7.0	7.5
Eastcote to Ruislip	9.0	17.5	12.0	15.0
Ickenham to Uxbridge	15.0	18.0	16.5	15.5

*Average headways eastbound at Heathrow Terminals 1, 2, 3 are half those presented in this table because trains originating from both Heathrow Terminal 4 and Terminal 5 provide service to Terminals 1, 2, 3.

Table 3-7: Scheduled weekday headways on the Piccadilly line

in Table 3-7. As this table shows, average scheduled headways vary significantly by timeband on the Uxbridge branch, but not on the main line or Heathrow branch.

3.2.2 Ridership

Table 3-8 shows the distribution of demand on the Piccadilly line for the four weekday timebands from 07:00 to 22:00. The data in this table is based on ridership data from 2002 and shows that 72% of weekly demand occurs from 07:00 to 22:00. This table also illustrates how demand is distributed by origin and destination during timebands 2 through 5. As was the case with the analagous table for the Bakerloo line, these weightings are derived from RODS data and represent the proportion of passengers traveling in the given timeband who board in the *from* segment and alight in the *to* segment. The segments are the same as those given in Table 3-7 except that a few of the segments presented in Table 3-7 are combined for a more manageable number of OD pairs. Specifically, the entire Heathrow branch is one segment and all stations from Eastcote to Uxbridge make up one segment. One more important note is that passengers traveling from one branch to the other branch have their trips included in the segment-to-segment OD pair that ends at Ealing Common or South Ealing

because these passengers will transfer at Acton Town and all trains serving Ealing Common and South Ealing continue to Acton Town. Table 3-8 indicates that the two heaviest traveled segment-to-segment OD pairs are from Arnos Grove to Acton Town and Acton Town to Arnos Grove; the third and fourth heaviest traveled segment-to-segment OD pairs run from Heathrow to Arnos Grove and Arnos Grove to Heathrow.

3.3 London Underground train tracking data

3.3.1 Data collection process

Data included in the NetMIS database, intended to include train identification, arrival time, and departure time for every train at every station in the LU network, are transferred between several systems before entering the NetMIS database. This data transfer process is shown schematically in Figure 3-6. To begin, track circuits indicate whether a given track segment is occupied by a train. These track circuit data are sent to a signaling computer, and the signaling computer sends its data to the TrackerNet database. Finally, because track circuits do not match station platforms exactly, slight adjustments are made to the TrackerNet data, which indicate when individual track circuits are occupied, to produce the NetMIS data that indicate when stations are occupied by trains. The rest of this section will explain these processes in more detail.

Track circuits

The collection of NetMIS data begins with track circuits. Track circuits are defined by electrical circuits that correspond to specific segments of track. Track circuits are laid out in a contiguous fashion throughout the LU network; tracks owned by Network Rail have longer track circuits than tracks owned by LU. When a train crosses into a new track circuit, the electrical circuit is shorted, indicating to the signaling system that a train is occupying the track circuit. Once the train leaves the track circuit, a

		Timeband			
From	**To**	**2**	**3**	**4**	**5**
Cockfosters	Southgate	0.00	0.00	0.00	0.00
Cockfosters	Acton Town	0.04	0.02	0.01	0.01
Cockfosters	Heathrow	0.00	0.00	0.00	0.00
Cockfosters	Rayners Lane	0.00	0.00	0.00	0.00
Cockfosters	Uxbridge	0.00	0.00	0.00	0.00
Arnos Grove	Acton Town	0.44	0.40	0.34	0.36
Arnos Grove	Heathrow	0.04	0.05	0.07	0.06
Arnos Grove	Rayners Lane	0.01	0.02	0.04	0.02
Arnos Grove	Uxbridge	0.00	0.00	0.00	0.00
South Ealing	Heathrow	0.02	0.01	0.01	0.01
Ealing Common	Rayners Lane	0.01	0.00	0.01	0.01
Ealing Common	Uxbridge	0.00	0.00	0.00	0.00
Eastcote	Uxbridge	0.00	0.00	0.00	0.00
Uxbridge	Eastcote	0.00	0.00	0.00	0.00
Uxbridge	Ealing Comming	0.00	0.00	0.00	0.00
Uxbridge	Arnos Grove	0.01	0.00	0.00	0.00
Uxbridge	Cockfosters	0.00	0.00	0.00	0.00
Rayners Lane	Ealing Common	0.02	0.01	0.01	0.01
Rayners Lane	Arnos Grove	0.05	0.02	0.01	0.01
Rayners Lane	Cockfosters	0.00	0.00	0.00	0.00
Heathrow	South Ealing	0.01	0.01	0.01	0.02
Heathrow	Arnos Grove	0.09	0.06	0.04	0.03
Heathrow	Cockfosters	0.00	0.00	0.00	0.00
Acton Town	Arnos Grove	0.26	0.38	0.42	0.46
Acton Town	Cockfosters	0.01	0.02	0.03	0.01
Southgate	Cockfosters	0.00	0.00	0.00	0.00
	Timeband Weight	0.18	0.23	0.21	0.10

Table 3-8: Demand weightings for the Piccadilly line by origin, destination, and timeband

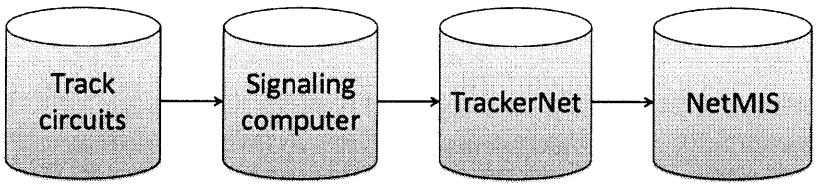


Figure 3-6: London Underground train tracking data transfer process

complete electrical circuit exists and the signaling system recognizes that there is no train in the track circuit.[8]

Signaling computer

On six of the 11 LU lines, track circuit data are transferred to a central signaling computer that holds track circuit data for the entire line. However, on the Piccadilly, Circle, District, and Hammersmith & City lines as well as on the northern part of the Metropolitan line beginning between Wembley Park and Preston Road, there is no central control system. As a result, the track circuit data are sent to one of a number of smaller computers located along the line. The non-central signaling computers on a specific line are not linked, so problems sometimes arise at the boundary points when a different signaling computer begins receiving the track circuit data. In the case of the Piccadilly line, there are seven track segments that provide signaling data to non-central signaling computers. Two of these track segments provide data to the

[8]See London Underground Operational Learning (2010) for a more detailed description of track circuits.

same signaling computer although these two segments are on different parts of the line – one is on the Uxbridge branch while the other is on the eastern part of the main line. Thus, there are six non-central signaling computers on the Piccadilly line that provide data to TrackerNet.

One of the problems associated with non-central signaling computers involves the identification of trains when they cross these signaling computer boundaries. Because the signaling computers are not linked, train identification information does not always follow each individual train as it crosses a signaling computer boundary. As a result, trains must be matched when data are sent from the individual signaling computers to TrackerNet. TrackerNet matches trains when they cross the boundary between two signaling computers by looking at time records associated with train events. This matching process is best demonstrated through an example. Consider contiguous signaling segments A and B and the situation where Train 1 is recorded at the last track circuit in segment A at time t. Then, the first train event to occur in the first track circuit in segment B after time t will be recorded as Train 1. The boundaries between signaling segments are located at places where trains must run through to the next station. Thus, it can be said with certainty that the next train observed in the following segment was the last train to leave the previous segment.

Problems can arise when the clocks on the computers for contiguous signaling segments are misaligned. When clocks are misaligned, it is possible for Train IDs to get reassigned. For example, consider the situation where signaling computer A receives the track circuit data from track segment A, signaling computer B receives the track circuit data from track segment B, and track segments A and B are contiguous. If the clock on signaling computer A is five seconds ahead of the clock on signaling computer B, a train that passes from track segment A to track segment B will appear from the data to be in both track segments at the same time. That is, the train will exit track segment A at time x but will appear in track segment B at time $x - 5$ seconds. Because track segments A and B are contiguous, it will appear that the train was in both segments for five seconds. When this happens, TrackerNet may

not recognize that these two Train Events in segments A and B belong to the same physical train.

TrackerNet

Once the signaling computers have received data from the track circuits, the signaling computers send their data to TrackerNet. One important aspect of this transmission process is that a train event's timestamp in TrackerNet is not the time at which the train entered a track circuit. Instead, an event's timestamp in TrackerNet corresponds with the time that TrackerNet received the event's data from the signaling computer. While this manner in which NetMIS assigns timestamps usually has only a negligible impact on the NetMIS data, there have been instances where slow data transmission has meant that NetMIS indicates that an event occurred significantly later than it did in reality.

NetMIS

Two main processes are completed to transform the track circuit information in the TrackerNet database into the station-level information in NetMIS. The first process references a database to match track circuits with specific, named locations, including stations, sidings, and depots. The second process revises the track circuit entry and exit times recorded in TrackerNet. These revisions are necessary because track circuits do not correspond exactly with station platforms. In order to get the desired wheel stop and wheel start times at station platforms, station-specific offset times are applied to the times recorded by track circuits.

In most cases, the station arrival offset times are the time between a train exiting the track circuit immediately preceding a station platform and the train's wheels stopping. Similarly, when trains depart a station, these offset times usually are the time between a train's wheels starting to turn and the train entering the track circuit immediately after the platform. However, in a small number of cases where multiple track circuits coincide with a station platform, the offset time is applied to track circuit occupation times in a manner that minimizes the required wheel stop and

wheel start offset times. The offset times are station-specific and were generated by calculating the average difference between manually recorded wheel stop and wheel start times and those times recorded automatically by the track circuits. Offset times are updated annually and after station modifications and rolling stock changes.

There are some portions of lines that do not have any NetMIS data because these track segments are controlled completely automatically. Segments without NetMIS data exist on the Circle, District, Hammersmith & City, and Metropolitan lines. Because no person monitors the service on these segments of track in real-time, the signaling computers do not collect any track circuit data. As a result, the data do not exist with which to populate the NetMIS database. A possible way to workaround this lack of track circuit data involves using the radio data transmitted by LU trains. This process would work as follows. A radio cell surrounds each station. In theory, the boundary of a radio cell should be halfway between two stations. If this were always the case, the radio data could be used to determine the time at which a train crossed the radio cell boundary. The problem is that the location of radio cell boundaries is known to shift based on the weather. As a result, LU has determined that radio data do not provide sufficiently accurate or consistent train location data. Thus, all time and location data in NetMIS originate from track circuit data.

Although the radio data are not used to determine train location, they are used to provide two pieces of data in the NetMIS database: train number and leading car number. The leading car number always comes from the radio data; the train number comes from the radio data if there is no central signaling computer or if there is no train number recorded in the central signaling computer. These two pieces of information are only recorded if a train's radio data is successfully matched with that same train's track circuit data. This matching process requires that a train is the only train in a radio cell for two consecutive radio cells. Once this occurs, the signaling computer associates the train's train number and leading car number with its track circuit data. If the radio system is functioning properly, it should take only two stations for a train's train number and leading car number to become associated with its track circuit data.

3.3.2 Use of NetMIS data in the Journey Time Metric

One major use of train tracking data at the London Underground is in the calculation of certain components of the Journey Time Metric (JTM). This section begins with a review of LU's JTM and concludes by highlighting how NetMIS data contribute to JTM and how LU staff use JTM results and NetMIS data.

LU's JTM[9], introduced in July 1997, measures the time passengers spend in the LU system, from entering the origin station to exiting the destination station. Part of the motivation for using JTM is that it provides a means to measure the impacts of operations and infrastructure changes. For example, did a new timetable reduce PWT? Did signal upgrades reduce on train time? JTM results are produced for each of the 13 four-week periods that comprise one calendar year.

Five factors contribute to JTM. Two of these factors – PWT and On Train Time (OTT) – and two of the three elements of the Access, Egress, and Interchange (AEI) time component of JTM apply to every passenger's journey. The fourth component of JTM – Ticket Purchase Time (TPT) – applies only to a subset of all passengers, and the fifth component of JTM – Closures – accounts for changes to journey time resulting from planned closures and unplanned service disruptions. When closures last at least two weeks and are announced at least two weeks beforehand, any resulting additional journey time counts as scheduled journey time; in all other cases of planned closures and unplanned service disruptions, additional journey time counts as actual journey time. Further, when unplanned service disruptions and closures last more than 30 minutes, the scheduled values for PWT and OTT are used as the actual values in JTM. The PWT and OTT that exist beyond the scheduled amounts are then accounted for in the Closures component of JTM.

Two values – scheduled and actual – are calculated for the PWT, OTT, AEI, and TPT components of JTM. Times are computed in both unweighted and weighted forms, with the weighted times based on value of time (VOT) weights that LU has developed for the various portions of a passenger's journey. These weights indicate

[9]See London Underground (2009) and London Transport (1999) for more information on LU's JTM.

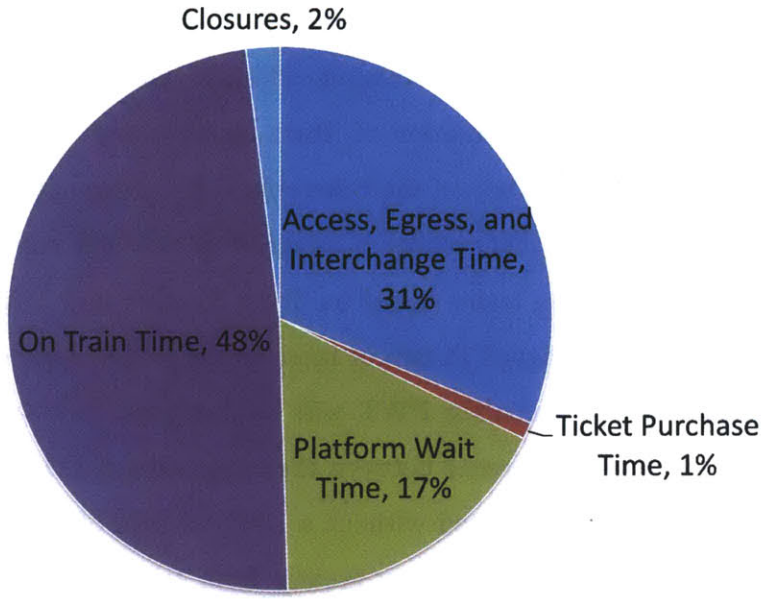


Figure 3-7: Distribution of weighted journey time between the five JTM components (Adapted from London Underground (2009))

how onerous passengers find specific parts of their journey. For example, time spent waiting on a platform has a VOT weighting of two, time spent walking up stairs has a VOT weighting of four, and the VOT weighting for time spent traveling on a train varies based on level of crowding. The OTT weights range from 1 to 2.4, where a weight of 1 is used if there are enough seats for all passengers. Therefore, traveling on an uncrowded train serves as the base from which all other VOT weights are determined. Figure 3-7 shows the distribution of weighted journey time between the five JTM components as of January 2009. The excess time for each component is calculated for unweighted and weighted values by subtracting the scheduled time from the actual time.

The time and train identification data provided by NetMIS are required to determine the OTT and PWT components of JTM. The time data are used to calculate OTT and PWT while the train identification data are used to verify that a train observed at an origin reached a specific destination. In the case of OTT, a specific train's

Train ID is required to match between the start and end of a track segment on nearly all segments of all lines; if Train IDs are known to be unreliable on a specific segment, trains are matched based on Train Number, which is different than a Train ID, and Trip Number, where the combination of Train Number and Trip Number links an actual trip with a scheduled trip in the timetable. The advantage of matching trains based on Train ID is that this number is assigned to only one train on a given day; the problem with matching trains based on Train Number and Trip Number is that these numbers may be assigned to two or more trains on the same day.

The process used to calculate PWT will be discussed in detail in Section 4.1. However, one important difference between the calculation of OTT and PWT is that OTT can be accurately calculated without a 100% sample of OTTs experienced by all trains because OTT does not vary greatly from trip to trip. However, having an incomplete set of NetMIS data causes problems when calculating PWT because missing just one record of a train at a station will lead to the calculation of a higher-than-actual PWT at that station.

The outputs from JTM are disseminated throughout LU and are posted on LU's website. The results published internally allow staff to examine how a specific line, or the entire network, performed over different time periods. For example, JTM results could be analyzed over all timebands and days in a four-week period or on the more disaggregate level of line, day, and timeband. One main set of internal users of JTM are managers of individual lines who use JTM results to identify performance issues on their lines. Once a particular issue has been identified, LU staff may try to diagnose the problem by looking at records of past service disruptions or may choose to analyze NetMIS data to get a better idea about the specifics of service delivery during a given time period. This analysis of NetMIS data may include a focus on Train Numbers and Trip Numbers to determine what happened to a scheduled trip or it may include a focus on Train ID to determine what happened to a specific train.

Chapter 4

London Underground's platform wait time methodology

As mentioned in Section 2.2, passengers tend to perceive waiting times as being longer than they really are. Therefore, estimating the average PWT experienced by customers provides LU with a passenger-centric metric for quantifying one of the parts of a journey that passengers find most onerous. Additionally, PWT accounts for 17% of passengers' weighted journey time on the Underground (see Figure 3-7), a sizable portion of LU passengers' total weighted journey time. This chapter explains how LU currently calculates average PWT then presents results from using LU's PWT estimation method over the four-week period from July 25, 2010 through August 21, 2010.

Before introducing LU's method for estimating PWT, a few terms related to NetMIS data need to be defined. Figure 4-1 provides a sample of NetMIS data from the Bakerloo line that will be used to help define these terms. A Train Event, or simply "event", is one entry in the NetMIS database and provides data for a train at one station; each Train Event has a unique Train Event ID. The Arrival Time and Depart Time fields give the wheel stop and wheel start times, respectively, of the train at the station listed in the Station field. The Train ID field contains a seven-digit number; although one train may be assigned two or more Train IDs on a specific day, each Train ID is assigned to only one train each day. A Train ID block,

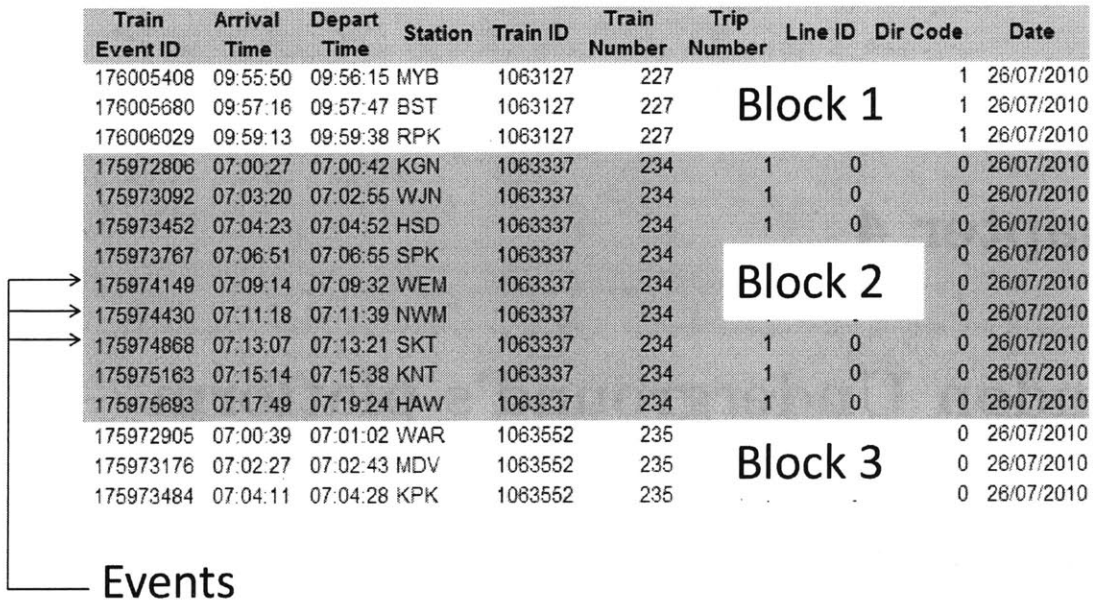


Figure 4-1: Sample NetMIS data

or simply "block", consists of all Train Events that have the same Train ID. When used together, Train Number and Trip Number identify a specific scheduled trip in the timetable; the Train Number identifies a scheduled train while the Trip Number increments by one each time a train reverses. The final three fields in Figure 4-1 identify the line, direction, and date associated with a Train Event.

4.1 Methodology

LU defines PWT as "the time from customer arrival at midpoint of a platform to wheel start of boarded train." (London Underground (2009)) PWT is calculated for segments of a line and depends on passengers' destinations. Thus, passengers departing from the same station but traveling to different stations may have different platform wait times. For example, passengers traveling on the Piccadilly Line from Russell Square to Green Park likely have a different PWT than passengers traveling from Russell Square to Uxbridge because not all trains that go to Green Park continue to Uxbridge. Data from the NetMIS database, including train identification informa-

tion, arrival times, and departure times, are used to estimate actual PWT. Scheduled PWT is the average PWT passengers would experience if a line were running exactly on schedule and is calculated based on a line's published timetable. The difference between actual PWT and scheduled PWT is excess PWT.

As discussed in Chapter 3 and shown in Table 3-2, LU lines are classified based on the quality of their NetMIS data. Specifically, lines with good NetMIS data (e.g., the Bakerloo line) are those where a train recorded at an origin can be reliably matched with a train recorded at a destination by using Train ID or the combination of Train Number and Trip Number; this reliable matching of trains is not possible on lines with poor NetMIS data (e.g., the Piccadilly line). Although the quality of a line's NetMIS data determines the exact processes used to estimate PWT on that line, the same general procedures are used to estimate PWT on all lines. The following list outlines the PWT estimation steps used for all lines. The rest of this section explains each of these steps in more detail.

1. Divide each line into frequency-based segments, define segment-to-segment OD groups, and choose a representative PWT station for each segment-to-segment OD group.

2. Average PWT is a function of departure headways, and departure headways are a function of departure times. This step ensures that the departure times used to calculate average PWT at a representative PWT station correspond as closely as possible with trains that served all stations in a segment-to-segment OD group.

3. The final step uses the average PWT formula (Equation (2.2)) to estimate average PWT for a specific segment-to-segment OD, timeband, and day. These results are then aggregated to the timeband, line, and network levels.

4.1.1 Choosing representative PWT stations

Before selecting representative PWT stations, segments are created based on train frequency. That is, "each line is subdivided into sections where the scheduled service

frequency is normally the same." (London Underground (2009)) After defining the segments on each line, segment-to-segment OD groups are created to account for all possible station-to-station OD pairs. The term *group* is used instead of *pair* because each OD group may consist of multiple segment-to-segment OD pairs. That is, stations included in the origin and/or destination portions of an OD group may come from more than one segment. Because transfers are accounted for at the end of the JTM calculation process, all segment-to-segment OD groups consist only of stations on the same line.

One station in each segment-to-segment OD group is selected to serve as the representative PWT station for that OD group. LU assumes that all passengers boarding in a segment-to-segment OD group experience the same PWT as the passengers at the representative PWT station. When selecting the representative PWT station, LU staff ensure that the chosen station has consistently recorded NetMIS data. If some trains are not recorded in NetMIS at a specific station or if a train's direction is not accurately recorded at a specific station, then that station will not be selected as a representative PWT station.

Lines with good NetMIS data

The default representative PWT station on lines with good NetMIS data is the first station in the origin segment. If the first station does not have consistently recorded NetMIS data, then the next station in the same segment that has high quality NetMIS data is selected as the representative PWT station. Because LU determines PWT based on destination as well as origin, a representative destination station in each destination segment also must be selected. The NetMIS data at this representative destination station are used to verify that a train actually reached that station. The preferred representative destination station is the last station in a segment. However, if this station does not have consistently recorded NetMIS data, then the closest preceding station with consistently recorded NetMIS data is chosen instead.

