The Value of Automated Fare Collection Data for Transit Planning: An Example of Rail Transit OD Matrix Estimation

By

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Submitted to the Engineering Systems Division and the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the degrees of

Master of Science in Technology and Policy

and

Master of Science in Transportation

at the
Massachusetts Institute of Technology
September 2006

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Abstract:

Traditionally, transit agencies across the world have relied on traveler surveys and manual counts to inform many of their service and operations planning decisions. Today, many agencies can add to their existing planning toolbox the data obtained from new Automated Fare Collection (AFC) technologies. By adding this dataset, transit agencies can boost their analytical capabilities and deal with some planning questions that they previously could not easily address. In fact, while with surveys and manual counts transit agencies were able to form a reasonable snapshot of existing demand on their transit system, with accurate AFC data, planners should be able to get a detailed, continuous and accurate vision of the travel behavior of their customers, at a fraction of the prior cost.

Nevertheless, there are some technical and operational issues that can affect the quality of AFC data that must be addressed before the new dataset can be fully integrated into the planning process of transit agencies. This research begins to explore these issues in general as well as in the context of the transit system serving London in the United Kingdom. In particular, it identifies bias in the AFC entry and exit data and develops a methodology for building an unbiased estimate of existing travel patterns on the London Underground.

The outcome of the research is a methodology to build unbiased estimates of existing travel patterns. The use of this methodology presents two main advantages over the existing survey methods: (i) the resulting estimate corrects the bias in the Oyster dataset and better reflects existing travel patterns than the traditional survey-based methodology and (ii) the methodology should be easy to replicate, offering planners the capability to build origin – destination matrices specific to different time periods, days of week and seasons of the year. The availability of this large set of origin - destination matrices should enable planners to keep track of changes in travel patterns and tackle many planning questions that they could not easily address before.

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Acknowledgement

Nigel Wilson with the collaboration of John Attanucci, provided all that I came looking for at MIT. Working with them has been an intellectual and personal challenge that made these two years of my life an intense and rich learning experience. I am very grateful for their dedicated and savvy advice.

I would also like to thank many people at Transport for London who provided data and advice to make this research possible. In particular, I would like to thank Geoffrey Maunder, Peter Svensson, Mike Collop, Will Judge, Lauren Sager Weinstein and all the people working at Prestige and at the London Underground.

Finally, thanks to Catalina, my family and my friends. They have provided the unconditional love, which gives me strength and motivation to be persistent and work hard to give something back to the world. In praise of all that they represent, I would like to dedicate this thesis to the future generation, to my dear nephew, Antonio.

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Chapter One: Introduction

Traditionally, transit agencies across the world have relied on traveler surveys and manual counts to inform many of their service and operations planning decisions. Today, many agencies can add to their existing planning toolbox the data obtained from new Automated Fare Collection (AFC) technologies. By adding this dataset, transit agencies can boost their analytical capabilities and deal with some planning questions that they previously could not easily address. In fact, while with surveys and manual counts transit agencies were able to form a reasonable snapshot of existing demand on their transit system, with accurate AFC data, planners should be able to get a detailed, continuous and accurate vision of the travel behavior of their customers, at a fraction of the prior cost.

Nevertheless, there are some technical and operational issues that can affect the quality of AFC data that must be addressed before the dataset can be fully integrated into the planning process of transit agencies. This research begins to explore these issues in general as well as in the context of the transit system serving London, in the United Kingdom. In particular, it identifies biases in existing methods used for estimating passenger origin-destination travel patterns and develops a methodology for building an unbiased estimate of existing travel patterns on the London Underground.

1.1 Overview of AFC systems

The main goals of a fare collection system are to provide an inexpensive, fast, secure and user-friendly platform for collecting passenger fares and controlling access to the service. Currently, there is a strong tendency towards automating the fare collection process, shifting from traditional fare collection platforms to Automated Fare Collection (AFC) Systems. With the automation of the fare collection process, transit agencies can reduce their operational expenses, or shift ticketing staff to more productive tasks. They can also improve revenue protection, by minimizing human intervention, and develop a wider array of fare products to meet the broad spectrum of needs of the population (TCRP, Report 94).