Figure 3-4 showed the four segments, which are separated by blue lines, for the Bakerloo line. Scheduled weekday headways on each of the segments were presented in

OD	Origin stations	Destination stations	Representative PWT station	Representative destination station
1	HAW–WEM	HAW–WLO	HAW	WLO
2	HAW–WEM	LAM–ELE	HAW	ELE
3	SPK–KGN	SPK–WLO	SPK	WLO
4	SPK–KGN	LAM–ELE	SPK	ELE
5	QPK–EMB	QPK–WLO	QPK	WLO
6	QPK–LAM	LAM–ELE	QPK	ELE
7	ELE–LAM	ELE–QPK	LAM	QPK
8	ELE–LAM	KGN–SPK	LAM	SPK
9	ELE–LAM	WEM–HAW	LAM	HAW
10	WLO–KPK	WLO–QPK	WLO	QPK
11	WLO–HSD	KGN–SPK	WLO	SPK
12	WLO–KNT	WEM–HAW	WLO	HAW

Table 4-1: Bakerloo line segment-to-segment OD groups

Table 3-4. Table 4-1 presents the segment-to-segment OD groups on the Bakerloo line and the representative PWT station used in each group. Passengers boarding at all stations listed in the "Origin stations" column are assumed to have the same PWT. The stations included in the "Destination stations" column are used to determine ridership on each OD, which is then used to calculate the demand weightings to apply to each OD. The "Representative PWT station" column provides the station at which NetMIS data are used to calculate average PWT for the given OD group while the "Representative destination station" column lists the station used to verify that a train reached the destination segment. Station codes are listed in Appendix A.1.

Table 4-1 shows that, for example, in the northbound direction, PWT in the two-station Elephant & Castle segment is based on NetMIS data at Lambeth North. This is because the departure times of northbound trains are not recorded at Elephant & Castle. Further, Figure 3-4 shows that southbound trains that originated at Queen's Park are checked to determine if they terminated at Waterloo or Elephant & Castle. If a train that originated at Queen's Park terminated at Waterloo, then that train is excluded from the calculation of PWT experienced by passengers traveling from any station south of Queen's Park to Lambeth North or Elephant & Castle.

Lines with poor NetMIS data

As was the case with lines with good NetMIS data, a representative PWT station that has consistently recorded NetMIS data is chosen for each segment-to-segment OD group on lines with poor NetMIS data. In the first of two possible scenarios on lines with poor NetMIS data, this representative PWT station is located in the origin segment. In this first scenario, each segment-to-segment OD group has one representative PWT station in the origin segment and one or more representative destination stations in the destination segment. Then, a train recorded at the representative PWT station only contributes to the estimation of PWT if the scheduled destination of that train, as recorded in NetMIS, is one of the representative destination stations.[1] In the second scenario, the representative PWT station is located in the segment of a segment-to-segment OD group that receives the lowest frequency of service. Although most representative PWT stations in the LU network are located in the origin segment, all of these stations are referred to as representative *PWT* stations throughout this thesis instead of representative *origin* stations to account for the cases where the representative PWT station is located in the destination segment. No representative destination station is used in this second scenario.

Figure 3-5 showed the frequency-based segments defined by LU for the Piccadilly line. LU's frequency-based segments generally correspond with the frequency-based segments presented in Table 3-7, but LU includes the Heathrow stations in the Boston Manor to Hatton Cross segment and combines the Eastcote to Ruislip and Ickenham to Uxbridge segments. Table 4-2 lists the 18 Piccadilly line segment-to-segment OD groups used with LU's PWT methodology; station codes are listed in Appendix A.2. For all but one of the segment-to-segment OD groups used to calculate PWT on the Piccadilly line, the second scenario listed in the previous paragraph applies. Table 4-2 shows that, for example, westbound passengers boarding at stations from Arnos Grove to Acton Town and alighting at stations in the same segment are assumed to expe-

[1] More than one representative destination station is used when a destination segment does not include the last station on the line/branch because this segment will be served by trains that have a scheduled destination station located in, and after, the given destination segment.

OD	Origin stations	Destination stations	Representative PWT station
1	ACT–AGR	ACT–AGR	ACT
2	ACT–CFS	SGT–CFS	ACT*
3	SEL	NFD	SEL
4	ECM–RLN	ECM–RLN	ECM
5	AGR–ACT	AGR–ACT	KXX
6	AGR–ACT	BOS–HRA	HTX
7	AGR–ACT	SEL–NFD	SEL
8	AGR–ACT	ECM–RLN	SHR
9	AGR–ACT	ETE–UXB	ICK
10	CFS–SGT	All stations WB	†
11	HRA–BOS	NFD–CFS, ECM–RLN	HTX
12	HRA–BOS	HRA–BOS, ETE–UXB	HTX
13	NFD–SEL	NFD–CFS, ECM–UXB	SEL
14	SEL–HRA	BOS–HRA	BOS
15	RLN–ECM	RLN–CFS, SEL–HRA	SHR
16	ECM–UXB	ETE–UXB	ICK
17	UXB–ETE	RLN–CFS, SEL–HRA	ICK
18	UXB–ETE	UXB–ETE	ICK

*A train recorded at ACT is only used to calculate PWT for this OD group if the train's scheduled destination is Cockfosters.

† See the text for an explanation of PWT estimation for this segment-to-segment OD group.

Table 4-2: Piccadilly line segment-to-segment OD groups

rience the PWT calculated using departure headways at King's Cross St. Pancras. Further, it should be noted that the representative PWT station is located in the destination segment for OD groups 6, 7, 8, 9, 14, and 16; a discussion about the validity of using departure headways in the destination segment to estimate PWT in the origin segment is provided in Section 5.3.

It is important to describe how PWT is estimated for passengers traveling from Cockfosters, Oakwood, or Southgate to any westbound station. Instead of using departure headways from one of these three stations to estimate PWT, LU's PWT methodology estimates PWT for these passengers by first estimating PWT for passengers traveling from Acton Town to Cockfosters. LU's PWT methodology then

uses this PWT estimate to calculate the ratio of actual-scheduled PWT for passengers traveling eastbound from Acton Town to Cockfosters. Applying this ratio to the Cockfosters to Acton Town scheduled PWT by timeband provides the estimated actual PWT for westbound trips starting in the Cockfosters segment.

All lines

As noted earlier, LU's method for estimating PWT assumes that passengers boarding at all stations in each segment experience the same PWT. The PWT estimated for each segment is not perfectly accurate because, while the number of trains per hour will be the same on each segment, train headways can change within a segment. Intermediate representative stations are not included in segments because this would increase computation time when calculating PWT. As it stands now, it takes at least three hours to compute PWT for the entire system for one four-week period. The methodology proposed in Section 5.2 will shed light on whether long segments such as from Queen's Park to Waterloo on the Bakerloo line and Arnos Grove to Acton Town on the Piccadilly line should be split into smaller segments.

4.1.2 Choosing departure times at representative PWT stations

Because the calculation of average PWT depends on departure headways, which in turn depends on departure times, of trains at representative PWT stations, it is important to use only those departure times at each representative PWT station that correspond with trips that served all stations in a segment-to-segment OD group. Accomplishing this task is much easier on lines with good NetMIS data because high-quality NetMIS data provide a means for determining if a train observed at an origin served a destination. In the case of lines with poor NetMIS data, assumptions must be made about which stations a train served. The next two sections describe how departure times are chosen at representative PWT stations on lines with good and

poor NetMIS data; the third section describes procedures used to validate the chosen departure times.

Lines with good NetMIS data

On lines with good NetMIS data, a departure time recorded at the representative PWT station is only used to calculate departure headways and average PWT if the train associated with the departure time is recorded at the representative destination station. When this is the case, it is known that the train served all stations in the segment-to-segment OD group. Two methods exist for matching trains seen at the representative PWT station with trains seen at the representative destination station. The preferred method for matching two Train Events observed at different stations is to match the Train Events based on Train ID. This is the preferred method because, although a train's Train ID sometimes incorrectly changes in the middle of a run, new Train IDs are always Train IDs that have not already been used during the given day. Therefore, if two Train Events have the same Train ID, then it is certain that the same train was associated with both Train Events. Part of the motivation for improving the robustness of NetMIS data, which is discussed in Section 5.1, is to obtain more Train ID matches.

The second method for matching two Train Events involves examining Train Events' Train Numbers and Trip Numbers. As mentioned at the beginning of this chapter, using both of these numbers allows a trip to be linked with a specific scheduled trip in the timetable. If both of these numbers are the same for both Train Events, then it is assumed that the same train was associated with both Train Events. However, this is not a fail-safe method because the same Train Number may be assigned to two or more trains during the course of one day because a train receives a Train Number previously assigned to a different train when operations staff change the scheduled train with which an actual train is associated.

The method used by LU for matching Train Events depends on the intricacies of the NetMIS data for a specific line. If the NetMIS data at the representative PWT and destination stations are of high quality, then LU may decide that two Train

Events can be matched if either the Train ID or Train Number/Trip Number method produces a train match. However, if LU staff determine that the Train Number/Trip Number method cannot be trusted to yield accurate matches, then LU will match trains based only on Train ID. Train Events are matched for all OD groups on the Bakerloo line using the Train ID and Train Number/Trip Number methods. If either of these methods produces a match, then two Train Events are assumed to correspond with the same train.

Lines with poor NetMIS data

As noted in Section 4.1.1, two scenarios exist on lines with poor NetMIS data regarding the choice of representative PWT and representative destination stations. If a segment-to-segment OD group has one or more representative destination stations, then a departure time recorded at the representative PWT station is only used to calculate average PWT if the scheduled destination of the train associated with the departure time is one of the representative destination stations. When no representative destination station exists, all departure times recorded at the representative PWT station are used to calculate average PWT.

When estimating PWT on lines with poor NetMIS data, LU assumes that trains observed at representative PWT stations served all stations in a given segment-to-segment OD group. As an example on the Piccadilly line, and as shown in Table 4-2, all eastbound trains recorded at Acton Town are assumed to serve all stations from Acton Town to Arnos Grove while all westbound trains recorded at Hatton Cross are assumed to serve all stations from Arnos Grove to Heathrow. This method is less accurate than those used on lines with good NetMIS data because trains may not be scheduled to serve all stations in a segment-to-segment OD group, especially in the early morning and late evening. For example, some westbound trains that serve Hatton Cross are scheduled to begin at Acton Town or Northfields Depot. Furthermore, even if trains are scheduled to serve all stations in a segment-to-segment OD group, real-time control actions may cause trains to serve only a subset of those stations.

Based on the Piccadilly line's timetable, this assumption that trains serve all stations in a segment-to-segment OD group generally holds. However, it does not hold for the westbound segment-to-segment OD groups originating at Arnos Grove and ending on the Heathrow and Uxbridge branches because some scheduled trips do not provide service to all stations on these OD groups.[2] As shown in Table 3-6, 12 of the 229 westbound trips that serve the Heathrow terminals on weekdays do not call at stations east of Acton Town while 17 of the 145 westbound trips that serve the Uxbridge branch on weekdays do not call at stations east of Acton Town. However, only 1 of the 12 and 2 of the 17 trips serving only the Heathrow and Uxbridge branches, respectively, start between 07:00 and 22:00. Therefore, this assumption fails very infrequently during the busiest times of the day when PWT calculation errors would have the largest impact. Because PWT is based on the departure headways of trains recorded on these destination branches instead of trains recorded in the origin segment, the PWT calculated using LU's methodology for the timebands during which these non-complete trips operate will underestimate PWT for passengers boarding east of Acton Town.

Based on the analysis of NetMIS data for the five consecutive weekdays from July 26, 2010 to July 30, 2010, the number of scheduled trips cited in the previous paragraph as causing LU's assumption that Piccadilly line trains serve all stations in a segment-to-segment OD group to fail tends to match the number of actual trips that violate this assumption. For example, the actual number of westbound trips only serving stations from Acton Town to Heathrow and stations from Ealing Common to Uxbridge, but none of the stations east of Acton Town, is the same as specified in the timetable.

However, there was some unscheduled short turning of trains during the week analyzed that would introduce slight errors in the PWT calculated on the Piccadilly

[2]At first glance, it appears that this assumption also does not hold for passengers traveling from either western branch to the other branch and passengers traveling from the Heathrow branch to a station east of Acton Town and from the Cockfosters segment to a station west of Acton Town. However, as discussed later, LU assumes that passengers transfer trains, if necessary, at Acton Town in these cases, but LU only accounts for the PWT these passengers experience on the first leg of their trip.

line. Specifically, an average of one trip each day that served Heathrow started at Wood Green instead of Arnos Grove, which is two stations north of Wood Green. Additionally, although the only trains used to calculate PWT for passengers traveling from Acton Town to Cockfosters are those trains that have a scheduled destination of Cockfosters[3], between one and seven trains that served Acton Town and had a scheduled destination of Cockfosters reversed at Arnos Grove on each of the days analyzed, and, on one of the five days analyzed, three trains that served Acton Town with a scheduled destination of Cockfosters reversed at Wood Green. These unscheduled short turns of trains with scheduled destinations of Cockfosters lead to an underestimation of PWT for passengers traveling north of Arnos Grove. However, about 300 trains are scheduled to provide service from Acton Town to Cockfosters each weekday, so these unscheduled short turns make up only a small portion of all trips on this part of the line.

Two final sources of error in the calculation of PWT on the Piccadilly line should be mentioned. On each of the weekdays analyzed, about 40 to 48 eastbound trains recorded at Acton Town did not provide service to stations east of Acton Town. Instead, about half of these trains provided service to the Uxbridge branch while the other half provided service to the Heathrow branch. Although only about five of these trains reversed back to one of the western branches between 07:00 and 22:00, the large number of eastbound trips recorded at Acton Town in the early mornings and late evenings lead to an underestimation of PWT for passengers traveling from Acton Town to Arnos Grove. Additionally, because between one and five trains that left Acton Town eastbound each day reversed at Wood Green, passengers traveling from Acton Town to Bounds Green or Arnos Grove experienced longer PWT than the PWT estimated based on departure headways from Acton Town.

[3]This is the only OD group on the Piccadilly line where a train's stated destination is consulted before deciding whether to use a train's departure time to calculate PWT.

Departure time validation procedures

For the lines with good NetMIS data, once it has been determined that two Train Events belong to the same train, a few validation procedures are used to verify the matching of these two Train Events. First, when two Train Events are matched based on Train ID, LU verifies that the Train Event at the representative destination station was part of the same trip as the Train Event at the representative PWT station. This verification involves two checks[4]: (1) the difference between the destination station arrival time and the origin station departure time must be no greater than 30 minutes over the scheduled running time for that OD pair; (2) the difference between the destination station arrival time and the origin station departure time must be less than twice the scheduled running time for the given OD pair. When two Train Events pass these checks, it is known that the departure time associated with the Train Event at the representative PWT station can be used to calculate average PWT.

The value of 30 minutes is used for the first check because delays longer than 30 minutes are classified as closures. In these cases, LU assigns the scheduled amount of PWT to the PWT component of JTM and accounts for any excess PWT incurred during the delay in the Closures component of JTM. The reason twice the fixed scheduled running time is used is best illustrated with an example. Consider a train that leaves Station A at $t = 0$ and has a scheduled running time of 20 minutes. This train is then scheduled to arrive at Station B at $t = 20$. If the train reverses at Station B, then it would be scheduled to arrive back at Station A at $t = 40$. Reversing at Station A again would get the train back to Station B at $t = 60$. Although this example does not include reversing time or layover time, this example shows that allowing Train Events to be matched when the running time is longer than three times the scheduled running time could allow incorrect matching of Train Events. Therefore, while it can be argued that this running time verification process should check that the running time associated with two matched Train Events is no more than three times the scheduled running time, LU believes that using twice

[4]These checks are not required when Train Events are matched using Train Number and Trip Number because these two events are known to be part of the same trip.

the scheduled running time accomplishes the goal of ensuring that Train Events are accurately matched.

The second validation procedure is used on lines with good and poor NetMIS data. This procedure involves checking the departure headways at the representative PWT station. The first check associated with this validation procedure requires that the departure headways are greater than 60 seconds. When this check fails, it indicates a flaw in the data. The second check associated with this validation procedure determines if a delay greater than 30 minutes occurred by requiring the departure headways to be less than 30 minutes plus the scheduled headway.

4.1.3 Calculating average platform wait time

Average PWT is calculated for trains serving a given segment-to-segment OD during a specific timeband and day; the same calculation procedure is used for lines with good and poor NetMIS data. If the representative PWT station is not the first station in the origin segment, then a time offset is used along with the departure time at the representative PWT station to determine the departure time that would have been observed at the station at the start of the origin segment. This offset is used to make sure that trips are placed in the correct timeband.

Average PWT for each segment-to-segment OD group is calculated using the departure times, which are then used to calculate departure headways of trains at the representative PWT station. The methods used to determine which departure times to use at each representative PWT station were described in Section 4.1.2. The formula for calculating average PWT is given in (4.1), where departure time is denoted by dt and departure headway is denoted by H.

$$\text{Average PWT} = \frac{\sum(dt_n - dt_{n-1})^2}{2 \cdot \sum(dt_n - dt_{n-1})} = \frac{\sum H^2}{2 \cdot \sum H} \tag{4.1}$$

This equation follows from the ideas presented in Section 2.2 and is equivalent to Equation (2.2). This average PWT model assumes that passenger arrivals at a stop are random, uniformly distributed, and independent of actual and scheduled vehicle

arrival and departure times. Further, this model assumes that passengers can board the next vehicle that arrives at their station.

It should be emphasized that the way in which average PWT is calculated assumes that demand is constant over each timeband. This is an acceptable assumption if actual departure headways do not vary over each timeband. However, if actual departure headways do vary over each timeband, error will exist in the PWT estimation because the estimated PWT value will not account for the proportion of a timeband's total passengers experiencing the varying levels of PWT. Future work could determine whether departure headways vary significantly during individual timebands.

Left behind passengers

Because of crowding, some passengers cannot board the first train that arrives at their origin. LU explicitly includes this extra waiting time in their calculation of PWT by estimating when passengers are left behind by a train. LU determines if passengers are left behind by considering a given line's passenger demand and reliability, the latter of which is measured by the excess PWT when all passengers are assumed to board the first possible train. Higher levels of excess PWT will lead to more left behind passengers, all else being equal. The passengers who are deemed left behind are assigned one full headway of additional PWT. This additional PWT incurred by left behind passengers is integrated into the measure of actual PWT to determine the final value of excess PWT. In LU's current PWT methodology, the effect of left behind passengers is accounted for separately for each timeband and line but only at the four-week period level.

Choosing a train to board at the origin

Another intricacy of the PWT calculation process is that LU assumes that passengers try to board the first train that *serves* their destination. However, if a passenger's destination receives a low frequency of service, then LU may assume that the passenger will board the first train that travels *in the direction of* their destination. This passenger will then transfer, if necessary, to the lower frequency service at a station

downstream. (London Underground (2009)) LU's definition of segment-to-segment OD groups determines when this latter assumption is used. Specifically, LU uses this assumption when passengers must transfer trains to reach at least some of the stations in a segment-to-segment OD group. LU's PWT methodology accounts for the PWT experienced at the origin, but not at the transfer station, by passengers who make intra-line transfers to reach their destination.

LU does not use this latter assumption about passengers transferring to reach destinations that receive a low frequency of service at any locations on the Bakerloo line. However, it is used on the Piccadilly line for passengers traveling from Cockfosters, Oakwood, and Southgate to all stations on the Uxbridge and Heathrow branches and passengers traveling from the Uxbridge and Heathrow branches to the other branch or any station east of Acton Town. It is not possible to say *a priori* whether a passenger using this transferring approach to reach a low frequency destination would experience a higher or lower PWT than the PWT that would be experienced using the approach, when feasible, of simply waiting at the start of the trip for a train running through to the low frequency destination. Whether PWT is higher or lower depends on (1) whether a higher frequency of service is provided to the destination from a station downstream from the origin than at the origin and (2) whether the gap between the lower frequency train that serves the origin and destination and the higher frequency train(s) in front of it that serve the origin but not the destination grows or shrinks while the passenger is on a higher frequency train.

Although it cannot be determined *a priori* whether PWT is higher or lower if a passenger boards a low frequency train at the origin or at a transfer station, it is known that a small percentage of passengers make trips for which LU's transferring assumption is used. For example, as Table 3-8 shows, the (rounded) proportion of passengers traveling from Cockfosters, Oakwood, and Southgate to either western branch and from either western branch to Cockfosters, Oakwood, and Southgate is zero in timebands 2–5. Additionally, the proportion of Piccadilly line passengers traveling from either western branch to a station between Acton Town and Arnos Grove ranges from 4% between 19:00 and 22:00 (timeband 5) to 15% between 07:00

and 10:00 (timeband 2). However, because nearly all eastbound trains provide service to at least Arnos Grove, as shown in Table 3-6, passengers traveling eastbound from one of the western branches will generally only need to transfer to reach stations on the other western branch or east of Arnos Grove.

Aggregate PWT

The segment-to-segment OD average PWT is used to produce more aggregate PWT results. To begin, demand weightings that give the percentage of passengers boarding and alighting in a segment-to-segment OD group are used to aggregate segment-to-segment OD average PWT to line-level PWT for a given timeband. Passengers traveling on an OD group for which LU assumes that passengers transfer to get to a low frequency destination are included in the demand weighting for their trip from their origin to the transfer station but not from the transfer station to their destination.[5] The equation for line-level PWT is given in (4.2).

$$PWT_{l,tb} = \sum_i \sum_j t_{l,tb,i,j} \cdot T_{l,tb,i,j} \tag{4.2}$$

where $PWT_{l,tb}$ = average PWT on line l during timeband tb

$t_{l,tb,i,j}$ = average PWT for passengers traveling from segment i to segment j on line l during timeband tb

$T_{l,tb,i,j}$ = proportion of all boarding passengers on line l during timeband tb who board in segment i and alight in segment j

Demand weightings are used again to aggregate the line-level PWT by timeband to line-level PWT and to aggregate this line-level PWT to network PWT. These PWT

[5]One small exception exists on the Piccadilly line as LU has included passengers boarding at stations from Heathrow to Boston Manor and alighting from Eastcote to Uxbridge in the demand weighting for trips ending at Northfields. The demand weightings would be more accurate if these passengers were included in the demand weighting for trips ending at Acton Town because passengers will transfer trains at Acton Town, not Northfields, to reach their destination at the end of the Uxbridge branch.

aggregations are calculated in a manner analogous to the equation in (4.2). It should be noted that LU keeps the demand weightings constant over a number of years in order to remove the effect of ridership changes on the trend of PWT over time. The demand weightings currently used by LU are based on 2002 ridership data, but 2009 ridership data will begin to be used starting in April 2011. Finally, LU assumes that passengers transferring from one line to another have the same average PWT as non-transferring passengers, so the network PWT is multiplied by 1.4 because "approximately 40% of all journeys involve at least one interchange." (London Underground (2009))

This approach to accounting for transferring passengers provides a first-order approximation of the PWT experienced by these passengers as it does not account for the fact that some segment-to-segment OD groups are used by more transferring passengers than other OD group. Further, each OD group's usage by transferring passenger varies by timeband, and, at a more aggregate level, some lines are used by more transferring passengers than other lines. Therefore, when excess PWT is unusually large (or small) on a segment-to-segment OD group (or line) that serves a large number of transferring passengers, this basic approach of allocating transfers equally over all segment-to-segment OD groups leads to an underestimation (or overestimation) of actual PWT.

Being able to allocate transferring passengers to segment-to-segment OD groups and timebands would improve the accuracy of PWT estimation. For example, if 0.01% of all LU passengers transfer to segment-to-segment OD group x during timeband y, then the actual PWT and scheduled PWT calculated for OD group x during timeband y should be multiplied by 1.0001. If these transferring passenger weights are applied to all segment-to-segment OD groups and timebands, then network-level actual, scheduled, and excess PWT that includes the effect of transferring passengers can be estimated using the same aggregation procedure explained earlier. If this level of detail is too difficult to achieve, accounting for transferring passengers at the line level, instead of the network level, would be a worthwhile next step. Additional research is required to determine if this disaggregated approach to accounting

for transferring passengers would have more or less impact on the accuracy of PWT estimates than the ideas presented in Chapter 5.

4.2 Results

This section presents PWT estimates[6] for the Bakerloo and Piccadilly lines by timeband and day for the five weekdays from July 26 through July 30, 2010. Then, timeband- and line-level PWT estimates are presented for each line for the four-week period starting from July 25, 2010 to August 21, 2010. For all PWT results presented in this thesis, all timeband-day combinations for which LU has determined that delays greater than 30 minutes occurred have been assigned the scheduled PWT for that timeband. For the four-week period anlyzed, three of the 148 timeband-day combinations on the Bakerloo line and two of the 148 combinations on the Piccadilly line have been assigned the scheduled PWT; none of these timeband-day combinations where scheduled PWT is used correspond with the five weekdays from July 26 to July 30. Although this section is brief, these results serve as the baseline against which the PWT estimates calculated with the new PWT methodologies presented in Chapter 5 are compared.

Tables 4-3 and 4-4 present the PWT estimates for the six weekday timebands during five consecutive weekdays. These tables also provide the average PWT for these six timebands over the 20 weekdays during the four-week period starting on July 25, 2010 and the line-level PWT estimate for these four weeks (including weekends). The latter (very aggregate) PWT estimate is frequently used by LU staff who want a quick way to quantify a line's performance. Although this research focuses on the accuracy of estimated actual PWT, the scheduled PWT values provided in the first row of these tables provide a benchmark for the actual PWT values presented.

As will be discussed in Section 5.1, because some departure times and Train Events are missing from NetMIS data and because some Train IDs change mid-trip

[6]The VBA code for calculating PWT using LU's methodology was written by Nigel Kelt, a Senior Planner in Transport Planning at LU.

	Timeband					
	1	**2**	**3**	**4**	**5**	**6**
Scheduled	4.88	1.95	1.96	1.86	2.15	2.87
July 26, 2010	5.52	2.05	1.99	1.90	2.17	3.08
July 27, 2010	4.55	2.02	1.99	2.04	2.95	3.00
July 28, 2010	5.35	2.03	2.05	2.10	2.37	3.00
July 29, 2010	4.79	2.13	2.00	1.91	2.18	3.03
July 30, 2010	5.33	2.19	2.09	1.85	2.11	2.99
4-week average	4.80	2.05	2.09	2.07	2.40	3.20
4-week line-level PWT estimate: 2.26						

Table 4-3: Bakerloo line PWT estimates using LU's PWT methodology

	Timeband					
	1	**2**	**3**	**4**	**5**	**6**
Scheduled	3.05	1.74	1.81	1.64	1.82	2.24
July 26, 2010	3.12	1.93	2.19	2.04	2.06	2.45
July 27, 2010	3.20	2.10	2.19	1.75	2.01	2.46
July 28, 2010	3.00	1.86	1.94	1.89	2.11	2.35
July 29, 2010	3.43	1.90	1.91	1.84	1.95	2.42
July 30, 2010	3.03	1.98	1.94	2.22	2.19	2.31
4-week average	3.26	1.90	2.02	1.93	2.04	2.41
4-week line-level PWT estimate: 2.05						

Table 4-4: Piccadilly line PWT estimates using LU's PWT methodology

preventing some trains from being matched between an origin and destination, PWT may be overestimated for some timeband-day combinations. The missing departure times and Train Events affect the Bakerloo and Piccadilly lines while the Train IDs that change mid-trip affect only the Bakerloo line because trains are not matched between origin and destination on the Piccadilly line.

Chapter 5

New platform wait time methodologies

This chapter describes new methods developed to estimate PWT and improve the quality of NetMIS data. Three ways of estimating PWT are described in this chapter – LU's PWT methodology with revised NetMIS data, LU's PWT methodology but using more line segments, and a new train-count-based (TCB) PWT methodology. Section 5.1 explains the methods used to revise NetMIS data before presenting results from using LU's PWT methodology with this revised data. Next, Section 5.2 presents the motivation for, and results from, using more line segments with LU's PWT methodology. Finally, Section 5.3 presents the TCB PWT methodology, which has been developed during this research to overcome weaknesses in LU's current PWT methodology.

All of the PWT estimation methods and the NetMIS data improvement methods have been programmed in Microsoft VBA. The VBA code for calculating PWT using LU's current methodology was written by Nigel Kelt, a Senior Planner in Transport Planning at LU. The VBA code for the TCB PWT methodology and the NetMIS data revision methodologies was written by the author of this thesis.

5.1 Improving NetMIS data

This section focuses on fixing two main NetMIS data deficiencies – missing arrival and/or departure times and Train IDs that are reassigned mid-trip. Although the *types* of data problems highlighted here are consistent across days, the locations of the data problems vary by time and day. Therefore, one day may appear to have performed better than another, but this better performance may simply be due to the quality of that day's NetMIS data. Further, because the times and locations of data problems vary by day, it is not a trivial task to revise the recorded data to make it more robust.

Although the main goal for revising NetMIS data is to increase the accuracy of PWT calculated with this data, the use of NetMIS for other applications also motivated this work. For example, the work by Paul (2010) relating to the use of smart card and train location data to assign passengers to individual trains will benefit from more robust NetMIS data. The specific impact of more robust NetMIS data on the models proposed by Paul can be seen in the list of her NetMIS-related assumptions, which were originally presented in Section 1.1 and are reproduced here:

1. When a train erroneously receives a new Train ID, passengers who boarded the train before the Train ID changed but alighted after the Train ID changed are assumed to have on-train times within two minutes of the expected running time given by LU's Route Choice Model (RCM).

2. Inferred running times match those given by LU's RCM when passengers board or alight at a station for which there are no NetMIS data.

3. Train departure time is set to train arrival time for trains that have only the arrival time recorded in NetMIS.

Additionally, LU operations and planning staff use NetMIS data to analyze performance beyond just the calculation of PWT. For example, staff may analyze running times of specific trains operating during the peak of the morning or evening peak.

LU staff use different train identification data in NetMIS based on the goal of their analysis. The majority of LU staff use NetMIS data to investigate the performance of specific scheduled trains, which involves looking at the Train Number and Trip Number; a smaller portion of staff analyze the performance of individual trains by looking at a specific Train ID. One of the revisions of NetMIS data proposed in this thesis focuses on correcting erroneous Train IDs. The reason for this is that Train IDs are the most reliable way to identify trains, and the current method for calculating PWT, which is the main, but not sole focus of this work, produces the most accurate results when individual trains can be reliably identfied. The joint use of Train Number and Trip Number also provides a fairly reliable way to track trains, but Train Numbers are sometimes assigned to multiple trains during the same day.

Poor NetMIS data cause two problems when calculating PWT. First, when an event is not recorded in its entirety or is missing its departure time, the departure headways at the affected representative PWT stations will be larger than they were in reality. As a result, the PWT calculated from the departure headways will overestimate the PWT actually experienced by passengers. It is important to emphasize that this problem exists only when poor data exist at a representative PWT station. For example, a southbound departure time missing at Regent's Park on the Bakerloo line would not cause a problem because Regent's Park is not a representative PWT station. However, a missing southbound departure time at Queen's Park, which is a representative PWT station on the Bakerloo line, will lead to the calculation of a higher-than-actual departure headway. Second, poor train identification data can prevent the matching of trains between an origin and destination. The specific role that train matching plays in the calculation of PWT was discussed in Section 4.1, but two important things to remember are (1) on lines with good NetMIS data, a departure time is used to calculate average PWT at a representative PWT station only if the train associated with that departure is recorded at the representative destination station for the given segment-to-segment OD group, and (2) trains are matched based on Train ID or Train Number and Trip Number. As mentioned in Section 4.1, no effort is made to match trains between origin and destination on lines with poor

NetMIS data. Instead, all trains that depart from the representative PWT station are assumed to serve all stations in the given segment-to-segment OD group. The implications of this assumption were discussed in Section 4.1.2.

5.1.1 Improving departure time data

There are four possible outcomes involving the recording of arrival and departure times in NetMIS data. In the best case scenario, both the train's arrival and departure times are recorded in NetMIS; in the worst case scenario, neither the arrival nor departure time is recorded. The worst case scenario occurs only when an entire Train Event, including train identification data, fails to be recorded in NetMIS. The two remaining scenarios involve the recording of only an arrival time or only a departure time. Because the headways used to calculate PWT are based on departure times, the focus here is on the two cases where departure times are missing.

Before explaining the methodology used to fill in missing data, it is instructive to consider the frequency with which departure or arrival and departure times are missing from NetMIS data. Table 5-1 illustrates how often these data deficiencies occur over all events on each of five consecutive weekdays in July 2010. The count of missing departure times does not include events that are missing arrival *and* departure times, occur at terminals, or are the last event for a train before it reverses. Missing departure times are not counted in the latter two cases because, as will be discussed shortly, the methods developed here will not add departure times to the NetMIS data in these cases.

As this table shows, data-deficient events make up a very small portion of all events. The largest percentage of events with missing departure times occurs on July 28, 2010 on the Bakerloo line when approximately 0.7% of events are missing a departure time. The same day also provides the largest percentage of missing Train Events during this week as nearly 0.1% of events on the Piccadilly line were not recorded in NetMIS. However, not all of these missing departure times and missing Train Events affect the calculation of PWT because not all of these data deficiencies occur at representative PWT stations. As Table 5-2 shows, there are virtually no

	Events w/Missing Departure Times		Missing Train Events		Total Events	
	Bakerloo	Piccadilly	Bakerloo	Piccadilly	Bakerloo	Piccadilly
July 26, 2010	24	60	0	16	13,671	34,361
July 27, 2010	58	14	5	5	13,819	34,440
July 28, 2010	99	13	0	33	13,803	34,429
July 29, 2010	11	18	0	5	13,648	34,679
July 30, 2010	18	36	1	26	13,655	33,789

Table 5-1: Frequency of missing departure time events

	Events w/Missing Departure Times		Missing Train Events		Total Events	
	Bakerloo	Piccadilly	Bakerloo	Piccadilly	Bakerloo	Piccadilly
July 26, 2010	1	40	0	8	1,299	2,671
July 27, 2010	1	3	1	4	1,302	2,646
July 28, 2010	0	1	0	2	1,289	2,654
July 29, 2010	1	4	0	3	1,295	2,675
July 30, 2010	0	3	0	2	1,292	2,592

Table 5-2: Frequency of missing departure time events at representative PWT stations

instances where a departure time or Train Event is missing at a representative PWT station on the Bakerloo line. On the Piccadilly line on July 26, a total of 48 events at representative PWT stations are missing a departure time, far more than any of the other four days analyzed, but this still accounts for only 1.8% of Piccadilly line Train Events at representative PWT stations on that day. Figures 5-1 through 5-4 present the distribution of these missing data over the six weekday timebands on each day.

Although these data deficiencies occur at representative PWT stations very infrequently, it is still important to fix these errors because they can lead to an inaccurate calculation of PWT using LU's current PWT methodology. However, it is not possible to say with certainty by how much each added departure time will change estimated PWT. In fact, adding departure times to NetMIS data will usually, but not always, decrease estimated PWT. Estimated PWT will not always decrease because an added departure time could eliminate an instance where a departure headway is not used because it is greater than 30 minutes plus the scheduled headway. If only one de-

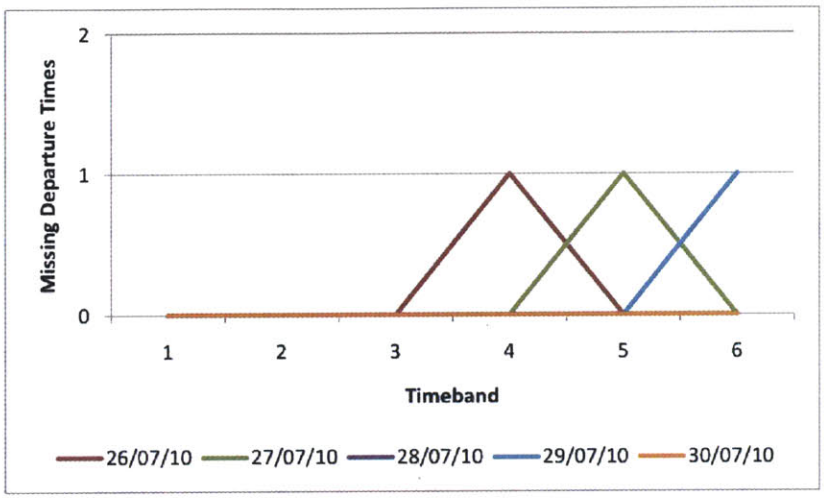


Figure 5-1: Bakerloo line missing departure times

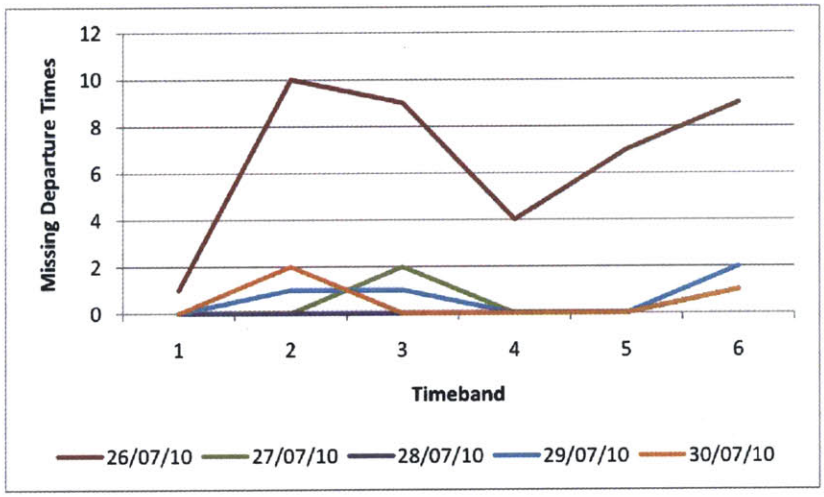


Figure 5-2: Piccadilly line missing departure times

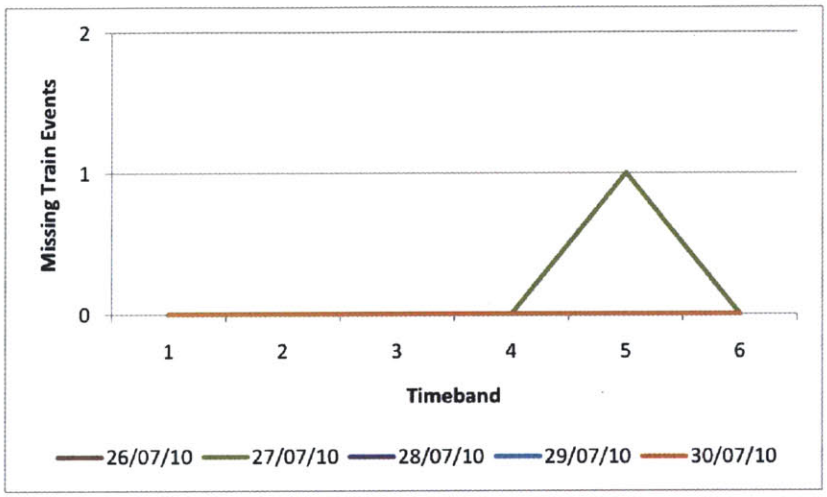


Figure 5-3: Bakerloo line missing Train Events

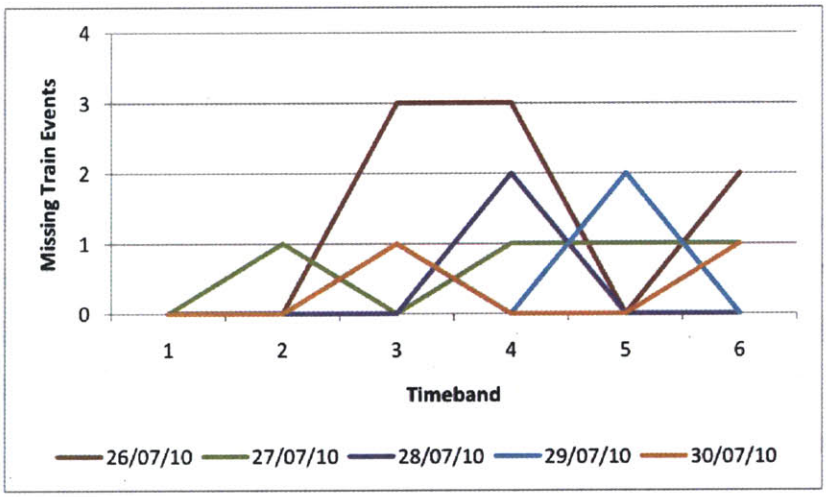


Figure 5-4: Piccadilly line missing Train Events

parture time is added during this long (and previously unused) headway, then the new estimated PWT is very likely to increase from the value calculated with original NetMIS data.

Missing departure time only

When the NetMIS data are missing only the departure time for an event, an estimated departure time that is 20 seconds greater than the recorded arrival time will be entered in place of the missing departure time as long as two conditions are met. First, the event with the missing departure time must not occur at a terminal because it cannot be assumed that dwell times at terminals are 20 seconds. Second, the train cannot reverse at the location where the departure time is missing. A train is assumed not to reverse if the next event in the same Train ID block occurs in the same direction as the event with the missing departure time. Further, if the Train ID block ends after the event with the missing departure time, then the train is assumed to continue in the same direction as long as the location where the departure time is missing is not a common reversing location[1]. Departure time is not added when a train reverses because these trains do not provide service to the stations after the reversing location. An indicator is placed in a "flag" field when a missing departure time is added so future users of the revised data are aware that a given event's departure time has been estimated.

When a departure time is not recorded, the dwell time is assumed to be 20 seconds because this is the amount of dwell time provided in LU's timetables. This assumed 20 second dwell time will certainly not be accurate in all cases, so future work could allow the assumed dwell time to vary by station and time of day. Each station's assumed dwell time could be a fixed value based on whether the station is in central or outer London or it could be based on historical dwell times at a given station during a specific timeband.

[1]Stations defined as common reversing locations are Lambeth North, Waterloo, Queen's Park, and Stonebridge Park on the Bakerloo line and Arnos Grove, Acton Town, Northfields, Boston Manor, Rayners Lane, and Ruislip on the Piccadilly line

Missing Train Events

Finding missing Train Events and inserting estimated data for them is a much more complicated task than filling in missing departure times. This process begins by cycling through all recorded Train Events for a given line and date; the Train Events are sorted such that all events with the same Train ID are grouped and sorted based on arrival time. For each Train Event, TE_x, in a given Train ID block, the next Train Event, TE_{x+1}, is checked to see if the station associated with TE_{x+1}, denoted S_{x+1}, immediately follows the station associated with TE_x, denoted S_x. In the cases of lines with branches, a check is conducted to determine if S_{x+1} is the first station on a branch that immediately follows the branch on which TE_x occurred. When this is not the case, it indicates that either at least one Train Event is missing between the beginning of the next branch and TE_{x+1} or the next branch recorded in the NetMIS data does not sequentially follow the branch on which TE_x occurred. In the latter case, no new events are added between TE_x and TE_{x+1}. If a Train Event is determined to be missing, then the row where the Train Event is missing in the NetMIS data is recorded so a new Train Event with estimated data can be added at that location.

At this point, it is known where in the NetMIS data Train Events are missing, but it is not known how many Train Events are missing in each instance. To determine the number of Train Events to add in any given instance, the program counts the number of stations between S_x and S_{x+1}. When these Train Events occur on different branches, the program determines which stations on each branch are missing Train Events. Although missing stations on both branches are identified when S_{x+1} is not the first station on its branch, there is currently no procedure in place to check that S_x is the last station on its branch when S_{x+1} is the first station on its branch. Therefore, future work could add a check to make sure S_x is the last station on its branch and, when this is not true, add the necessary Train Events between TE_x and TE_{x+1}.

Consider a few examples on the Piccadilly line, the relevant portion of which is shown in Figure 5-5. If S_x = Acton Town and S_{x+1} = Boston Manor, then it is known

Figure 5-5: Piccadilly line near Acton Town

that two stations, South Ealing and Northfields, were not recorded in the NetMIS data. However, if S_x = Hammersmith and S_{x+1} = Boston Manor, then the program will recognize that one[2] station (Acton Town) needs to be added on the trunk portion of the line while two stations (South Ealing and Northfields) need to be added on the Heathrow branch.

Departure times are estimated for missing Train Events by using scheduled running times and the known actual running time between S_x and S_{x+1}. Specifically, the scheduled running time between S_x and S_{x+1} is calculated from the timetable. Then, the actual running time between S_x and S_{x+1} is calculated from the NetMIS data. Finally, the ratio of the actual running time to the scheduled running time is calculated. This ratio is applied to the scheduled running time between S_x and each missing station between S_x and S_{x+1} in order to estimate the actual running time between S_x and a missing station.

Figure 5-6 illustrates how this proportional running time method works. Assume that complete NetMIS data exist at Stations A and D while Stations B and C are not recorded in NetMIS. The scheduled running times from A to B, A to C, and A to D are two, six, and eight minutes, respectively; the actual running time, as calculated

[2]Turnham Green is served by the Piccadilly line only in the early morning and late evening. If Train Events are missing at a time when Turnham Green receives service, then a Train Event at Turnham Green should also be added to the NetMIS data. The program currently never adds missing Train Events at Turnham Green, so future work could add this functionality.

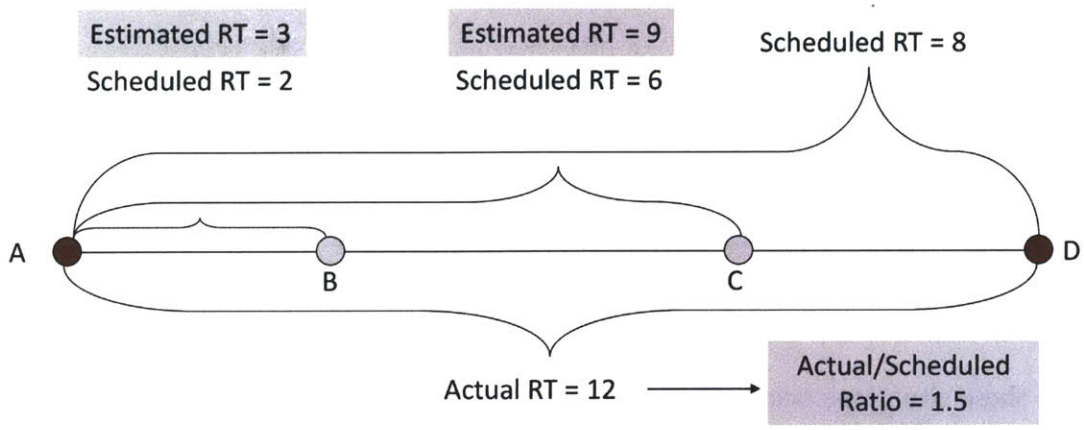


Figure 5-6: Example of the proportional running time methodology

from NetMIS, between A and D is 12 minutes. Therefore, the ratio of actual running time to scheduled running time between A and D is 1.5. This ratio is then applied to each scheduled running time from Station A to each station with missing NetMIS data to calculate an estimated running time. As Figure 5-6 shows, the estimated running times from A to B and A to C are three and nine minutes, respectively.

Once actual running times are estimated, the estimated departure time for the missing event is set by adding the estimated running time to the known departure time from S_x. The arrival time for the new event is assumed to occur 20 seconds prior to the estimated departure time. A check is in place to ensure that a new event is not added at a time that would put two trains at the same station at the same time. Specifically, if a missing Train Event would be the y^{th} event to occur at Station S_m, then the estimated arrival or departure time of event y at S_m, denoted by $at_{m,y}$ and $dt_{m,y}$, respectively, cannot fall between the arrival and departure times associated with Train Event $y-1$ or Train Event $y+1$ at S_m. That is, the following inequalities must be *false*:

$$at_{m,y-1} \leq at_{m,y} \leq dt_{m,y-1}$$

$$at_{m,y-1} \leq dt_{m,y} \leq dt_{m,y-1}$$

$$at_{m,y+1} \leq at_{m,y} \leq dt_{m,y+1}$$

$$at_{m,y+1} \leq dt_{m,y} \leq dt_{m,y+1}$$

If any of these situations occur, then event y is not added at S_m because this would create the impossible situation where two trains occupied the same station at the same time. An indicator is assigned to the flag field of an added Train Event to make clear that the arrival and departure times of the event are estimated; this indicator differs from the one used when only departure time is added to a Train Event.