From a customer perspective, AFC systems differ from traditional fare collection in the fare payment media used: while in a traditional fare collection system customers use coins, bills, tokens or paper tickets to pay for and gain access to transit, in an AFC system, passengers use electronic fare payment media in the form of magnetic stripe tickets or smart cards. Through the use of electronic fare payment media, transit agencies can collect a large volume of transactional data from customers. These data corresponds to ticket sales, customer entries and in some cases – usually in systems that have distance or zone based fares – customer exits (Wilson, N et al).

Currently there are two main types of electronic fare payment media: printed tickets with a magnetic stripe (magnetic stripe tickets) and contactless smart cards. Magnetic stripe tickets were implemented for the first time in the 1960s (TCRP, Report 94). Today, they are used to control fare payment on many rail and bus systems across the world. Magnetic stripe tickets have provided transit agencies a proven, reliable, cheap and reasonably fast payment medium. Contactless smart cards were implemented on transit for the first time it the late 1990s, in Hong Kong and Seoul (TCRP, Report 94). These cards are usually of the size and shape of a credit card and have embedded an integrated circuit and an antenna that can send, receive and update data content when placed in close proximity to a reader. These cards are quickly becoming a global standard for ticketing in public transportation systems. In fact, by 2003, more than 50 cities in four continents have chosen to upgrade their existing fare collection systems or to build new ones using this technology (TCRP, Report 94).

Contactless smart cards have many advantages over magnetic stripe tickets: they are faster, safer, have a longer life and can be associated with a unique cardholder. Smart cards also provide useful demographic information that can be linked to transactional data. In addition, with smart cards transit agencies can offer a whole new portfolio of services to customers, including on-line sales, balance protection and even an e-purse for micro payments at retail stores (TCRP, Report 94).

Broadly speaking, two categories of data can be obtained through an AFC system: transactional data and personal data. Transactional data is obtained through the use of contactless smart cards and magnetic stripe tickets on the transit system and generally includes sales and entry records and, in some cases, exit records. Personal data is obtained for some smart card users when the card is issued and can include: cardholder name, home address, office address, postal code, gender, age, phone number and e-mail address. Since personal data and transactional data are associated with a unique smart card ID, it is possible to use database tools to link transactional records with personal records (Utsonomiya et al).

1.2 Ridership estimates

Transit planners analyze passenger demand through different ridership estimation techniques for different levels of the network and different timeframes. The selection of the appropriate network level and timeframe are dependant on the particular issue being addressed. In this thesis we distinguish between three interrelated network levels: system level, station level and origin-destination level. These three network levels must be internally consistent, that is, for a given timeframe, the system level is the sum of all station level estimates and each station level estimate is the sum of the corresponding estimates at the origin-destination level. For each one of these network levels it is possible to define many different timeframes of interest. **Figure 1-1** illustrates these two basic dimensions of ridership estimates.

Some examples of ridership estimates are:

1) At the system level: Average weekday ridership on the network, during a specific year.
2) At the station level: Average monthly entries per station, during a specific year.
3) At the origin-destination level: Average number of passengers travelling in the weekday peak period between a pair of stations.