5.1.2 Revising Train IDs

Train IDs are the preferred means of following trains because, unlike Train Numbers and Trips Numbers, a Train ID is assigned to only one train on a given day. Although a Train ID is supposed to correspond with only one train for an entire day, it is known that an individual train may be assigned two or more different Train IDs throughout an entire day. Therefore, analysis of NetMIS data would become more accurate if Train IDs remained consistent every day. It is important to note that, although it is desirable to be able to follow an individual train during an entire day, being able to follow a train from its origin to destination for one trip is sufficient for the calculation of PWT. Therefore, this work aims to revise NetMIS data to ensure that each trip is assigned only one Train ID.

Quantifying Train ID problems

The quality of Train IDs varies by line and, on a given line, it varies by day and location on the line. That is, although some lines consistently have higher quality Train IDs than other lines, this quality can fluctuate unpredictably by day or location

on a line due to temporary data transmission errors. Tables 5-3 and 5-4 illustrate how many Train ID blocks end on each of five consecutive weekdays between 07:00 and 22:00 on the Bakerloo and Piccadilly lines. This time period was chosen for this analysis because, as noted in Sections 3.1 and 3.2, 77% and 72% of weekly demand on the Bakerloo and Piccadilly lines, respectively, occurs during this period. Therefore, one of the major focuses of revising Train IDs should be to make the Train IDs during this time period as consistent as possible so the calculated PWT during this heavily-traveled time period is as accurate as possible.

As Table 5-3 shows, the Bakerloo line timetable in effect from May 18, 2008 through December 12, 2010 had 34 trains scheduled to be in service between 07:00 and 22:00. Of these 34 trains, 10 were scheduled to end service for the day during this time period. In comparison, the data provided in NetMIS indicate a much larger number of blocks operating during this time period. This large discrepancy between the actual and scheduled number of blocks is due in part to trains erroneously receiving new Train IDs when they reverse. As mentioned earlier, this type of Train ID reassignment is acceptable but not desirable. The number of blocks ending between 07:00 and 22:00 is always less than the number of blocks that operate during this time period because some of these blocks end after 22:00.

The final two rows in Table 5-3 are the most relevant to this research. The first of these rows shows the number of blocks that end "incorrectly". A block is said to end incorrectly if it ends at a place where a train could not reverse or go out of service. For example, on the Bakerloo line, a block that ends at Stonebridge Park ends "correctly" because trains both reverse and go out of service here, but a block that ends at Embankment ends "incorrectly" because trains neither reverse nor go out of service here. The final row in this table shows the number of blocks ending incorrectly for which the Train Event at the representative PWT station in the block that ends incorrectly cannot be matched with the same train's Train Events at all representative destination stations by using the Train Number/Trip Number matching approach. For example, on July 26, 40 blocks end incorrectly, making it impossible to match Train Events at representative PWT and representative destination stations

	Schd	7/26	7/27	7/28	7/29	7/30
Blocks	34	169	263	331	192	274
Blocks ending	10	146	236	304	167	249
Blocks ending incorrectly	0	40	94	183	54	116
Blocks ending incorrectly that cannot be matched	0	7	5	4	9	11

Table 5-3: Frequency of Train ID blocks ending incorrectly on the Bakerloo line

	Schd	7/26	7/27	7/28	7/29	7/30
Blocks	79	364	308	281	306	401
Blocks ending	18	299	244	216	242	328
Blocks ending incorrectly	0	121	117	91	120	179

Table 5-4: Frequency of Train ID blocks ending incorrectly on the Piccadilly line

based on only Train ID, and seven of the 40 trains associated with a block that ends incorrectly cannot be matched between the representative PWT station and all representative destination stations based on Train Number and Trip Number. Although it is desirable to correct all instances where blocks end incorrectly, the goal of the Train ID revision methods proposed in this section as they relate to the calculation of PWT is to allow the blocks ending incorrectly that cannot be matched by Train Number and Trip Number to be matched by Train ID.

The data presented in Table 5-4 for the Piccadilly line is similar to that presented in Table 5-3 for the Bakerloo line. The one difference is that PWT estimates on the Piccadilly line are not impacted by revised Train IDs because Piccadilly line trains are not matched between representative PWT and representative destination stations when LU estimates PWT. Therefore, no count is provided of the number of blocks ending each day that cannot be matched given LU's current methods. However, the count of the number of blocks that end incorrectly each day is used later in this section to determine the effectiveness of the Train ID revision methods on the Piccadilly line. One thing to note about this Piccadilly line data is that the length of the Piccadilly line requires the use of more than twice as many trains as on the

Bakerloo line (79 vs. 34). Additionally, there is greater day-to-day consistency of blocks that end incorrectly on the Piccadilly line, but reassigned Train IDs tend to occur more frequently on the Piccadilly line.

It is instructive to consider the frequency with which Train ID blocks end at specific stations. If Train IDs consistently change at the same location, then action could be taken, either through back-end data processing or physical changes to track circuit infrastructure, to fix the problems. In the case of the Bakerloo line, approximately 30 Train ID blocks end incorrectly on the same section of northbound track between Queen's Park and Kensal Green each of the first four weekdays shown in Table 5-3; 74 Train ID blocks end at this location on the Friday. On the Piccadilly line for the same five weekdays, approximately 40 Train ID blocks end incorrectly each day at Bounds Green while nearly 20 Train ID blocks end incorrectly each day at Hatton Cross.

Fixing Train ID problems

A "sandwich" method has been developed to revise Train IDs stored in NetMIS in an effort to make the Train IDs consistent for each trip completed by a train. The goal is to join two Train ID blocks by determining if the events recorded in each block were associated with the same train. To do this, the general idea is to use Train IDs recorded for three trains at two consecutive stations. This method is illustrated in Figure 5-7. For simplicity, the trains in this diagram have one-digit Train IDs. The example in this figure assumes that the NetMIS data indicate that the Train ID block for Train 2 has ended southbound on the Bakerloo line at Charing Cross. Train 2 is then said to be "lost" at Charing Cross. NetMIS data show that the train recorded immediately before Train 2 at Charing Cross was Train 1 while the train recorded immediately after Train 2 at Charing Cross was Train 3. The NetMIS data also indicate that a new train, Train 4, was recorded between Trains 1 and 3 at Embankment. The conclusion using the sandwich method is that Train 2 and Train 4 are the same train.

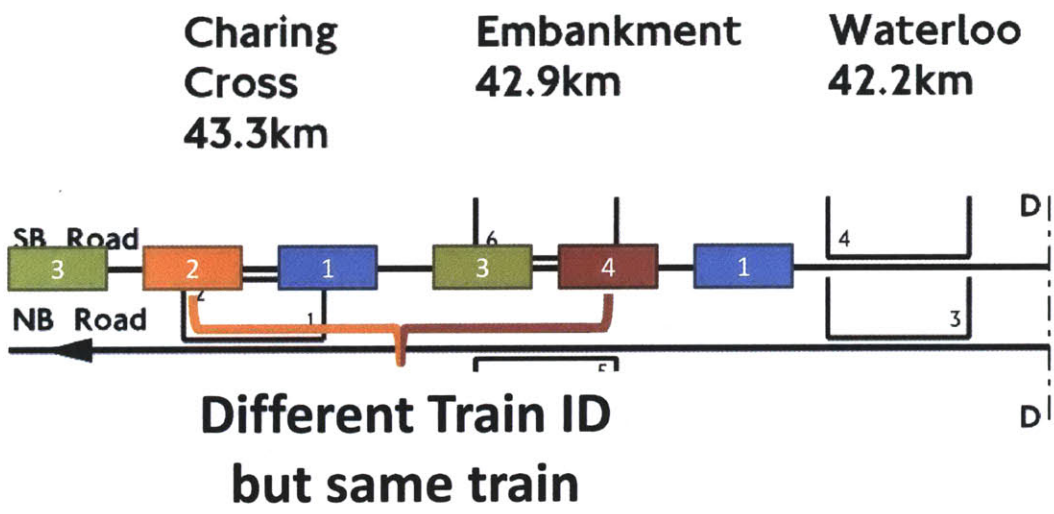


Figure 5-7: Illustration of the sandwich method for joining Train ID blocks

In reality, the process for joining Train ID blocks is not as simple as that illustrated in Figure 5-7. First, there are locations on each line where a phenomenon called Middle Train Replacement (MTR) can occur. MTR locations are stations where the middle train in a sandwich could get replaced between the MTR station and the next station. The problem caused by MTR stations while using the sandwich method is that the middle train recorded at the station after the MTR station may not be the same train as the one recorded in the middle of the sandwich at the MTR station. Therefore, in places where MTR can occur, the danger is that a lost train will be assigned the wrong Train ID using the sandwich method.

MTR is best illustrated at Arnos Grove on the Piccadilly line. As Frame A in Figure 5-8 shows, Train 1 begins at the outer eastbound platform at Arnos Grove. While Train 1 is at this platform, Train 2 stops at the middle platform and continues on to the next station, Southgate (Frame B). Next (Frame C), after Train 3 stops at the middle platform, Train 1 departs from the outer platform for Southgate. Train 3 remains at the center platform (Frame D) and Train 4 serves the outer platform (Frame E). Train 4 then departs for Southgate followed by Train 3 exiting the center platform and pulling into the Arnos Grove Sidings (Frame F).

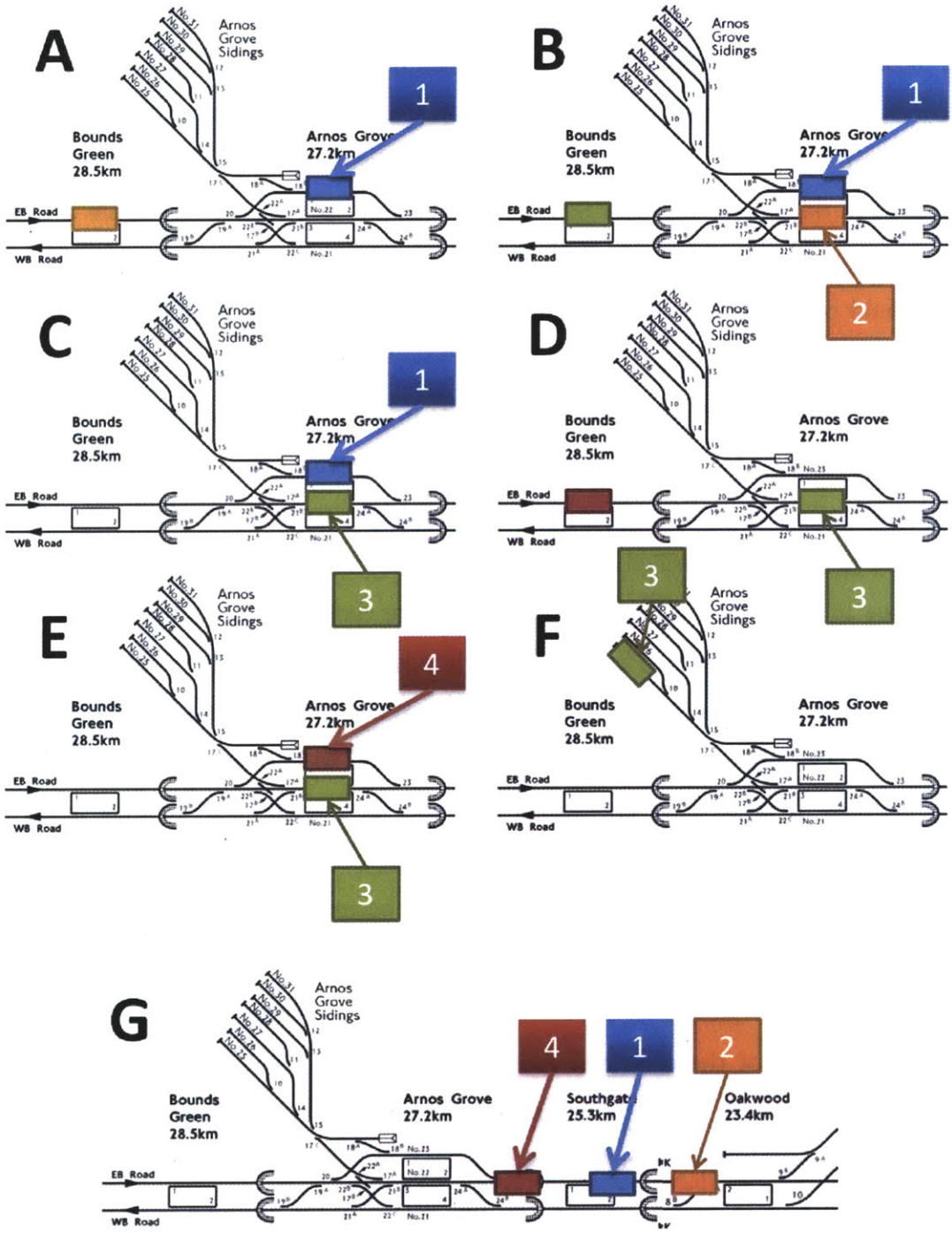


Figure 5-8: Example of Middle Train Replacement

Assume that the last time Train 3 was recorded in NetMIS was at the Arnos Grove center platform. The sandwich method will then try to match Train 3 with a train that is recorded at Southgate. In this case, the sandwich at the first station consists of Trains 2, 3, and 4 because these three trains arrive sequentially at Arnos Grove. Although Train 1 departs before Train 4 arrives, sandwiches are built based on arrival time instead of departure time. At Southgate, as shown in Frame G of Figure 5-8, the sandwich consists of Trains 2, 1, and 4. The problem in this scenario is that this method would conclude that Train 3 became Train 1 despite the fact that Train 3 actually pulled into the sidings.

It should be noted that trains generally do not provide through service at Arnos Grove from the center platform, which is what occurred in this example with Train 2. However, this scenario could happen, so it is important to be prepared for it. A complete list of stations classified as MTR locations for the Bakerloo and Piccadilly lines is given in Table 5-5. The MTR locations were chosen after consulting track diagrams for each line. It should be noted that it is assumed that MTR never occurs via single crossovers such as the one located between Warwick Avenue and Paddington in Figure 5-9. The reason for this is because trains need to reverse direction to use these crossovers. It takes train operators about four or five minutes[3] to walk from one end of the train to the other, so it is not feasible to use these single crossovers during normal operations. Additionally, for MTR to occur at a single crossover, one train in each direction would have to reverse via the crossover, a movement that is very unlikely as both trains might as well have continued in their original directions.

The effectiveness of the sandwich method is evaluated using conservative and liberal assumptions about MTR. When using the conservative MTR assumption, the full list of MTR stations given in Table 5-5 is used to determine where no attempt should be made to join blocks. Using the full list of MTR stations ensures that blocks are only joined when it is known that MTR cannot occur. Additionally, when a conservative set of MTR stations is used, a check is in place to ensure that the

[3]This estimate was provided by Chris Baitup, Technical Specialist in the Transport Planning group at London Underground.

Bakerloo	Piccadilly
Harrow & Wealdstone (L)	Cockfosters (L)
Stonebridge Park	Oakwood (EB only)
Kensal Green (SB only)	Arnos Grove
Queen's Park	Green Park (WB only)
Waterloo (SB only)	Hyde Park Corner (EB only)
Lambeth North (NB only)	Barons Court (WB only)
Elephant & Castle (L)	Hammersmith (EB only)
	Acton Town
	Northfields (EB only)
	Heathrow Terminal 5 (L)
	Sudbury Hill (WB only)
	South Harrow (EB only)
	Rayners Lane (WB only)
	Ruislip (WB only)
	Ickenham (EB only)
	Hillingdon (WB only)
	Uxbridge (L)

Note: Stations marked with (L) are included in
the conservative *and* liberal lists of MTR stations

Table 5-5: Middle Train Replacement locations on the Bakerloo and Piccadilly lines

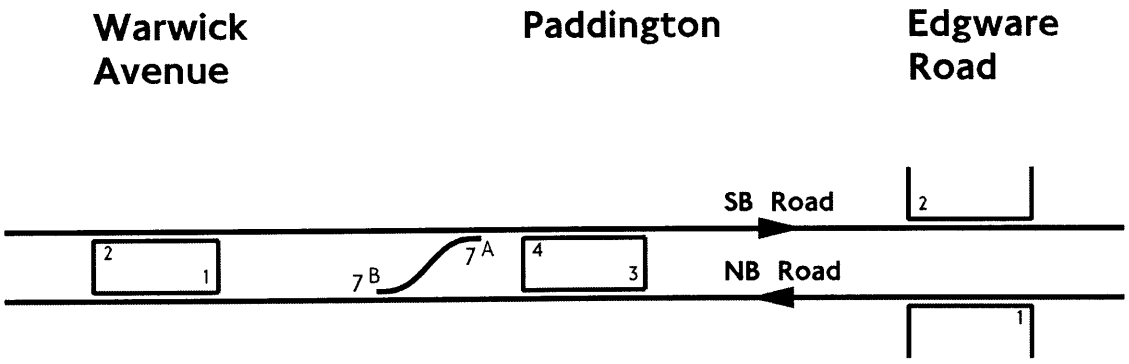


Figure 5-9: Example of a single crossover location on the Bakerloo line

same sandwich used to match two Train ID blocks exists at all stations between the station where the Train ID block ended and the previous MTR station or station where the line branches. Therefore, one can have full confidence that no mistakes were made when joining blocks using the conservative MTR approach. On the other hand, the liberal MTR assumption, which stipulates that the only stations classified as MTR locations are terminals[4], relies on the belief that it is very unlikely that MTR will occur at non-terminal stations. As a result, it should be possible to find more sandwiches and match more Train ID blocks when using the liberal MTR assumption.

No attempt is made to join blocks that end at an MTR station in order to prevent the realization of the errors discussed earlier that are associated with blocks ending at MTR stations. The number and percentage of all blocks ending on a given day that end at conservative and liberal sets of MTR stations between 07:00 and 22:00 are presented for the Bakerloo and Piccadilly lines in Tables 5-6 and 5-7. Not surprisingly, a higher percentage of blocks end at conservative MTR stations than liberal MTR stations. Additionally, these tables show that blocks ending at MTR stations cause more problems on the Bakerloo line than the Piccadilly line.

Tables 5-6 and 5-7 also show the frequency with which blocks are joined using conservative and liberal MTR stations. It is not surprising to see that a substantially higher percentage of blocks that end incorrectly are joined when liberal MTR stations are used than when conservative MTR stations are used. These tables also show that, although the percentage of blocks joined using each set of MTR stations is relatively constant across the five weekdays analyzed on the Piccadilly line, the proportion of blocks that end incorrectly on the Bakerloo line and get joined using either set of MTR stations varies substantially by day. While all of the incorrectly ending blocks that get joined will not contribute to a more accurate PWT estimation, especially on the Piccadilly line as Train IDs are not used to match trains between stations,

[4]Terminals are classified as MTR locations under the liberal MTR assumption for two reasons. First, MTR is more likely to occur at terminals than any other station because trains can arrive and/or depart from at least two platforms, and there are, at some terminals, berths beyond the platforms. Second, the complexity of the program used to join Train ID blocks using the sandwich method has (so far) prevented the development of an effective approach to joining blocks that end at a terminal.

	7/26	7/27	7/28	7/29	7/30
Blocks ending	146	236	304	167	249
Blocks ending at conservative MTR stations	132 (90%)	175 (74%)	155 (51%)	157 (94%)	212 (85%)
Blocks ending at liberal MTR stations	55 (38%)	76 (32%)	71 (23%)	65 (39%)	68 (27%)
Blocks ending incorrectly	40	94	182	52	112
Blocks joined using conservative MTR stations	8 (20%)	2 (2%)	9 (5%)	10 (19%)	6 (5%)
Blocks joined using liberal MTR stations	26 (65%)	16 (17%)	25 (14%)	25 (48%)	26 (23%)
New blocks joined based on revised Train IDs	3	1	2	5	6

Table 5-6: Frequency of Train ID blocks ending and joined on the Bakerloo line

the successfully joined blocks will make it easier for LU staff to follow specific trains while conducting analyses. Additionally, the joined blocks will improve the methods developed by Paul (2010).

As mentioned earlier, joined blocks affect the estimation of PWT on the Bakerloo line only if the two joined blocks cannot be matched using Train Number and Trip Number. The last row in Table 5-6 shows the number of blocks that could not be matched by using Train IDs or Train Numbers and Trip Numbers in the original NetMIS data but can be matched using Train IDs revised based on liberal MTR stations. When these values are compared to the number of blocks that need to be joined by using revised Train IDs in order for all blocks ending incorrectly to be joined by either Train ID or Train Number and Trip Number (see the last row of Table 5-3), it is seen that between 20% and 56% of these blocks are joined using revised Train IDs. For example, revised Train IDs allow for the joining of three of the seven blocks that need to be joined by revised Train IDs on July 26. Based on the results of estimating PWT for the five weekdays analyzed in this section, each new block that can be joined on the Bakerloo line based on revised Train IDs leads to a decrease in

	7/26	7/27	7/28	7/29	7/30
Blocks ending	299	244	216	242	328
Blocks ending at	100	94	93	93	123
conservative MTR stations	(33%)	(39%)	(43%)	(38%)	(38%)
Blocks ending at	48	49	52	49	64
liberal MTR stations	(16%)	(20%)	(24%)	(20%)	(20%)
Blocks ending incorrectly	121	117	91	120	179
Blocks joined using	26	20	22	27	38
conservative MTR stations	(21%)	(17%)	(24%)	(23%)	(21%)
Blocks joined using	40	33	33	38	71
liberal MTR stations	(33%)	(28%)	(36%)	(32%)	(40%)

Table 5-7: Frequency of Train ID blocks ending and joined on the Piccadilly line

estimated PWT during a specific timeband and day of between 0.2% and 1.1% when compared to the estimated PWT calculated when these blocks are not joined.

The choice of using the conservative or liberal MTR assumption comes down to a balance between risk and reward. The conservative MTR assumption is clearly the least risky, but it also offers substantially fewer opportunities to match Train ID blocks; the liberal MTR assumption is on the opposite end of the risk/reward tradeoff. Although MTR is technically feasible at all of the locations listed in Table 5-5, these stations are unlikely to experience MTR in typical operations because, at all non-terminal MTR stations on the Bakerloo line and nearly all non-terminal MTR stations on the Piccadilly line, MTR can occur only if either the original or new middle train reverses while occupying a portion of track used by all trains providing through service.

The MTR stations on the Piccadilly line that do not require trains to reverse while on through track for MTR to occur are Oakwood, Barons Court, Hammersmith, and Hillingdon. In the case of the latter three stations, MTR will not occur according to the Piccadilly line schedule because no westbound trains are scheduled to go out of service at the Uxbridge Sidings between Hillingdon and Uxbridge and the only trains scheduled to use the sidings between Barons Court and Hammersmith are eastbound trips reversing back to the west. Of all the non-terminal stations listed

in Table 5-5, MTR is most likely to occur eastbound at Oakwood because trains go out of service at the Cockfosters depot between Oakwood and Cockfosters and enter service at Cockfosters from the Cockfosters depot. Therefore, a Train ID block that ends when a train that goes out of service after Oakwood could get joined with a Train ID block that begins at Cockfosters. Although this is not desirable, it does not introduce significant error because it will only make it so the Train ID block that actually ended at Oakwood appears in the NetMIS data to end at Cockfosters, a difference of only one station.

As shown in the results of revising Train IDs earlier in this section, the conservative MTR assumption greatly reduces the effectiveness of the sandwich method. This result, combined with the belief that MTR will only occur in extreme circumstances, motivates the decision to use NetMIS data that has been revised using the liberal MTR assumption throughout this thesis, including when calculating PWT using revised NetMIS data. It should be noted that these extreme circumstances under which MTR may occur will very likely correspond with the existence of delays greater than 30 minutes. Because excess PWT will be determined by the Closures component of JTM when delays exceed 30 minutes, any errors caused by MTR will not be harmful because in these cases NetMIS data will not be used to calculate PWT.

Although a specific process is required to deal with the unlikely but error-causing phenomenon of MTR, more common train movements do not require special treatment to prevent errors from occurring when using the sandwich method. For example, consider the situation where a Train ID block ends at Station A and trains have access to a depot or siding between Station A and the next station, Station B. If a train enters service from the depot or siding after the first train in a sandwich arrives at Station B but before the lost train leaves Station A, then the desired sandwich will not exist at Station B. The sandwich method will fail in this case, but it will not erroneously conclude that two Train Events corresponded with the same physical train.

In addition to MTR, one other major exception to the simple sandwich presented in Figure 5-7 is that the first and last trains of the sandwich (Trains 1 and 3 in

Figure 5-7) are not automatically the trains immediately preceding and following the train that has its Train ID block ending. Northbound service on the Bakerloo line will be used to illustrate the choice of the first and last trains of a sandwich. Consider six trains, Trains A–F, that arrive sequentially at Queen's Park. Assume that Train C's Train ID block ends at Queen's Park. The two trains that would logically serve as the first and last trains of the sandwich around Train C are Trains B and D. However, if NetMIS data indicate that either Train B or Train D reverses at Queen's Park, then Train B and/or Train D will not be used as part of the sandwich. The reason for this is to increase the likelihood that Train ID blocks will be joined by using as a part of the sandwich only those trains that are known to serve the next station. It is important to note that if either Train B or Train D has its own Train ID block end at Queen's Park, then no effort is made to join Train C's block with a block that begins at the next station (Kensal Green) because it is known that the Train B-Train D sandwich does not exist at Kensal Green.

A check is in place to deal with the case of reversing trains while determining which Train IDs serve as the first and last trains of a sandwich. If NetMIS data indicate that the "logical" first and/or last train of a sandwich reverses, then the train before the logical first train and/or the train after the logical last train are tested to see if they can be used as either end of a sandwich. This process continues until a satisfactory sandwich is constructed. In the example from Queen's Park, if Trains B, D, and E reverse at Queen's Park, then Trains A and F are tested for their suitability as the first and last trains, respectively, of the sandwich. For the sake of this example, assume that Trains A and F do not reverse at Queen's Park and that their Train ID blocks continue beyond Queen's Park.

Once the first and last trains of a sandwich are set, the program determines if those two trains have only one train between them at the station immediately after the station where a Train ID block ends. In the Queen's Park example, this involves testing whether only one train is recorded at Kensal Green between the events recorded there for Trains A and F. If this is the case, the desired sandwich still exists at Kensal Green and the train recorded between Trains A and F at Kensal Green is

assumed to be the same train as Train C, the train with its Train ID block ending at Queen's Park.

Some practical issues related to how the Train ID revision program operates are worth noting. First, missing Train Events are added before the process of revising Train IDs begins, making it more likely that sandwiches will exist and that Train ID blocks will be joined. Second, an attempt to join one Train ID block with another Train ID block is only made if the first Train ID block ends before the maximum start time of all blocks on the given day. If one block ends after all other block starts, then it is known that there are no feasible Train ID blocks with which the ending block can be joined. Finally, when one Train ID block is joined to a second Train ID block, all Train Events in the second Train ID block receive the Train ID associated with the first Train ID block, and a flag is added to the data to indicate that the Train IDs in the second block have been revised. This will allow analysts using revised NetMIS data to easily identify, and eliminate, if desired, any Train Events that feature a revised Train ID.

5.1.3 PWT results using revised NetMIS data

Tables 5-8 and 5-9 present the estimated PWT using LU's PWT methodology with NetMIS data that has been revised using the methods introduced earlier in Section 5.1. That is, missing departure times and Train Events have been added to the original NetMIS data and Train IDs have been revised using the set of liberal MTR stations. Additionally, some basic pre-processing of Bakerloo line NetMIS data removes Train Events associated with National Rail trains and repetitive Train Events that, if not removed from the data set, would provide two or more departure times for the same train at one station. The percentages in parentheses in these tables give the percent difference between the estimated PWT calculated using original and revised NetMIS data. A positive (negative) percentage indicates that PWT is higher (lower) when revised NetMIS data are used. Figures 5-10 and 5-11 provide a graphical representation of the percent differences for the five days shown in the tables. In most cases on both lines, the magnitudes of these percent differences are less than

0.5%. Because the revised NetMIS data is more complete and robust than the original NetMIS data, it is known that the estimated PWTs calculated from revised NetMIS data are more accurate than those calculated from the original NetMIS data.

Figures 5-1 through 5-4, which show the timebands during which departure times and Train Events have been added at representative PWT stations on each day, along with knowledge about when revised Train IDs allow for the joining of previously unjoined blocks on the Bakerloo line, help explain the percent differences observed between the estimated PWTs calculated with original and revised NetMIS data. On the Bakerloo line, decreases in PWT when using revised NetMIS data are largely due to the revised data allowing more blocks to be joined, but added departure times and Train Events also contribute to reductions in PWT. For example, the added departure time on July 26 during timeband 4 (see Figure 5-1) turned a six-minute departure headway for the segment-to-segment OD group from Elephant & Castle to Queen's Park into two three-minute headways. Increases in PWT when using revised NetMIS data, which are particularly common during timeband 1, can be mostly attributed to the elimination of Train Events associated with National Rail trains and repetitive departure times that exist in the original NetMIS data; increases in PWT may also be due to the addition of departure times and Train Events that fall in the middle of a headway in the original data that was greater than 30 minutes plus the scheduled headway.

Because train identification data are not used to match trains between representative PWT and representative destination stations on the Piccadilly line, revised Train IDs do not affect Piccadilly line PWT. Instead, the changes in estimated PWT seen in Figure 5-11 are due to added departure times and Train Events. The effect of adding missing departure times is particularly noticeable on the Piccadilly line on July 26. On this day, the magnitude of the difference between the PWT estimated using original and revised NetMIS data is an approximate function of the number of added departure times and Train Events shown in Figures 5-2 and 5-4, respectively. The exceptionally large decrease in PWT during timeband 6 on July 26 is due to the

	Timeband					
	1	**2**	**3**	**4**	**5**	**6**
July 26, 2010	5.59 (1.2%)	2.03 (−1.0%)	1.99 (−0.3%)	1.89 (−0.1%)	2.17 (0.0%)	3.08 (0.0%)
July 27, 2010	4.66 (2.3%)	2.00 (−1.1%)	1.99 (0.0%)	2.04 (0.0%)	2.95 (0.1%)	3.00 (0.0%)
July 28, 2010	5.48 (2.3%)	2.01 (−0.9%)	2.05 (0.0%)	2.10 (0.0%)	2.37 (0.0%)	3.00 (0.0%)
July 29, 2010	4.84 (1.1%)	2.13 (0.0%)	2.00 (−0.2%)	1.91 (−0.1%)	2.18 (−0.1%)	3.01 (−0.6%)
July 30, 2010	5.42 (1.7%)	2.14 (−2.2%)	2.08 (−0.3%)	1.85 (0.0%)	2.11 (0.0%)	2.99 (0.0%)
4-week average	5.01 (4.3%)	2.04 (−0.4%)	2.08 (−0.1%)	2.07 (−0.2%)	2.39 (−0.3%)	3.19 (−0.1%)
	4-week line-level PWT estimate: 2.26 (0.1%)					

Table 5-8: Bakerloo line PWT estimates using LU's PWT methodology with revised NetMIS data

	Timeband					
	1	**2**	**3**	**4**	**5**	**6**
July 26, 2010	3.10 (−0.7%)	1.89 (−2.0%)	2.15 (−1.8%)	2.02 (−0.9%)	2.01 (−2.6%)	2.25 (−8.3%)
July 27, 2010	3.20 (0.0%)	2.10 (−0.1%)	2.18 (−0.5%)	1.75 (0.0%)	2.00 (−0.1%)	2.45 (−0.1%)
July 28, 2010	3.00 (0.0%)	1.86 (0.0%)	1.94 (0.0%)	1.89 (−0.2%)	2.11 (0.0%)	2.34 (−0.1%)
July 29, 2010	3.43 (0.0%)	1.88 (−0.8%)	1.91 (−0.1%)	1.84 (0.0%)	1.94 (−0.3%)	2.41 (−0.5%)
July 30, 2010	3.03 (0.0%)	1.95 (−1.8%)	1.93 (−0.1%)	2.22 (0.0%)	2.19 (0.0%)	2.30 (−0.3%)
4-week average	3.25 (−0.1%)	1.90 (−0.3%)	2.01 (−0.2%)	1.92 (−0.1%)	2.04 (−0.3%)	2.39 (−0.8%)
	4-week line-level PWT estimate: 2.05 (−0.2%)					

Table 5-9: Piccadilly line PWT estimates using LU's PWT methodology with revised NetMIS data

addition of seven departure times at South Harrow and two departure times at Hatton Cross. In general, these departure times cut in half 20-minute departure headways at South Harrow and 12-minute departure headways at Hatton Cross.

The number of departure times missing at representative PWT stations varies by line, day, and time of day, so the impact of correcting instances of missing departure times will also vary by line, day, and time of day but will not be known until the data has been collected and analyzed. For instance, the one missing departure time on the Bakerloo line on July 26, 2010 occurred between 16:00 and 19:00 (timeband 4). Adding this missing departure time to the NetMIS data for that timeband causes the estimated PWT during that timeband to decrease from 1.90 minutes to 1.89 minutes, a decrease of 0.1%. On the Piccadilly line on July 26, 2010, a total of 10 departure times are missing at representative PWT stations between 07:00 and 10:00 (timeband 2). Estimated PWT decreases by 2.0% when these departure times are added to the NetMIS data for this timeband.

An added departure time, whether it is added where only the departure time is missing or where both arrival and departure times are missing, is never observed to cause estimated PWT to change by more than 1% during a timeband-day combination on the five July weekdays analyzed. Further, no more than 12 instances of missing departure times are observed during a single timeband on a specific day. Therefore, an upper bound for the effect on estimated PWT of adding departure times to the original NetMIS data can be estimated. Specifically, if estimated PWT changes by 1% due to the addition of each of 12 departure times, then adding missing departure times should not cause estimated PWT to change by more than 12% during one timeband.

In order to conservatively estimate the impact of missing departure times on estimated PWT for a four-week period, assume there are 12 instances of missing departure times during each timeband on one weekday[5] each week and two instances of missing departure times during each timeband on the other six days, a reasonable assumption

[5]Because weekday demand is much higher than weekend demand, assigning the 12 instances of missing departure times to a weekday ensures the estimation of a conservative upper bound for the impact of missing departure times on estimated PWT.

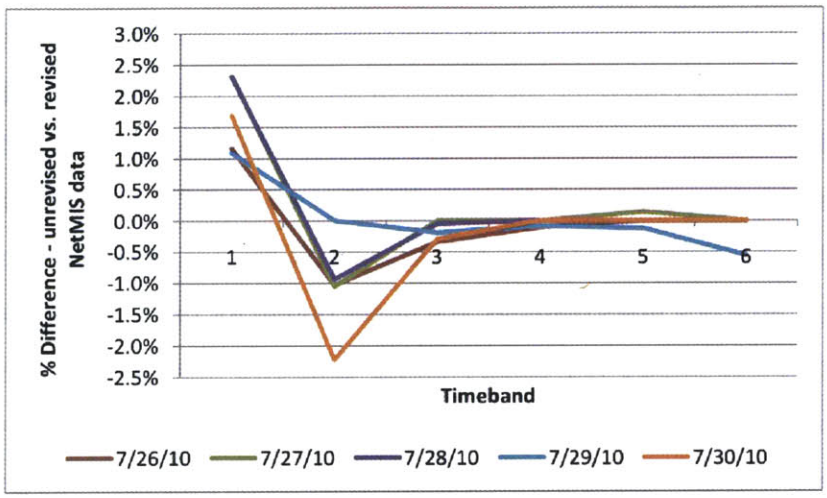


Figure 5-10: Change in PWT on the Bakerloo line using revised NetMIS data

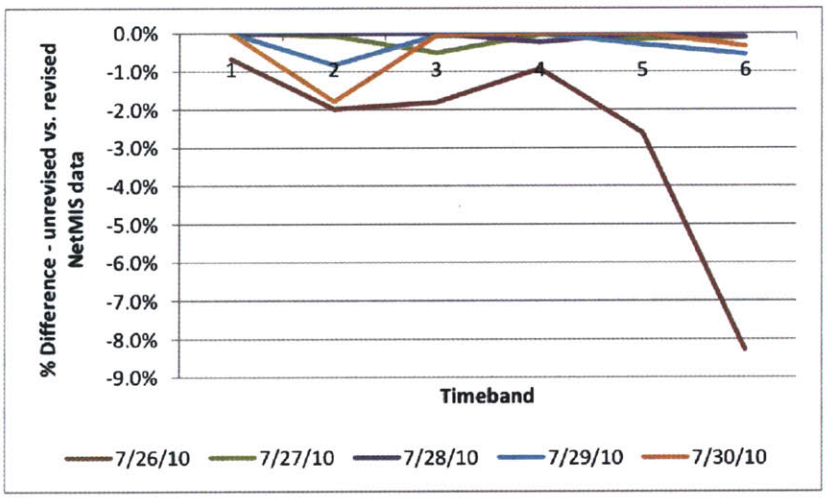


Figure 5-11: Change in PWT on the Piccadilly line using revised NetMIS data

given the missing departure times observed on the Piccadilly line. Additionally, assume that all weeks during a four-week period follow this pattern of missing departure times and that each missing departure time contributes a 1% change to the estimated PWT, which is the upper bound for the change in estimated PWT when a departure time is added. It then follows that the average estimated PWT for each weekday and weekend timeband is, respectively, $(12\% + 4 \cdot 2\%)/5 = 4\%$ and 2% different than the PWT estimated from original NetMIS data. Because the weekday timebands account for approximately 80% of a line's demand, the upper bound for the difference between the four-week-level estimated PWT using NetMIS data with missing departure times added instead of original NetMIS data is approximately $4\% \cdot 80\% + 2\% \cdot 20\% = 3.6\%$.

The four-week averages indicate that PWT estimates on both lines are generally between 0.1% and 0.5% smaller during the six weekday timebands when using revised NetMIS data than when using original NetMIS data. This result matches the general trend seen during the five days for which timeband-level PWT estimates are presented. The small magnitudes of the four-week line-level PWT estimates reflect the small differences seen in the timeband-level PWT estimates when original and revised NetMIS data are used. Two things should be noted, however, about the Bakerloo line-level PWT estimate. First, although PWT is, on average, 4.3% higher during timeband 1 when revised NetMIS data are used, only 1% of weekly demand on the Bakerloo line occurs during this timeband. Therefore, PWT estimates from this timeband have a very small impact on the line-level PWT estimate. Second, the line-level PWT estimate is (slightly) *larger* when revised NetMIS data are used on the Bakerloo line. Although the average effect of using revised NetMIS data during timebands 2-6 is a *smaller* PWT estimate, the PWT estimates during the weekend timebands are larger when revised NetMIS data are used and cause the revised-data line-level PWT estimate to be larger than the original-data PWT estimate.

5.2 London Underground's PWT methodology with more line segments

The PWT methodology used in this section differs only slightly from LU's PWT methodology presented in Chapter 4. Specifically, the number of line segments used when calculating PWT is higher with this methodology than LU's current methodology, but everything else from LU's PWT methodology still applies. The reason for increasing the number of line segments, and thus the number of representative PWT stations, when calculating PWT is to determine whether the PWT experienced by passengers varies substantially along long segments. Because LU's PWT methodology assumes that passengers at all stations in a segment experience the same PWT as passengers who board at the representative PWT station in the given segment-to-segment OD group, any variation in PWT that occurs across stations in a segment-to-segment OD group will not be captured by LU's methodology. However, intuition suggests that the PWT experienced by passengers will vary by station. The methodology presented in this section will test whether this intuition is correct.

LU's assumption that passengers boarding at all stations on a line segment experience the same PWT will be investigated by considering the longest segments on both the Bakerloo and Piccadilly lines. If PWT does not vary across these long segments, then it can be concluded that this assumption does not introduce significant error. The analysis of PWT on these long segments will not consider scheduled and excess PWT because the focus of this analysis is on how the *actual* PWT changes when smaller segments are used.

5.2.1 Definition of smaller segments

The longest segment on the Bakerloo line stretches from Queen's Park to Waterloo; approximately 23 minutes of running time is scheduled for trips serving the 14 stations in this segment. Depending on the timeband, between 73% and 79% of all Bakerloo line passengers board and alight on this segment in both directions weekdays from

07:00 to 22:00. Figure 5-12 shows how this long segment is split into three smaller segments – Queen's Park to Paddington (5 stations), Edgware Road to Piccadilly Circus (6 stations), and Charing Cross to Waterloo (3 stations). The first and last stations in each segment serve as a segment's representative PWT and representative destination stations, respecitvely. These smaller segments were created by ensuring that at least one station in each smaller segment has reliable NetMIS data and by taking into account where trains could feasibly reverse direction; between Queen's Park and Waterloo, trains can reverse only at Paddington and Piccadilly Circus.[6] It is important to note that the reason for using smaller segments in this methodology is not to account for instances when trains may reverse within a long segment. Instead, the goal of this methodology is to determine whether PWT varies between stations on long segments due to changing headways along the segment.

The Piccadilly line's longest segment runs from Arnos Grove to Acton Town, covering 25 stations in 54 minutes of scheduled running time. Depending on the timeband, between 70% and 82% of all Piccadilly line passengers board and alight on this segment in both directions weekdays from 07:00 to 22:00. As shown in Figure 5-13, this segment from Arnos Grove to Acton Town is split into five segments, with the segments varying slightly by direction. The westbound segments are Arnos Grove to Wood Green, Turnpike Lane to King's Cross St. Pancras, Russell Square to Green Park, Hyde Park Corner to Hammersmith, and Hammersmith to Acton Town; the eastbound segments are Acton Town to Hammersmith, Barons Court to Hyde Park Corner, Green Park to King's Cross St. Pancras, Caledonian Road to Wood Green, and Bounds Green to Arnos Grove. The first station in each segment serves as that segment's representative PWT station. Like those on the Bakerloo line, these smaller segments on the Piccadilly line were created to ensure the existence of at least one station with reliable NetMIS data in each section and based on the locations where Piccadilly line trains can reverse or go out of service. Because LU's PWT methodology does not verify that Piccadilly line trains reached their destination, care

[6]Although trains can feasibly reverse at these locations, reversing only occurs at these locations in emergencies.

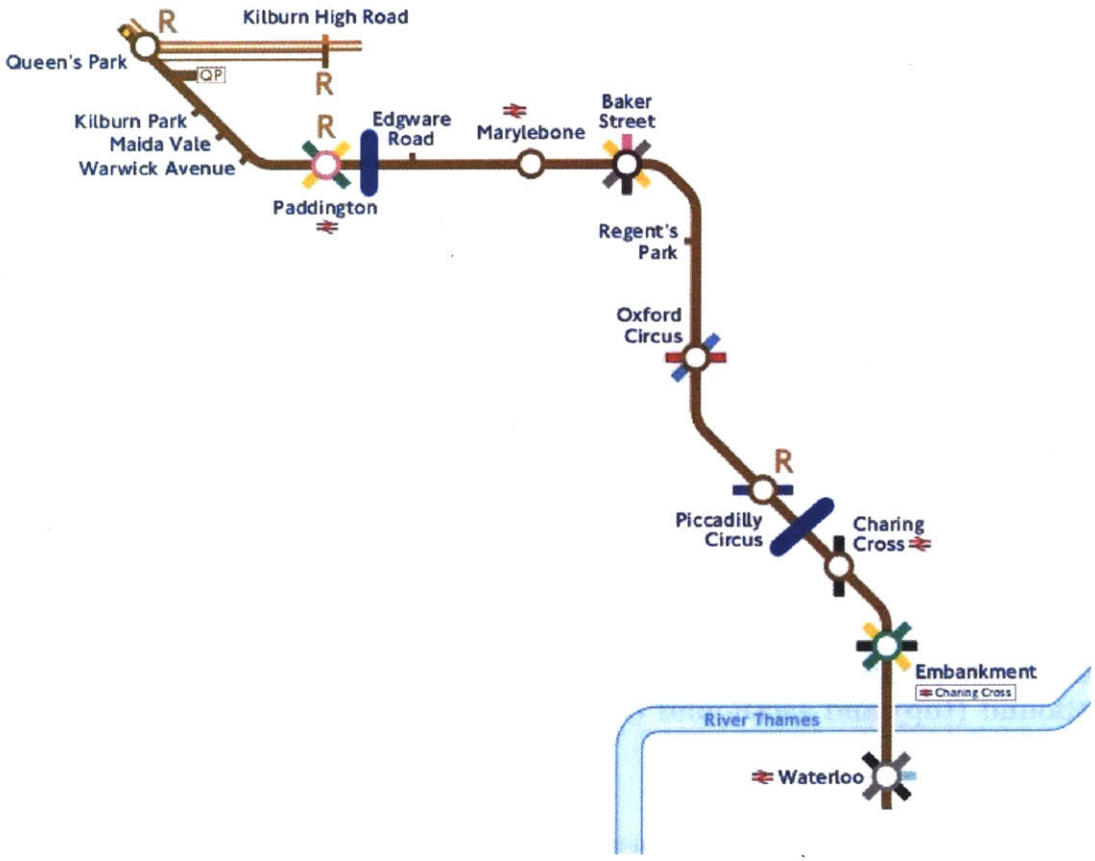


Figure 5-12: Smaller segments on the central portion of the Bakerloo line

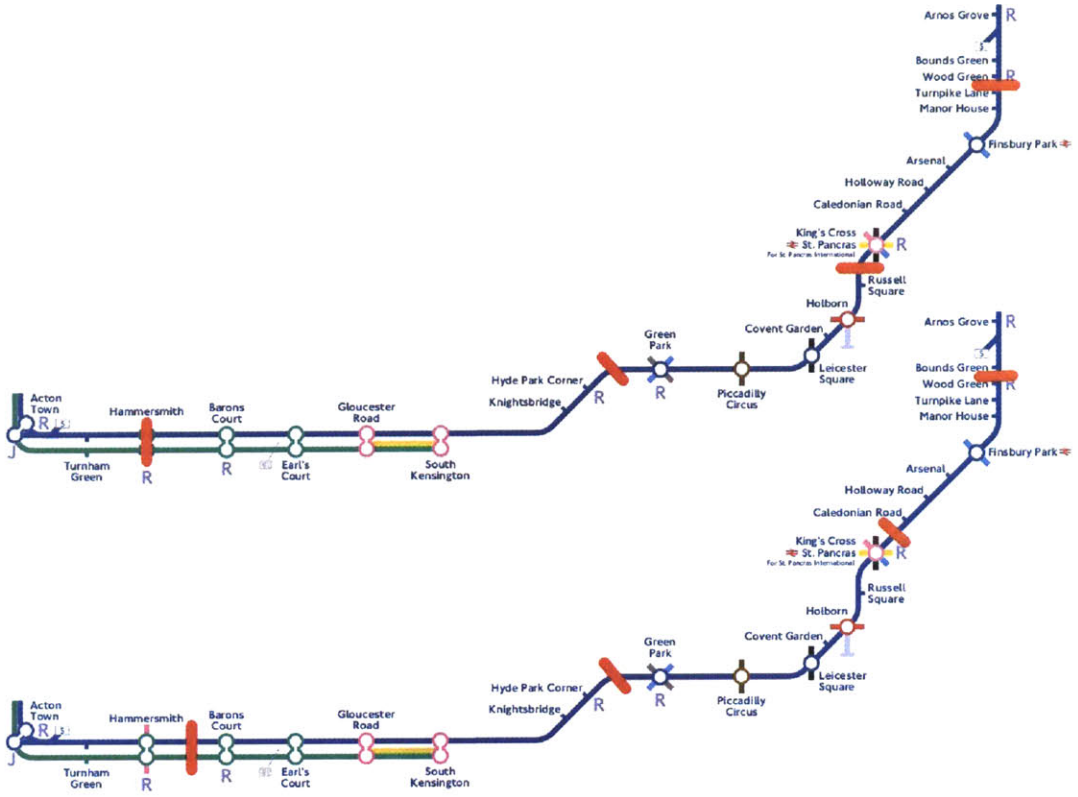


Figure 5-13: Smaller segments on the central portion of the Piccadilly line westbound (top) and eastbound (bottom)

was taken to define these smaller segments such that PWT will be the same on each segment even if a train reverses or goes out of service at one of the reversing locations.

5.2.2 Results

For the Bakerloo and Piccadilly lines, PWT is calculated for each of the smaller segment-to-segment OD *pairs* in each direction. Thus, six PWTs are calculated in each direction on the Bakerloo line and 15 PWTs are calculated in each direction on the Piccadilly line. The PWTs are calculated using the original NetMIS data.

The results from using these smaller segments to calculate PWT are presented in Tables 5-10 and 5-11.

The values in these tables are the result of performing several calculations on the estimated PWT for each segment-to-segment OD pair on each line. Although only one segment is analyzed for each line, this one segment corresponds to two (one in each direction) segment-to-segment OD pairs. The steps used to obtain the values in the tables are as follows:

1. Calculate demand weightings for each segment-to-segment OD pair. These demand weightings are the ratio of passengers boarding in the origin segment and alighting in the destination segment to the total number of passengers boarding and alighting on the long segment-to-segment OD pair (e.g., Queen's Park to Waterloo) being analyzed.

2. Apply the segment-to-segment OD pair demand weightings to each OD pair's estimated PWT to calculate for each timeband and day a weighted PWT for the long segment being analyzed. This weighted PWT can be compared to the estimated PWT calculated on the long segment using LU's current PWT methods.

3. Calculate the percent difference between the PWT calculated on a long segment split into smaller segments and LU's current PWT methodology.

4. Multiply these percent differences, which are given by timeband and day, by the proportion of a line's total passengers who board and alight on the given long segment-to-segment OD pair during a specific timeband. These proportions are given for timebands 2–5 in Tables 3-5 and 3-8.

5. Sum the products calculated in the previous step to obtain the amount by which PWT estimated using LU's current PWT methodology would change during each timeband if smaller segments were used on only the two segment-to-segment OD pairs analyzed for each line. The products must be summed

because, for each timeband and day, there is an estimate for how much PWT would change for *each direction* on the long segment.

Tables 5-10 and 5-11 present the results produced by this final step. For example, the estimated PWT for all Bakerloo line passengers traveling during timeband 2 on July 27 would be approximately 1.2% greater if PWT were calculated using smaller segments between Queen's Park and Waterloo instead of treating this group of stations as one segment as LU does currently. Similarly, using smaller segments between Arnos Grove and Acton Town on the Piccadilly line would lead to a 0.4% decrease in the estimated PWT for all passengers traveling during timeband 5 on July 29.

These results indicate that PWT varies along longer segments. Additionally, these results indicate that using smaller segments increases the robustness of LU's PWT methodology. For example, as noted earlier, more eastbound trains are recorded at Acton Town, especially in the early morning and late evening, than serve stations east of Acton Town. The large positive difference between calculating PWT using smaller and larger segments during timeband 1 on the Piccadilly line shows that LU's PWT methodology substantially underestimates PWT for passengers traveling eastbound on the trunk portion of the line. The severity of the data problem at Acton Town during timeband 1 is illustrated in Table 5-12, which shows that estimated PWT for eastbound trains at Acton Town is between 48% and 76% less than the estimated PWT for eastbound trains two stations away at Barons Court, which is known to have consistent and accurate NetMIS train recordings on each of the five weekdays analyzed.

The contribution of smaller segments to a more robust PWT methodology can be seen in a different example where using smaller segments allows for the capturing of a scenario during timeband 5 on July 27 when northbound Bakerloo line trains were either reversing after Paddington or trains were not recorded in either direction at Queen's Park. Because Queen's Park is a representative PWT station and a representative destination station in LU's methodology, those passengers traveling to or from stations between Waterloo and Paddington are not assigned the longer PWT experienced by passengers traveling to or from stations between Queen's Park

	Timeband					
	1	**2**	**3**	**4**	**5**	**6**
July 26, 2010	0.4%	0.5%	0.3%	0.9%	−0.9%	−3.4%
July 27, 2010	2.0%	1.2%	0.2%	−1.8%	−9.6%	−1.8%
July 28, 2010	1.6%	0.0%	1.1%	−0.3%	−1.1%	−2.6%
July 29, 2010	1.9%	0.7%	0.3%	0.7%	−0.4%	−3.5%
July 30, 2010	1.9%	0.8%	−0.3%	1.4%	−0.9%	−4.1%

Table 5-10: Impact of smaller segments on PWT estimates on the Bakerloo line

	Timeband					
	1	**2**	**3**	**4**	**5**	**6**
July 26, 2010	10.4%	5.5%	3.0%	−2.6%	0.7%	−1.1%
July 27, 2010	8.9%	0.8%	3.0%	1.4%	−0.9%	1.9%
July 28, 2010	21.3%	1.9%	5.9%	3.3%	0.4%	1.0%
July 29, 2010	18.8%	8.6%	2.9%	4.0%	−0.4%	−4.4%
July 30, 2010	14.1%	2.8%	2.1%	7.7%	0.7%	2.2%

Table 5-11: Impact of smaller segments on PWT estimates on the Piccadilly line

	7/26	**7/27**	**7/28**	**7/29**	**7/30**
Acton Town	1.51	1.46	1.54	1.33	1.40
Barons Court	3.22	2.83	4.30	5.48	3.32

Table 5-12: Eastbound PWT estimates at Acton Town and Barons Court during timeband 1

and Paddington when smaller segments are used. As a result, the estimated PWT when smaller segments are used is approximately 9.6% lower for all Bakerloo line passengers during timeband 5 on July 27 than when one longer segment is used to estimate PWT.

The overall trend in the signs on the percent changes in Tables 5-10 and 5-11 deserves discussion. As Table 5-10 shows, the difference in estimated PWT on the Bakerloo line when smaller segments are used instead of one longer segment transitions from being positive in the beginning of the day to negative at the end of the day. This indicates that train headways tend to increase as trains move in both directions along the Waterloo-Queen's Park segment earlier in the day but that they tend to decrease later in the day. One hypothesis is that the locations where passengers board and alight at different times of day contribute to these varying headways. The general idea is that headways will increase (decrease) when trains move from segments with higher (lower) demand to segments with lower (higher) demand because of track signal capacity restrictions. That is, when segments have higher passenger demand, dwell times will be higher and bottlenecks will form as trains have to wait for the downstream track to clear. These bottlenecks will lead to shorter headways at crowded stations.

The distribution of demand between Waterloo and Queen's Park and the percent differences in estimated PWT on the Bakerloo line as shown in Table 5-10 reflect this hypothesis about how headways vary along a line. For passengers traveling southbound from Queen's Park to Waterloo during timeband 2, 51% of passengers board between Queen's Park and Paddington while 33% of passengers alight between Charing Cross and Waterloo. However, the analogous values for timeband 5 are 24% for boardings from Queen's Park to Paddington and 58% for alightings from Charing Cross to Waterloo. For passengers traveling northbound from Waterloo to Queen's Park during timebands 2 and 5, respectively, 60% and 39% of passengers board between Waterloo and Charing Cross while 27% and 41% of passengers alight from Paddington to Queen's Park. Thus, for both northbound and southbound trips, trains move from segments with higher demand to segments with lower demand during time-

band 2 and from lower demand to higher demand during timeband 5. As Table 5-10 shows, and as expected given the discussion in the previous paragraph, PWT increases as trains move along the Waterloo-Queen's Park segment during timeband 2 and decreases during timeband 5. Although not discussed in detail here, similar shifts in the location of demand along the Piccadilly line occur over the day, but the impact of these shifts is not as pronounced in the percent changes seen in Table 5-11.

Although introducing smaller segments on all lines would undoubtedly increase the accuracy of PWT estimations, the gains from this change in methodology must be weighed against the cost of using this new methodology. For example, it would take a non-trivial amount of time to automate this new methodology. Further, the time invested to automate this methodology may yield no PWT accuracy improvements on some lines as it may not be feasible to create smaller segments from longer segments if there is only one station in the longer segment that has reliable NetMIS data. Finally, adding more segments would increase the computation time required each time someone wants to estimate PWT.

5.3 Train-count-based platform wait time

The theory behind the train-count-based (TCB) PWT methodology is that the number of trains serving a specific OD pair can be determined by counting the number of trains recorded in the origin and destination segments of a line. The motivation for developing this methodology comes from the desire to eliminate the need to use (sometimes unreliable) train identification data to calculate PWT on lines with good NetMIS data and to make the estimation of PWT on all lines more robust. This new methodology still requires dividing a line into multiple segments with each segment containing stations that (usually) receive the same frequency of service. The TCB PWT methodology will use the same segments defined in LU's current PWT methodology. (See Figures 3-4 and 3-5 for the Bakerloo and Piccadilly line segments.) Although the results presented in Section 5.2.2 demonstrate that splitting long segments into smaller segments will increase the accuracy of PWT estimates, the use of

smaller segments with the TCB PWT methodology is left for future work. Average PWT is based on the departure headways at one representative station ("representative PWT station") in a segment-to-segment OD pair and will be calculated using Equation (4.1), consistent with current LU practice.

5.3.1 Methodology

Step 1: Eliminate potential representative PWT stations

Before applying the TCB PWT methodology to a specific line, it is important to determine if some stations should not be used as representative PWT stations. An analysis must be conducted of the number of departure time records in each direction at each station to make sure that one station-direction combination in a segment does not have more departure time records than all other station-direction combinations in the same segment. If this occurs, more in-depth analysis must be conducted to determine if this high count of departure time records is due to erroneous NetMIS data. For example, multiple Train Events could be generated for the same train at one station. When flawed NetMIS data is the source of a high number of departure time records, the station and associated direction should be removed from the pool of possible representative PWT stations. In the case of the Bakerloo and Piccadilly lines, three stations, all on the Piccadilly line, are removed from the list of potential representative PWT stations due to having erroneously recorded departure time records. The stations removed are Acton Town, Ealing Common, and South Harrow; all three stations are removed in both directions.

Three other Piccadilly line stations are removed from the list of potential representative PWT stations to account for the way LU has defined track sections. On the Uxbridge branch of the Piccadilly line, 13 trains are scheduled to reverse at Ruislip each weekday, eight during the AM peak and five during the PM peak. However, the way LU has defined segments assumes that all stations from Eastcote to Uxbridge receive the same frequency of service. (Approximately 1% of Piccadilly line passengers travel to or from the stations from Eastcote to Uxbridge.) LU accounts for the

difference in service frequency on this segment by using Ickenham as the representative PWT station in their PWT methodology. In the TCB PWT methodology, Eastcote, Ruislip Manor, and Ruislip are removed from the list of potential representative PWT stations in both directions because they receive a higher frequency of service. By doing this, the calculated PWT will be overestimated for passengers traveling to and from Eastcote, Ruislip Manor, and Ruislip.

Step 2: Place departure times at destination stations in the correct timeband

The time offset applied in order to count the number of trains recorded at a destination that started their trip at the origin during a given timeband (timebands are defined in Table 3-1) varies based on origin segment and timeband. Consider the case of the AM peak, which starts at 07:00 and ends at 10:00. When measuring PWT for passengers traveling from Station A to Station Z, where Station A is the first station where trains originate for the given line and direction, the number of trains observed at Station Z will be the count of trains between $0700 + x_{A,Z,2}$ and $1000 + x_{A,Z,2}$, where $x_{A,Z,2}$ is the scheduled running time from Station A to Station Z during timeband 2. If there is a second station, Station B, where trains originate for the given line and direction, then the number of trains observed at destination Station Z that served Station B will be the count of trains between $0700 + x_{B,Z,2}$ and $1000 + x_{B,Z,2}$, where $x_{B,Z,2}$ is the scheduled running time from Station B to Station Z during timeband 2. In general, the period of time considered at destination station Z when trips begin at origin station A during timeband tb is $Start_{tb} + x_{A,Z,tb}$ to $End_{tb} + x_{A,Z,tb}$, where $Start_{tb}$ and End_{tb} are, respectively, the start and end times of timeband tb and $x_{A,Z,tb}$ is the scheduled running time from Station A to Station Z during timeband tb.

Step 3: Intra-segment representative PWT stations

The choice of a representative PWT station depends on the type of trip for which average PWT is being calculated. For trips such as the one from Embankment to Regent's Park on the Bakerloo line that are contained within one segment, the repre-

sentative PWT station will be the station in that segment with the maximum number of recorded train departures during a given timeband. Because segments contain stations that usually receive the same frequency of service, any discrepancy between the number of train departures recorded at each station in a segment will be strictly the result of poor NetMIS data. If multiple stations in one track segment have the maximum number of departure time records, then the representative PWT station in that segment is the first station in the segment with the maximum number of departure time records.

Step 4: Inter-segment representative PWT stations

A two step process is required to choose a representative PWT station for inter-segment trips such as the one from Embankment to Stonebridge Park on the Bakerloo line. First, determine the station in each segment with the maximum number of recorded train departures. Then, consider the stations with the maximum number of recorded train departures ("maximum departure stations") in each segment that is traversed for a given OD pair. Because some trains will reverse direction at the end of one segment before entering the next segment, the station from this group of maximum departure stations with the minimum number of recorded train departures indicates the number of trains that served all segments between a given OD pair and is used as the representative PWT station for the OD pair. If two or more maximum departure stations have the minimum number of departure time records, then the representative PWT station for the given segment-to-segment OD group is the maximum departure station in the segment that is closest to the origin.

Step 5: Calculate average PWT

Average PWT is calculated for each segment-to-segment OD *pair*; the segment-to-segment OD *groups* from LU's PWT methodology are not used. Using OD pairs creates a more robust PWT methodology because more representative PWT stations are used with OD pairs than OD groups. The Bakerloo line has 10 segment-to-segment OD pairs in each direction while the Piccadilly line has 17 segment-to-segment OD

pairs in each direction. The departure headways at each segment-to-segment OD pair's representative PWT station during each timeband are used to calculate average PWT. The formula used to calculate average PWT is identical to the formula used in LU's current PWT methodology and is shown in Equation (4.1).

With the exception of the few passengers who travel from one branch of the Piccadilly line to the other, all passengers on the Bakerloo and Piccadilly lines are assumed to wait at their origin for the first train that serves their destination. Passengers traveling from one branch of the Piccadilly line to the other are assumed to board the first train that goes to Acton Town, where they will transfer to reach their destination. PWT for these transferring passengers will be measured only at their origin, consistent with LU's current PWT methodology. Although the schedule indicates that there are some instances when the frequency of trains serving a given destination is higher on the trunk portion of the line than at a particular non-trunk origin, nearly all of these instances occur in the early morning or late at night. Therefore, for the vast majority of passengers, it is not advantageous to board a train that does not serve their destination with the plan of switching to a train serving their destination at a downstream location. In fact, the disutility experienced by passengers when they have to transfer will likely make this transferring strategy unattractive.

Step 6: Calculate timeband-level PWT

Demand weightings that give the proportion of passengers boarding in an origin segment and alighting in a destination segment are calculated for each of the segment-to-segment OD pairs based on 2002 ridership data. These demand weightings are applied to the calculated PWTs as shown in equation (4.2) to obtain the timeband-level PWT estimate for a given day.

TCB PWT strengths

The TCB PWT methodology offers several benefits over LU's PWT methodology. First, the TCB PWT methodology does not rely on the matching of trains between origin and destination based on train identification data, but LU's PWT methodology

on lines with good NetMIS data does require this matching. As seen in Table 5-3, 11 or fewer instances exist on each of five consecutive weekdays on the Bakerloo line where Train ID blocks from the original NetMIS data cannot be matched by Train ID or Train Number and Trip Number. Further, as noted in Section 5.1.2, the matching of one additional Train ID block on the Bakerloo line causes estimated PWT to decrease by 0.2% to 1.1%. By eliminating the use of train identification data to estimate PWT, the TCB PWT methodology removes these estimation errors that exist when train identification data do not allow trains to be matched between an origin and destination.

Second, the TCB PWT methodology is more robust than LU's PWT methodology because, although LU staff have chosen representative PWT stations that tend to have reliable NetMIS data, LU's PWT methodology experiences decreased accuracy if a representative PWT station unexpectedly has poor NetMIS data. Because the TCB PWT methodology chooses a representative PWT station based on the NetMIS data available for all stations in a segment for a specific timeband and day, it will not suffer from a similar loss of accuracy unless *all* stations in a segment have poor NetMIS data during a specific time period. This dynamic choice of a representative PWT station leads to increased PWT estimation accuracy on lines with both good and bad NetMIS data.

TCB PWT weaknesses

When using the TCB PWT methodology, it is possible for the representative PWT station to be in the destination segment of a segment-to-segment OD pair. This creates a potential weakness for the TCB PWT methodology, especially for long trips, as the average PWT calculated in the destination segment may not accurately reflect the average PWT experienced by passengers when boarding in the origin segment. An extensive analysis was completed on the Bakerloo and Piccadilly lines over five consecutive weekdays from 07:00 to 22:00 to determine by how much the calculated PWT varies when it is based on departure headways in the destination segment instead of the origin segment. In this analysis, the departure headways are based on only

those trains that are recorded at both the origin and destination stations. Although the TCB PWT methodology will not use train identification data to match trains between origin and destination, trains are matched between origin and destination based on Train ID in this analysis of the robustness of the TCB PWT methodology. If a Train ID changes mid-trip, then that train's departure times at the origin and destination are not included in the PWT calculation. The set of departure headways used to calculate PWT at the destination are based on a "shifted timeband." This shifted timeband begins when the first train that leaves the origin during the given timeband arrives at the destination. Similarly, the last train that leaves the origin during the given timeband and arrives at the destination marks the end of the shifted timeband.

The initial list of departure times at the origin and destination include the departure times of trains that leave the origin during the given timeband and arrive at the destination during the shifted timeband. Departure times are eliminated from this list based on the matching of trains based on Train ID and the scheduled running time from the origin to the destination. If the same Train ID is associated with a departure time at the origin and destination, then a check is made that the actual running time between these two departure times is between 80% of the scheduled running time and 30 minutes more than the scheduled running time. The 80% and 30-minute values are used to ensure that the Train ID recorded at the destination corresponds with the same trip during which the same Train ID was recorded at the origin. The 80% value was chosen because it allows for faster-than-expected running times while not being so loose as to allow train matching errors; the 30-minute value was chosen because any discrepancy in the PWT as measured at the origin and destination will not be important since the Closures component of JTM is used when delays exceed 30 minutes. This same process of determining which departure times to use is completed for departure times recorded at the destination to ensure that trains recorded at the destination were also recorded at the origin.

PWT is calculated at the origin and destination ends of only select segment-to-segment OD pairs. Specifically, the only OD pairs included in this analysis are those

where there are fewer trains scheduled to serve the destination segment than the origin segment. In these cases, the TCB PWT methodology will determine PWT based on the departure headways in the destination segment. Six OD pairs satisfy this constraint on the Bakerloo line while seven OD pairs do so on the Piccadilly line. In this analysis, the representative PWT station is the second station in the origin segment and the second-to-last station in the destination segment. The first and last stations are not used in the origin and destination segment to eliminate problems caused by trains not being recorded when they reverse. For clarity, however, the first and last stations in each segment are used to refer to each segment.

Figures 5-14 and 5-15 show the percent difference in the average PWT measured at the destination and origin stations for three segment-to-segment OD pairs on the Bakerloo and Piccadilly lines; a positive value indicates that PWT is higher when measured at the destination. The six OD pairs included in these figures are the three OD pairs on each line with the highest proportion of passengers on weekdays from 07:00 to 22:00 when considering only those OD pairs that have less scheduled service in the destination section than the origin section. Each OD pair's share of the line's total passengers during each timeband is shown in Table 5-13. These values represent all passengers boarding in the *From* segment and alighting in the *To* segment, where the segments are defined for the Bakerloo line in Figure 3-4 and for the Piccadilly line in Figure 3-5. All six OD pairs analyzed have their highest weekday ridership during the PM peak (timeband 4), so the values in Figures 5-14 and 5-15 come from the PM peak.

Table 5-14 provides some context for the information presented in Figures 5-14 and 5-15. Specifically, Table 5-14 shows the average PWTs for the three OD pairs being analyzed on the Bakerloo and Piccadilly lines for the week of July 26-30, 2010. This table also presents the average number of departure times used to calculate these average PWTs and the average number of departure times recorded at the station in each OD pair that receives a lower frequency of service. The difference between these two values gives the number of trains that could not be matched between origin and destination based on Train ID. Because this difference is small for all OD pairs,

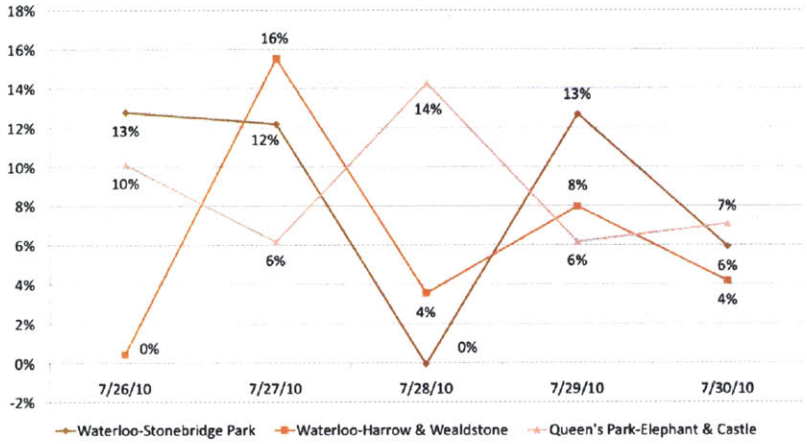


Figure 5-14: Difference in PWT between the origin and destination on the Bakerloo line during the PM peak

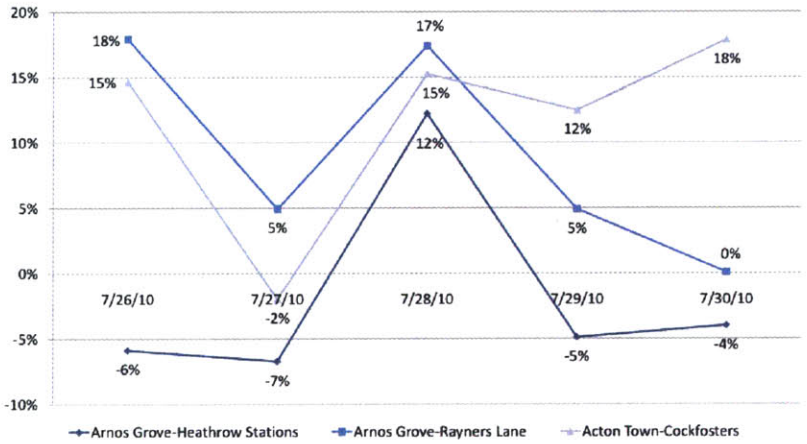


Figure 5-15: Difference in PWT between the origin and destination on the Piccadilly line during the PM peak

From	To	Timeband 2	3	4	5
Waterloo	Stonebridge Park	0.03	0.04	0.04	0.03
Waterloo	Harrow & Wealdstone	0.01	0.02	0.02	0.01
Queen's Park	Elephant & Castle	0.03	0.04	0.05	0.06
Arnos Grove	Heathrow	0.03	0.04	0.05	0.04
Arnos Grove	Rayners Lane	0.01	0.02	0.04	0.02
Acton Town	Cockfosters	0.01	0.02	0.03	0.02

Table 5-13: Proportion of ridership by OD pair on the Bakerloo and Piccadilly lines

From	To	Departure headways at	Departure times	Departure times used	Average PWT
WLO	SPK	WLO		25	4.53
		SPK	27	25	5.00
WLO	HAW	WLO		16	6.55
		HAW	18	16	6.98
QPK	ELE	QPK		64	1.53
		ELE	64	64	1.67
AGR	HRA	AGR		32	3.83
		HRA	36	32	3.76
AGR	RLN	AGR		24	4.60
		RLN	28	24	5.10
ACT	CFS	ACT		49	2.37
		CFS	50	49	2.67

Table 5-14: Average PWT at the origin and destination during the PM peak on the Bakerloo and Piccadilly lines

the average PWT values are known to be based on nearly all trains that served the lower and higher frequency stations in each OD pair, thus providing an accurate estimation of the difference between PWT as measured at the origin and destination stations. It is important to note that a large number of Train IDs changed during northbound trips on the Bakerloo line on July 28, 2010 and during westbound trips serving stations west of Acton Town on the Piccadilly line on July 30, 2010. As a result, data from the affected OD pairs were left out of the calculation of the values in Table 5-14.

Figure 5-14 shows that the percent difference between PWT at the origin and destination ends of a Bakerloo line OD pair can vary substantially by day. For the five days and three ODs analyzed, the percent difference between PWT measured at the origin and destination generally fluctuates from 4% to 13% but may be as low as 0% or as high as 16%. As shown in Figure 5-15, PWT is generally about 5% lower at Heathrow than at Arnos Grove, but PWT tends to be 5% to 18% higher at Rayners Lane than Arnos Grove. Passengers traveling eastbound from Acton Town usually experience approximately 15% less PWT than passengers who board at Cockfosters during this week in July 2010. (In reality, passengers would never board eastbound trains at Cockfosters, but this example helps demonstrate the weakness of using departure headways at the destination to measure PWT at the origin when using the TCB PWT methodology.) Additional analysis indicates that the absolute percent differences between origin and destination PWT are no more severe during timebands 2, 3, and 5 than during timeband 4.

The results presented in Figures 5-14 and 5-15 illustrate one of the weaknesses of the TCB PWT methodology. That is, in most cases, the actual PWT experienced by passengers will be lower than the PWT calculated using the departure headways of trains in the destination segment. As these figures show, the discrepancy from using departure headways from the destination instead of the origin to calculate PWT can reach close to 20%. Although this finding raises a serious accuracy concern when analyzing PWT for a specific timeband, day, and one of the six OD pairs on the Bakerloo line or the seven OD pairs on the Piccadilly line where fewer trains

are recorded in the destination segment than the origin segment, the severity of this accuracy issue decreases substantially when PWT results are aggregated to the timeband, day, and four-week period levels.

When the PWT for passengers traveling on a specific OD during a given timeband and day is weighted by the proportion of passengers traveling on that OD during the given timeband, the impact of any difference between the calculated and actual PWT on the timeband-level PWT will be determined by the OD's demand weighting. In the case of the six ODs on the Bakerloo and Piccadilly lines presented here, passengers traveling during a specific timeband who board and alight on one of the line's three OD pairs analyzed here make up no more than 13% of the line's total passengers. When the Bakerloo's three other OD pairs and the Piccadilly's four other OD pairs that have more scheduled service at the origin than the destination are included, no more than 20% of a line's total passengers during a specific timeband are on of these "problem" OD pairs. Therefore, even if there is a 20% difference between the PWT calculated in all of the problem origin and destination segments, then the error in the timeband-level PWT will not exceed 4%.

Aggregating timeband-level PWT to cover all timebands and aggregating all days during a four-week period will further decrease the effect of PWT accuracy errors that exist when PWT is based on departure headways at the destination instead of the origin. The reason the effect of PWT accuracy errors will decrease is because the error caused by using headways at the destination to estimate PWT is not expected to be as high as 20% for all timebands on a given day and for all days in a four-week period. The absolute percent difference between PWT measured at the origin and destination for the ODs considered in this analysis tends not to exceed 10% during a given timeband and day for at least two out of the three ODs considered for each line. Therefore, for the conservative estimate that 20% of passengers travel on these problem ODs on each line, if two-thirds of the problem OD pairs have a 10% error and the other one-third of the problem OD pairs have a 20% error, then the conservative estimate of the error associated with the PWT calculated for a given line, timeband, and day should not exceed $(2/3) \cdot 0.2 \cdot 0.1 + (1/3) \cdot 0.2 \cdot 0.2 \approx 3\%$. Assuming this trend

holds over all timebands and days, aggregating these timeband-level PWT estimates to an entire day and four-week period will yield aggregated PWT estimates that also have a conservative upper bound error of approximately 3%.

Another weakness exists with the TCB PWT methodology. This weakness stems from not using train identification data to check if a train reached a specific destination, and it exists when at least one non-terminal reversing or end-of-service location exists downstream from two or more locations where trips begin. Consider northbound service on the Bakerloo line. For a given time period, the count of trains at stations between Kensal Green and Stonebridge Park (SPK segment) will be less than the count of trains at stations between Waterloo and Queen's Park (QPK segment) and between Elephant & Castle and Lambeth North (ELE segment) because many trains reverse at Queen's Park. If the number of trains observed in the ELE segment is less than the number observed in the QPK segment due to trains starting northbound trips from the London Road Depot between Lambeth North and Waterloo, then it is not known which trains observed in the SPK segment originated in the ELE segment.

Because fewer trains will be observed in the SPK segment than in the QPK and ELE segments, the representative PWT station for trips from the ELE segment to the SPK segment will be located in the SPK segment. Therefore, some of the trains recorded at the representative PWT station will not have served stations in the ELE segment. This will lead to the inclusion of too many departure headways in the calculation of average PWT for passengers traveling from the ELE segment to the SPK segment and the underestimation of average PWT for these passengers.

The problems caused in this scenario northbound on the Bakerloo line stem from trains that provide service to a low frequency segment but not all other segments that receive a higher frequency of service. When this happens, there can be trains that are recorded in the low frequency segment that did not serve passengers on all higher frequency segments of the line. This problem only exists in low frequency segments because the TCB PWT methodology does not use records of trains in high frequency segments to calculate average PWT for OD pairs that span more than one

segment. Additionally, this weakness of the TCB PWT methodology does not apply to situations where a train provides service to the entirety of only one track segment after entering mid-line. Although a train entering or exiting service in the middle of a track segment will cause errors when calculating PWT for passengers traveling within that segment and for passengers traveling to that segment if it is a segment receiving a low frequency of service, the LU-defined track segments for the Bakerloo and Piccadilly lines are defined such that all scheduled trips on the Bakerloo line begin and end at the end of a track segment while only 9% of all scheduled trips on the Piccadilly line begin or end in the middle of a track segment. Future work could propose an increased number of Piccadilly line track segments in order to reduce this 9% value.

In the case of the two LU lines, the Bakerloo and Piccadilly, being analyzed here, it turns out that a small enough number of passengers are served by trains that provide service to a low frequency segment but not all other segments that receive a higher frequency of service that it can be assumed that all trains observed in a low frequency segment served all stations in segments that receive a higher frequency of service; this same assumption is made in LU's PWT methodology for lines with poor NetMIS data. Twelve of the 20 scheduled OD pairs on the Bakerloo line and 55 of the 70 scheduled OD pairs on the Piccadilly line serve a low frequency segment but not all stations in segments that receive a higher frequency of service. However, for scheduled weekday trips on the Bakerloo line, only 15 northbound trips and 10 southbound trips, or 3.5% of all trips in both directions, serve at least one low frequency segment but not all higher frequency segments. Further, only five of these trips, or less than 1% of all trips in both directions, begin from 07:00 to 22:00, the most heavily traveled times on weekdays. Two of these trips, or 0.3% of the 623 weekday scheduled trips from 07:00 to 22:00, contribute to the underestimation of PWT in segments that account for approximately 4% of demand on the Bakerloo line during this time period. If demand is evenly distributed over this time period, then only $0.003 \cdot 0.04 = 0.012\% \approx 0\%$ of Bakerloo line passengers are affected by the PWT estimation error from these two trips. The other three trips contribute to the underestimation of PWT in segments

that account for less than 1% of Bakerloo line demand during this time period, so the PWT estimation error from these trips also have a negligible impact on PWT estimates.

Of the 894 scheduled weekday trips on the Piccadilly line, 149 northbound trips and 145 southbound trips, or 33% of all trips in both directions, serve at least one low frequency segment but not all higher frequency segments on the line. When trips that begin from 07:00 to 22:00 are considered, this percentage drops to 17%. However, a large portion of these "problem" trips from 07:00 to 22:00 serve passengers traveling to or from Cockfosters, Oakwood, and Southgate, who account for only 3.5% of all weekday demand on the Piccadilly line, causing the PWT to be underestimated for these passengers because departure headways from trains that did not actually provide service to these passengers are used to calculate PWT. When these problem trips are removed from the group of trips that begin from 07:00 to 22:00, only 16 trips serve at least one low frequency segment but not all higher frequency segments on the Piccadilly line. However, the percentage of passengers who will have underestimated PWTs due to these 16 trips is small. Six trips, or 1% of the 758 trips in both directions from 07:00 to 22:00, affect segments that account for about 3% of all Piccadilly line passengers during this time period. Assuming an even distribution of demand over time, these six trips contribute to a PWT estimation error for only $0.01 \cdot 0.03 = 0.03\% \approx 0\%$ of Piccadilly line passengers. The remaining 10 trips affect segments that account for less than 1% of all Piccadilly line passengers, leading to a negligible effect on PWT estimates.

5.3.2 Results

Results from using the TCB PWT methodology with original NetMIS data[7] to calculate estimated PWT are presented in Tables 5-15 and 5-16. The values in parentheses

[7]None of the NetMIS data revision processes presented in Section 5.1 have been applied to the NetMIS data used do generate these TCB PWT results. However, two types of Train Events have been removed from the Bakerloo line data set – those events associated with National Rail trains and repetitive Train Events that, if not removed from the data set, would provide two or more departure times for the same train at one station.

give the percent difference between PWT estimated using LU's PWT methodology and the TCB PWT methodology, where a positive (negative) percentage indicates that the PWT estimate is higher (lower) using the TCB PWT methodology. These percent differences are also presented graphically in Figures 5-16 and 5-17 for the five days shown in the tables. Across all timebands and the five days analyzed on the Bakerloo line, PWT estimated using the TCB PWT methodology is generally 1% or 2% less than the PWT calculated using LU's PWT methodology, but there are a few timeband-day combinations where the percent difference is substantially larger. In contrast, estimated PWT is generally about 5% greater on the Piccadilly line for a specific timeband-day combination when the TCB PWT methodology is used in place of LU's PWT methodology.

One of the strengths of the TCB PWT methodology – trains do not need to be matched between origin and destination on lines with good NetMIS data – plays a role in the 17% decrease in PWT on the Bakerloo line on July 27 during timeband 5. Although approximately the same number of departure times were used on all segment-to-segment pairs with both methodologies during timebands 2, 3, and 4, more departure times were used to estimate PWT on nearly all segment-to-segment OD pairs during timeband 5 with the TCB PWT methodology. For example, because some northbound trains were not recorded as departing from Queen's Park, seven more departure times were used with the TCB PWT methodology during timeband 5 for passengers traveling to any station up to Queen's Park after boarding at Elephant & Castle or Lambeth North. However, for the same OD pair, the difference in departure time counts between the two methodologies was never more than two during timebands 2, 3, and 4. Therefore, this indicates that the TCB PWT methodology accurately corrected for an instance where flawed NetMIS data led to an inaccurate PWT estimate using LU's PWT methodology.

It is not surprising that the PWT estimated with the TCB PWT methodology for timeband 5 on July 27 is so much lower than the PWT estimated with LU's PWT methodology. Specifically, the PWT estimated with LU's methodology for timeband 5

	Timeband					
	1	**2**	**3**	**4**	**5**	**6**
July 26, 2010	4.68 (−15.2%)	2.00 (−2.5%)	1.99 (−0.1%)	1.88 (−0.9%)	2.16 (−0.4%)	3.12 (1.3%)
July 27, 2010	4.44 (−2.4%)	1.97 (−2.6%)	1.99 (0.0%)	2.08 (2.0%)	2.44 (−17.3%)	3.02 (0.6%)
July 28, 2010	4.41 (−17.7%)	2.01 (−1.0%)	2.03 (−1.2%)	2.10 (−0.2%)	2.29 (−3.5%)	2.97 (−0.8%)
July 29, 2010	4.54 (−5.0%)	2.11 (−0.9%)	1.99 (−0.4%)	2.01 (5.3%)	2.17 (−0.3%)	2.96 (−2.2%)
July 30, 2010	4.71 (−11.6%)	2.05 (−6.4%)	2.09 (0.3%)	1.86 (0.7%)	2.12 (0.4%)	3.00 (0.4%)
4-week average	4.67 (−2.9%)	2.01 (−2.1%)	2.11 (1.1%)	2.04 (−1.7%)	2.35 (−2.3%)	3.10 (−2.9%)
4-week line-level PWT estimate: 2.24 (−1.1%)						

Table 5-15: Bakerloo line PWT estimates using the train-count-based PWT methodology with the original NetMIS data

	Timeband					
	1	**2**	**3**	**4**	**5**	**6**
July 26, 2010	3.06 (−1.8%)	1.99 (2.9%)	2.31 (5.3%)	1.94 (−4.7%)	2.03 (−1.7%)	2.44 (−0.6%)
July 27, 2010	3.10 (−2.9%)	2.06 (−2.1%)	2.40 (9.5%)	1.79 (1.8%)	2.07 (3.0%)	2.68 (9.3%)
July 28, 2010	2.90 (−3.3%)	1.83 (−1.7%)	2.08 (7.6%)	2.04 (7.6%)	2.25 (6.7%)	2.57 (9.7%)
July 29, 2010	2.93 (−14.7%)	1.91 (−1.0%)	1.98 (3.9%)	1.93 (4.8%)	2.08 (6.9%)	2.42 (−0.1%)
July 30, 2010	2.91 (−3.9%)	1.91 (−3.7%)	1.99 (2.8%)	2.26 (2.0%)	2.30 (5.1%)	2.56 (10.8%)
4-week average	2.95 (−9.4%)	1.91 (0.4%)	2.23 (10.7%)	1.97 (2.4%)	2.12 (3.8%)	2.51 (4.1%)
4-week line-level PWT estimate: 2.13 (3.7%)						

Table 5-16: Piccadilly line PWT estimates using the train-count-based PWT methodology with the original NetMIS data

on July 27 is 2.95 minutes while the LU-estimated PWTs during timeband 5 on other weekdays during the same week range from 2.11 minutes to 2.37 minutes. Because it is known that no disruptions occurred at this time, intuition suggests an overestimation of the PWT for timeband 5 on July 27 when LU's PWT methodology is used. Indeed, the PWT estimated for this date and timeband using the TCB PWT methodology is 2.44, giving the 17% decrease mentioned earlier. Not surprisingly, other large percent differences observed in Figures 5-16 and 5-17 correspond with date-timeband combinations for which LU's estimated PWT value is substantially higher than the values estimated for the same timeband on other days.

In contrast to the previous example, the Bakerloo line provides a different example where LU's PWT methodology is expected to provide a more accurate estimation of PWT than the TCB PWT methodology. This example concerns passengers who board between Waterloo and Queen's Park and alight between Wembley Central and Harrow & Wealdstone during timeband 4 on July 27. LU's PWT methodology uses departure headways from trains observed at Waterloo that are also observed at Harrow & Wealdstone to estimate a PWT of 5.27 minutes. By contrast, the TCB PWT methodology estimates a PWT of 6.24 minutes based on departure times at Wembley Central. In this example, the PWT estimated with LU's PWT methodology is expected to be more accurate because it uses departure headways in the origin segment and, because all trains recorded at Waterloo during timeband 4 could be matched with a train at Harrow & Wealdstone by using Train ID or Train Number and Trip Number, the 5.27 minute PWT estimate does not suffer from errors caused by the inability to match trains between origin and destination.

Estimated PWT is more accurate on the Piccadilly line when the TCB PWT methodology is used because it is not affected by two situations in which estimation errors exist in LU's PWT methodology. First, LU's PWT methodology uses South Harrow as a representative PWT station for westbound and eastbound trips in the Rayners Lane segment; approximately 6% of weekday passengers travel to or from a station that relies on South Harrow as the representative PWT station in LU's PWT methodology. However, South Harrow has been removed as a potential representative

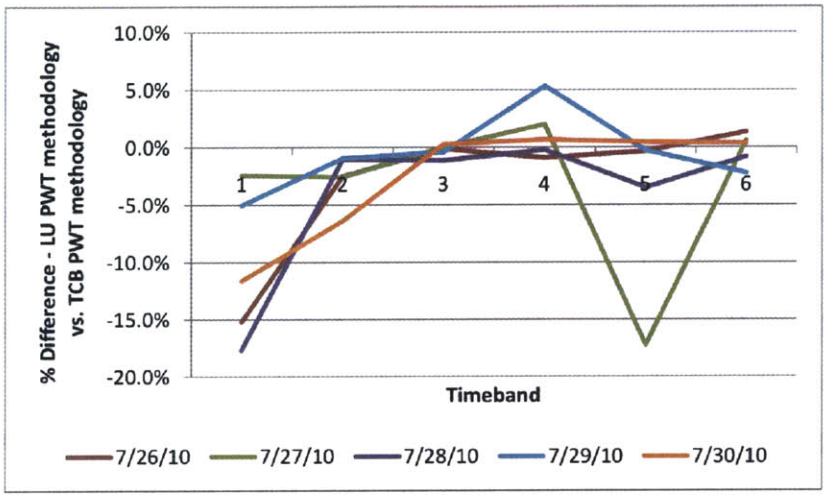


Figure 5-16: Comparison of estimated PWT on the Bakerloo line using LU's PWT methodology and the train-count-based PWT methodology

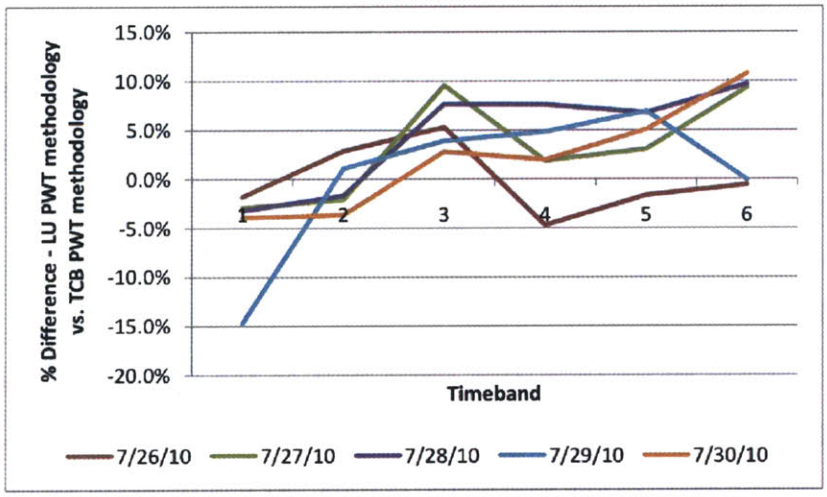
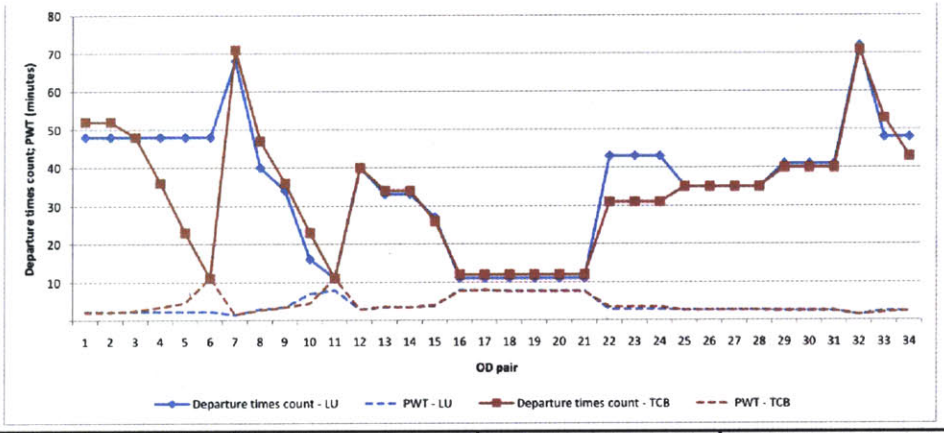


Figure 5-17: Comparison of estimated PWT on the Piccadilly line using LU's PWT methodology and the train-count-based PWT methodology

PWT station in the TCB PWT methodology because it has been identified as having unreliable NetMIS data.

Figure 5-18, which presents the estimated PWT for all 34 OD pairs on the Piccadilly line during timeband 2 on July 26 and the number of departure times used to generate these results, shows the existence of this unreliable NetMIS data and its impact on estimated PWT. LU's PWT methodology uses South Harrow as the representative PWT station for passengers traveling on the following segment-to-segment OD pairs: Arnos Grove–Rayners Lane, Rayners Lane–Ealing Common, Rayners Lane–Arnos Grove, and Rayners Lane–Cockfosters. These OD pairs are numbered 10, 22, 23, and 24, respectively, in Figure 5-18. This figure indicates that, when compared to the number of departure times used with the TCB PWT methodology, fewer departure times are used to estimate PWT for westbound trips ending in the Rayners Lane segment (OD pair 10) while more departure times are used to estimate PWT for eastbound trips beginning in the Rayners Lane segment (OD pairs 22, 23, and 24). Analysis of the number of departure times at other stations on the Rayners Lane segment confirms that not all westbound trains were recorded at South Harrow while too many eastbound trains were recorded at South Harrow. As Figure 5-18 shows, and as expected given this analysis of the data at South Harrow, the estimated PWT values using the TCB PWT methodology instead of LU's PWT methodology are lower (by about 35%) for westbound trips ending in the Rayners Lane segment (see OD pair 10, where the dashed red line is below the dashed blue line) and higher (by about 25%) for eastbound trips beginning in the Rayners Lane segment (see OD pairs 22, 23, and 24, where the dashed red line is above the dashed blue line).

The second instance where estimation errors exist on the Piccadilly line in LU's PWT methodology is in the calculation of PWT for passengers traveling from Cockfosters, Oakwood, or Southgate to any westbound station. As mentioned in Section 4.1.1, the estimated PWT for this *westbound* segment-to-segment OD group depends on the actual-scheduled ratio of PWT for passengers traveling *eastbound* from Acton Town to Cockfosters. The first six OD pairs in Figure 5-18 correspond with trips originating in the Cockfosters segment. The decrease in the number of departure times



OD pair	Orig Segment	Dest Segment	OD pair	Orig Segment	Dest Segment	OD pair	Orig Segment	Dest Segment	OD pair	Orig Segment	Dest Segment
1	CFS	SGT	10	AGR	RLN	19	UXB	ECM	28	HRA	CFS
2	CFS	ACT	11	AGR	UXB	20	UXB	AGR	29	NFD	SEL
3	CFS	NFD	12	SEL	NFD	21	UXB	CFS	30	NFD	AGR
4	CFS	HRA	13	SEL	HRA	22	RLN	ECM	31	NFD	CFS
5	CFS	RLN	14	BOS	HRA	23	RLN	AGR	32	ACT	AGR
6	CFS	UXB	15	ECM	RLN	24	RLN	CFS	33	ACT	CFS
7	AGR	ACT	16	ECM	UXB	25	HRA	BOS	34	SGT	CFS
8	AGR	NFD	17	ETE	UXB	26	HRA	SEL			
9	AGR	HRA	18	UXB	ETE	27	HRA	AGR			

Figure 5-18: Comparison of LU's PWT methodology and the train-count-based PWT methodology

used to estimate PWT and the increase in estimated PWT shown in this figure for passengers traveling to the Piccadilly line's western branches is typical of other days and timebands.

It is important to note, however, that the depiction of this error in Figure 5-18 makes this error seem worse than it actually is. The reason this error is not so bad is because the demand weightings are zero for all timebands for five of the six segment-to-segment OD pairs that originate in the Cockfosters segment. The exception is OD pair 2, which is responsible for up to 4% of the Piccadilly line's demand during a given timeband. The data show that PWT is usually overestimated when LU's PWT methodology is used instead of the TCB PWT methodology for OD pairs originating in the Cockfosters segment, and this overestimation usually does not exceed 10% on OD pair 2. Therefore, the upper bound of the error associated with PWT estimated using LU's PWT methodology for trips originating from the Cockfosters segment is 0.4%.

The difference between the PWT values estimated using LU's PWT methodology and the TCB PWT methodology are generally greater than those between the PWT values estimated using original and revised NetMIS data with LU's PWT methodology (see Tables 5-8 and 5-9). Specifically, as the four-week average PWT values in Tables 5-15 and 5-16 show, the magnitude of the percent difference between the TCB PWT methodology and LU's PWT methodology range from 1% to 3% on the Bakerloo line and from less than 1% to 11% on the Piccadilly line. Analysis of the 20 weekdays used to calculate these four-week average PWTs shows that the percent differences on two days within the same timeband may vary by 10% or 20%, which explains why the four-week average PWT values in these tables do not closely match the percent differences seen in individual timeband-day combinations for the five weekdays analyzed.

It is important to discuss the implication of NetMIS data deficiencies on August 18, 2010 on the four-week-level TCB PWT estimates. Due to data recording errors, no more than 105 of the more than 300 train movements at each station between Arsenal and Cockfosters were recorded in NetMIS over the entire day. Because

the entire three-station Cockfosters segment is included in this data-deficient zone, PWT using the TCB PWT methodology is overestimated for all segment-to-segment OD pairs starting and ending in the Cockfosters segment. LU's PWT methodology, however, is not affected by this lack of NetMIS data because LU's methodology does not have any representative PWT stations between Arsenal and Cockfosters. When the timeband-level TCB PWT estimates on August 18 are replaced by the analogous estimates from LU's PWT methodology, the four-week average PWT during timeband 3 decreases 5% from 2.23 minutes to 2.11 minutes; the four-week average PWT does not change by more than 1% for any of the other weekday timebands. Additionally, the line-level PWT estimate decreases from 2.13 minutes to 2.10 minutes and the percent difference between the TCB PWT line-level estimate and the line-level estimate using LU's PWT methodology decreases from 3.7% to 2.2%. Future work could develop automated processes that identify instances where an entire segment has too much or too little NetMIS data and, when these scenarios exist, choose a station outside the problem segment as the representative PWT station for that segment.

In the case of the Piccadilly line, the TCB PWT methodology is expected to almost always provide more accurate PWT estimates than LU's PWT methodology for two reasons. First, neither LU's PWT methodology nor the TCB PWT methodology use train identification data to verify that a train reached a destination. Therefore, both methodologies choose representative PWT stations in a segment-to-segment OD pair's (or group's) lowest frequency segment and assume that trains observed in that segment serve all other segments in the OD pair (or group). As a result, both methodologies are equally impacted by this imperfect assumption. Second, the TCB PWT methodology is much better suited to dealing with instances where a station that typically has reliable NetMIS data suffers from a temporary data deficiency during a time period. For example, although South Harrow usually has reliable NetMIS data, the TCB PWT methodology was better able to adapt to the situation presented earlier where South Harrow did not have good NetMIS data on one day. The one exception where the TCB PWT estimates will not be more accurate is when an entire segment has poor NetMIS and LU's PWT methodology does not have a

representative PWT station in that segment. It is expected that these conclusions about the comparative accuracy of the TCB PWT methodology are applicable to other lines that have poor NetMIS data.

It is more difficult to determine whether the TCB PWT methodology calculates more accurate PWTs than LU's PWT methodology on the Bakerloo line and other lines with good NetMIS data. The reason for this is because each methodology has its own weaknesses on lines with good NetMIS data – LU's PWT methodology suffers from a dependence on train identification data while the TCB PWT methodology is affected by the use of departure headways in the destination segment to calculate PWT in the origin segment. The question that needs to be answered is, Which weakness is worse? Because the PWT experienced by passengers is never known with certainty, there is no way to compare the results from each methodology with a baseline value to answer this question. Further, because data errors and realized operations, which will influence whether departure headways in the destination segment match those observed in the origin segment, vary unpredictably by line, day, and time of day, it would be speculation to declare one of these PWT methodologies better suited for lines with good NetMIS data.

5.3.3 Summary

This section has presented the TCB PWT methodology, the strengths and weaknesses of this methodology, and the PWT estimates produced by the TCB methodology. By using the count of trains at each station in each segment traversed by an OD pair to determine the representative PWT station for that OD pair, the TCB PWT methodology does not suffer from two weaknesses of LU's current PWT estimation method. First, the TCB PWT methodology does not rely on train identification data from NetMIS to match trains between origin and destination segments on lines with good NetMIS data. Second, the TCB PWT methods dynamically choose a representative PWT station for each segment-to-segment OD pair by timeband and day, so the TCB PWT methodology avoids the weakness in LU's current PWT estimation method that

the representative PWT station does not change based on the quality of NetMIS data during a specific timeband and day.

Despite these strengths, the accuracy of the TCB PWT methodology is hampered by two of its own weaknesses. First, the TCB PWT methodology suffers from a weakness that also exists in LU's current PWT methodology for lines with poor NetMIS data – all trains observed at a representative PWT station may not have served all stations in a segment-to-segment OD pair. However, it was shown that this weakness affects only a small number of trips and, on each of these trips, only a small percentage of a line's passengers will have their PWT underestimated. Second, for segment-to-segment OD pairs that start in a higher frequency segment and end in a lower frequency segment, the estimated PWT for passengers boarding in the origin segment is based on departure headways in the destination segment. It was concluded that the conservative upper bound for the error in line-level PWT estimates caused by this weakness will not exceed 4% for a given timeband and day and will be no more than 3% for an entire day or four-week period.

In general, timeband-day TCB PWT estimates were 1% or 2% less and approximately 5% greater on the Bakerloo and Piccadilly lines, respectively, than the estimates from LU's current methodology. When timeband-day PWT estimates were aggregated, it was seen that four-week line-level PWT estimates on the Bakerloo and Piccadilly lines were 1.1% less and 3.7% greater, respectively, than LU's estimates. It was noted that the 3.7% value was higher than it should be due to a lack of NetMIS data at all stations in the Cockfosters segment. If methods are developed to use a station outside a segment with poor NetMIS data as the representative PWT station for that segment, then this 3.7% value would decrease to approximately 2.2%. Because actual PWT values do not exist, it was not possible to determine the relative size of the errors caused by the weaknesses in LU's PWT methodology and the TCB PWT methodology. Therefore, no conclusion could be made regarding which methodology provides more accurate PWT estimates.

The suggested way forward is to combine the best aspects of LU's current PWT methodology and the TCB PWT methodology into a hybrid PWT methodology. This

hybrid approach would eliminate the use of departure headways from the destination segment to estimate PWT in the origin segment by using the train matching approach used in LU's current PWT methodology on all segment-to-segment OD groups that begin in a higher frequency segment and end in a lower frequency segment. Further, it is recommended that the representative PWT and representative destination stations used to match trains in the origin and destination segments in each OD group should be chosen dynamically, as done in the TCB PWT methodology, based on available NetMIS data for each timeband and day. For all segment-to-segment OD groups that begin in a lower frequency segment and end in a higher frequency segment, the TCB PWT methodology would be used in this hybrid methodology.

Because train matching is not possible on lines with poor NetMIS data, this hybrid approach should be used only on lines with good NetMIS data. The TCB PWT methodology should be used on lines with poor NetMIS data for two reasons mentioned earlier. First, the TCB PWT methodology dynamically chooses a representative PWT station for each timeband and day. Second, LU's current PWT methodology already uses departure headways in the destination segment on lines with poor NetMIS data, so maintaining this practice in the TCB PWT methodology would not introduce new error into PWT estimates on lines with poor NetMIS data.

Chapter 6

Conclusion

This chapter summarizes this research and offers ideas for future research. Specifically, Section 6.1 provides a research summary while Section 6.2 presents an overview of the findings from this research. This chapter concludes in Section 6.3 with suggestions for future work.

6.1 Research summary

The primary objective of this thesis was to determine the combination of methods and data that provides the most accurate and robust estimates of PWT. LU's PWT methodology was described in detail, including the division of each line into frequency-based segments and the classification of lines based on the quality of their NetMIS data. Further, descriptions were provided of how passengers boarding at all stations in a segment are assumed to experience the same PWT as passengers boarding at the segment's representative PWT station and how LU aggregates PWT estimates from the segment-to-segment OD group level to the timeband and line levels. The PWT estimates generated by LU's PWT methodology served as a baseline against which the results from other PWT methodologies were compared. All methodologies presented in this thesis were applied only to the Bakerloo and Piccadilly lines. These two lines were chosen because the Bakerloo line has good NetMIS data while the Piccadilly line has poor NetMIS data. Additionally, both lines' train tracking data

are not expected to improve in the next five years, giving the NetMIS data revision methods presented in this thesis a longer useful life on these lines.

One of the goals of this research was to improve the accuracy of PWT estimations through the revision of the data used to estimate PWT. To this end, three processes that identified and corrected data deficiencies in NetMIS were developed and tested on five weekdays on the Bakerloo and Piccadilly lines. First, if a Train Event did not have a recorded departure time, then that Train Event was assigned a departure time 20 seconds greater than the Train Event's recorded arrival time. Second, arrival and departure times were added when entire Train Events were missing; the departure times for these missing events were estimated using a proportional running time approach to allocate the known running time between neighboring stations to the station(s) with the missing Train Event(s). Third, a sandwich method was used to join two Train ID blocks when one block ended mid-trip.

In an effort to improve the accuracy of PWT estimates, and apart from the revision of NetMIS data, this thesis developed and tested a variant of LU's PWT estimation method and a new PWT methodology. The goal of developing the variant of LU's method was to test whether PWT varies along a segment or if the representative PWT station in that segment provides an accurate estimation of PWT at all stations in the segment. This analysis was completed on the longest segments on the Bakerloo and Piccadilly lines. The new train-count-based PWT methodology was developed in an effort to eliminate the need to use train identification data on lines with good NetMIS data to match trains between origin and destination segments and to make the estimation of PWT more tolerant of NetMIS data recording errors on all lines. These goals were achieved by defining representative PWT stations based on the NetMIS data available during a given timeband-day combination such that the representative PWT station for a given segment-to-segment OD pair was the station with the highest count of departure times in the segment receiving the lowest frequency of service.

Although the TCB PWT methodology does not suffer from two weaknesses of LU's current PWT method – the reliance on NetMIS data to match trains between origin and destination segments on lines with good NetMIS data and permanently defined

representative PWT stations – the TCB PWT methodology has two new weaknesses. First, departure headways in the destination segment are used to estimate PWT for passengers boarding in the origin segment of segment-to-segment OD pairs that serve a lower frequency destination segment. It was concluded that PWT estimated using departure headways in the destination segment would be no more than 3% different than the (more accurate) PWT estimated using departure headways in the origin segment. Another weakness of the TCB PWT methodology is that trains serving a low frequency destination segment may not have served all stations in higher frequency segments. When this occurs, PWT will be underestimated for passengers boarding in the higher frequency segment(s).

6.2 Research findings

The results from this research are summarized in this section. To begin, results from revising NetMIS data are presented. Next, comparisons are made between LU's PWT methodology and the three new PWT methodology-data combinations investigated in this thesis. This section concludes with a short discussion about whether this area of research yields benefits that outweigh the costs of developing and implementing these new methodologies.

6.2.1 Revised NetMIS data

The analysis of NetMIS data on the Bakerloo and Piccadilly lines indicated that a very small proportion of all Train Events were missing arrival and/or departure times – no more than 0.7% of events were missing a departure time on a given day while missing Train Events accounted for no more than 0.1% of daily Train Events on each of the two lines analyzed. However, it was seen that no more than 1.8% of daily Train Events at representative PWT stations on the Bakerloo and Piccadilly lines were missing departure time only or arrival and departure times at one of the representative PWT stations in LU's PWT methodology.

When all blocks that ended mid-trip were considered, it was seen that between 17% and 65% of the blocks ending incorrectly on the Bakerloo line and between 28% and 40% of the blocks ending incorrectly on the Piccadilly line were successfully joined with a second Train ID block using the sandwich method described in Section 5.1.2. In terms of incorrectly ending Train ID blocks that were not used to estimate PWT with LU's PWT methodology, between 4 and 11 Train ID blocks out of approximately 250 daily blocks on the Bakerloo line did not allow trains observed in the origin segment to be matched with the same train in the destination segment. However, the sandwich method had moderate success in these scenarios as between 20% and 56% of these blocks that needed to have their Train IDs revised in order to be used in the estimation of PWT received corrected Train IDs using the sandwich method.

6.2.2 LU's PWT methodology with revised NetMIS data

Because of the small percentage of Train Events that stood to benefit from revised NetMIS data, it was not surprising to see only small differences between the PWTs estimated using LU's methodology with original and revised NetMIS data. At the timeband-day level, four-week-average timeband level, and the four-week line level, the difference in these estimated PWTs was generally less than 0.5%. The PWTs estimated using revised NetMIS data are known to be better than those using original NetMIS data because it is known that the revised NetMIS data set is more complete and robust.

6.2.3 LU's PWT methodology with more line segments

Using LU's PWT methodology with the longest segment split into multiple smaller segments led to timeband-level PWT estimates for all passengers on the given line that generally exhibited a 1% or 2% difference from the same estimates using LU's PWT methodology with LU's current segment definitions. As was the case with the use of revised NetMIS data, more line segments make PWT estimates more accurate. However, it may not be feasible to increase the number of line segments on some lines

if the smaller segments would not contain at least one station with reliable NetMIS data.

6.2.4 Train-count-based PWT methodology

The Bakerloo and Piccadilly line TCB PWT estimates were usually 1% or 2% less and about 5% greater, respectively, for a timeband-day combination than the PWT estimated using LU's PWT methodology. The four-week line-level PWT estimates were 1.1% less and 3.7% greater on the Bakerloo and Piccadilly lines, respectively. However, it is important to note that a data recording error during one day at all stations in the Cockfosters segment on the Piccadilly line caused the four-week line-level PWT estimate to be greater than it would have been if the data error did not exist. To remove the effect of data recording errors at all stations in a segment, future work could develop a process that chooses a station outside of the problem segment to serve as the problem segment's representative PWT station. When the PWT estimated with LU's methodology, which did not have any representative PWT stations in the data-deficient portion of the line, was used in place of the PWT estimated from the flawed data, the Piccadilly line four-week line-level TCB PWT estimate was only 2.2% greater than the value estimated with LU's PWT methodology.

The TCB PWT methodology has been shown to be more robust than LU's PWT methodology on all lines when NetMIS data recording errors occur at some subset of stations within a segment. In these cases, and unlike LU's PWT methodology, the TCB PWT methodology will never use a station with poor NetMIS data as a representative PWT station. Additionally, the TCB PWT methodology has been shown to correct for instances where trains could not be matched on the Bakerloo line using LU's PWT methodology due to flawed NetMIS data. However, evidence was also presented showing that PWT estimation errors exist in the TCB PWT methodology when it relies on departure headways in the destination segment to estimate PWT in the origin segment. Because the relative errors associated with the weaknesses in LU's PWT methodology and the TCB PWT methodology are unknown and because the lack of actual PWT values prevents the LU- and TCB-

estimated PWTs from being compared to a known quantity, it was not possible to conclude which methodology provides more accurate PWT estimates.

6.2.5 Recommendations

Because the PWT estimate for a timeband-day combination is usually not more than five minutes and differences between the proposed methodologies and LU's PWT methodology are usually not more than 5%, the estimated upper bound of how much error may exist in LU's current PWT estimates is 15 seconds. This upper bound will be no more than six or nine seconds when four-week line-level PWT estimates are considered because these estimated PWTs tend to be only two or three minutes and PWTs between methodologies tend to vary by less than 5% at this level of aggregation. Some may argue that a 15 second error is quite significant when spread over all passengers using a line, but a strong argument can also be made that no individual passenger will care about a 15 second change in how long they wait for a train.

All of this discussion informs the evaluation of whether improving the quality of NetMIS data or introducing a new PWT estimation methodology is a prudent business decision for LU. To be sure, making this decision rests in large part on how the agency values small differences in PWT. However, from an outsider's perspective, higher quality NetMIS data and improved PWT estimation methods are a worthwhile investment because they ensure that variations in PWT, no matter how small, reflect actual operations and are not due to poor NetMIS data or estimation errors.

One option to improve PWT estimates is to implement the NetMIS revision processes presented in this thesis and/or split longer segments into smaller segments. Another option, which could be implemented in conjunction with, or separately from, the first option, is to create a hybrid PWT estimation methodology that combines the best of LU's current PWT methodology and the TCB PWT methodology. Specifically, representative PWT stations would be chosen dynamically as done in the TCB PWT methodology and estimated PWTs would be based on departure headways in the origin segment whenever possible, even if this means using train identification

data from NetMIS to match trains between origin and destination segments for the limited number of OD groups that begin in a higher frequency segment and end in a lower frequency segment.

6.3 Future research

There are multiple ways in which the research presented in this thesis could be extended. Four of these ways are presented here, with two of these future work ideas applying directly to PWT estimation methodologies while the other two apply to further improving the NetMIS data quality. The fifth proposal for future work pertains to using revised NetMIS data with the model developed by Paul (2010).

Account for intra-line transferring passengers in demand weightings: The demand weightings used in this thesis to estimate aggregate PWT values do not take into account passengers who transfer between trains to reach their destination. Instead, only one of a transferring passenger's two PWTs are accounted for in aggregate PWT estimates. The demand weightings could be made more accurate by using the count of all boardings in an origin segment, not just those boardings that correspond with the first leg of an intra-line journey, to estimate the demand weightings for each segment-to-segment OD group. For example, the 299 passengers traveling from the Heathrow branch to the Uxbridge branch on the Piccadilly line during timeband 2 should be included in the count of boardings at their origin station on the Heathrow branch *and* in the count of boardings at Acton Town. The total number of line-level boardings used to calculate the proportion of boardings on each segment-to-segment OD group should also include these 299 transferring passengers.

Identify times when errors in NetMIS data exist at a representative PWT station: LU's PWT methodology and the TCB PWT methodology experience significant estimation errors when poor NetMIS data exist at the fixed representative PWT station (LU's PWT methodology) or at all stations within a segment (TCB PWT methodology). Because neither PWT methodology accounts for these scenarios, processes could be developed that identify instances where these types of errors occur.

When flawed NetMIS data are found at a representative PWT station, the most acceptable replacement representative PWT station should be chosen.

Improve dwell time estimates: When a missing departure time is added to the NetMIS data, it is assumed that this departure time occurred 20 seconds after the given train's arrival time. Although this 20-second dwell time assumption provides a good first order approximation of dwell time, there is room for improvement. Specifically, the assumed dwell time could vary by station and time of day, where stations in central London are assumed to have longer dwell times than those in outer London. Alternatively, station- and timeband-specific dwell times could be a function of historical dwell times. Another possibility is to have the assumed dwell time vary based on the observed headway, where trains arriving at the end of a longer headway would be assumed to have a longer dwell time. More accurate dwell time estimates would lead to more accurate PWT estimates.

Alternative to the sandwich method for joining Train ID blocks: Instead of (or in addition to) using the sandwich method to join Train ID blocks, a running time-based block matching algorithm could be developed. The general idea is this: if Train ID block 1 ends at Station A at time x and Train ID block 2 begins at the next station, Station B, at time y, then these two Train ID blocks correspond with the same train as long as the running time $y - x$ is within an acceptable range. This acceptable range could be centered around the average or some percentile of the scheduled or historical running times for either a given timeband or an entire day. A minimum running time constraint would also need to be imposed. If this methodology does not identify a matching Train ID block at the next station after a Train ID block ends, matches could be investigated at stations farther downstream.

Continue the research related to assigning passengers to trains: Two changes to NetMIS data that have been completed, or will be completed soon, should improve the accuracy of the model proposed by Paul (2010), which estimates train loads and the number of left behind passengers at individual stations. First, the NetMIS data revision processes described in Section 5.1 fill in missing departure times and allow more trains to be matched between two stations, the latter of which

will reduce the number of instances where a passenger's on-train time is assumed to equal the expected running time between the passenger's origin and destination. Second, Oyster timestamps, which are used to determine when a passenger enters and exits the LU system, are expected to be recorded at the second-level, instead of the minute-level, beginning in the middle of 2011. Future research could revisit the model proposed by Paul to determine if these NetMIS data improvements allow for the more accurate estimation of train loads and left behind passengers. Additionally, because Paul matches trains at two different stations by using only Train IDs, future research could increase the accuracy of Paul's model by introducing the use of Train IDs *and* Train Numbers and Trip Numbers to match trains on lines with good NetMIS data.

Appendix A

Station codes

A.1 Bakerloo line

ELE – Elephant & Castle
LAM – Lambeth North
LRDD – London Road Depot
WLO – Waterloo
EMB – Embankment
CHX – Charing Cross
PIC – Piccadilly Circus
OXC – Oxford Circus
RPK – Regent's Park
BST – Baker Street
MYB – Marylebone
ERB – Edgware Road
PAD – Paddington
WAR – Warwick Avenue
MDV – Maida Vale
KPK – Kilburn Park
QPK – Queen's Park
KGN – Kensal Green
WJN – Willesden Junction
HSD – Harlesden
SPK – Stonebridge Park
WEM – Wembley Central
NWM – North Wembley
SKT – South Kenton
KNT – Kenton
HAW – Harrow & Wealdstone

A.2 Piccadilly line

Cockfosters – CFS
Oakwood – OAK
Southgate – SGT
Arnos Grove – AGR
Bounds Green – BGR
Wood Green – WGN
Turnpike Lane – TPL
Manor House – MNR
Finsbury Park – FPK
Arsenal – ARL
Holloway Road – HRD
Caledonian Road – CRD
King's Cross St. Pancras – KXX
Russell Square – RSQ
Holborn – HOL
Covent Garden – COV
Leicester Square – LSQ
Piccadilly Circus – PIC
Green Park – GPK
Hyde Park Corner – HPC
Knightsbridge – KNB
South Kensington – SKN
Gloucester Road – GRD
Earl's Court – ECT
Barons Court – BCT
Hammersmith – HMD
Acton Town – ACT

Uxbridge Branch

Ealing Common – ECM
North Ealing – NEL
Park Royal – PRY
Alperton – ALP
Sudbury Town – STN
Sudbury Hill – SHL
South Harrow – SHR
Rayners Lane – RLN
Eastcote – ETE
Ruislip Manor – RUM
Ruislip – RUI
Ickenham – ICK
Hillingdon – HDN
Uxbridge – UXB

Heathrow Branch

South Ealing – SEL
Northfields – NFD
Northfields Depot – NFDD
Boston Manor – BOS
Osterley – OST
Hounslow East – HNE
Hounslow Central – HNC
Hounslow West – HNW
Hatton Cross – HTX
Heathrow Terminals 123 – HRC
Heathrow Terminal 4 – HRF
Heathrow Terminal 5 – HRV
Heathrow All Terminals – HRA

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