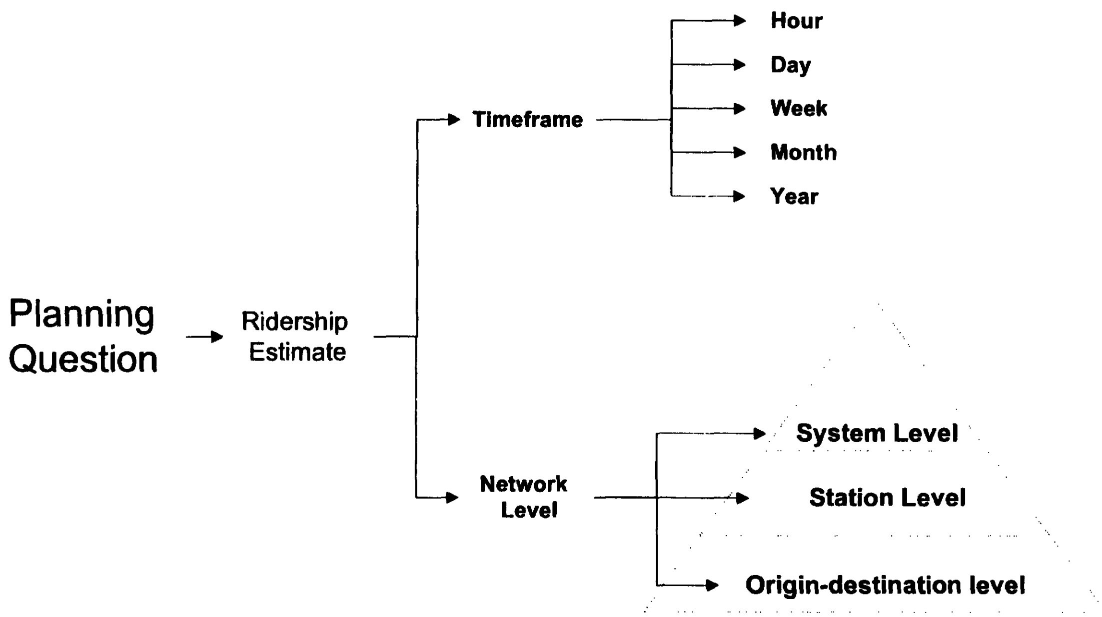

Figure 1-1: Time and Network dimensions of Ridership.

The time dimension and the network dimension define a large set of points from which to analyze travel patterns in a transit system. Planners can also analyze travel patterns of different segments of the market of transit users by introducing additional dimensions into the basic ridership estimation. For instance, planners can analyze the ridership associated with a fare product, a geographic location, by gender or by age group of transit users.

1.3 Research Objectives

The primary objective of the study is to explore how AFC transactional data can be used, either on its own or combined with survey data, to produce good estimates at the origin-destination level for a particular timeframe. Additionally, this research aims to prepare the ground for future investigation of ridership estimates at the other network levels and the incorporation of AFC personal data in the analysis of travel patterns.

This primary objective will be divided in two parts: the first will be to understand the characteristics and differences that exist in the content and quality of AFC transactional data and survey data. The second objective will be to demonstrate, through modeling and analysis techniques, that it is possible to correct the deficiencies of both survey data and AFC data, and end up with improved estimates at the origin-destination level for different timeframes.

1.4 Value of Improved Origin-Destination Level Estimations

Today most transit agencies build estimates of the origin-destination travel patterns using periodic passenger surveys, which are then scaled up to the station level entry and, if available, exit counts. On large transit networks, with hundreds of stations, it becomes very difficult and expensive to perform frequent surveys. Due to this practical limitation, transit agencies end up with origin-destination representations that they must assume as valid for arbitrary timeframes, defined more by budget constraints of the agency, than by real consideration of variations in travel patterns. Apart from the strong assumption on the extended time of validity for the origin-destination flows, estimates based on surveys can potentially be affected by non-response bias and might have limited accuracy that could negatively affect certain planning decisions.

Ideally planners could use transactional data from AFC systems to build more accurate origin-destination matrices, which can be easily updated to reflect changes on travel patterns over time. Further, planners could use AFC personal data in conjunction with transactional data to produce origin-destination estimates for different customer segments.

These improvements over existing estimates at the origin-destination level could translate into real benefits for transit agencies and eventually for transit users, since planners would have better and richer inputs for the following planning tasks: (1) service planning, (2) fare policy and (3) performance measurement.

The following subsections describe, for each one of these key planning tasks, the potential impact of having both more accurate estimates at the origin-destination level, and more frequent updates of these estimates. **Figure 1-2** summarizes the improvements that could be obtained.

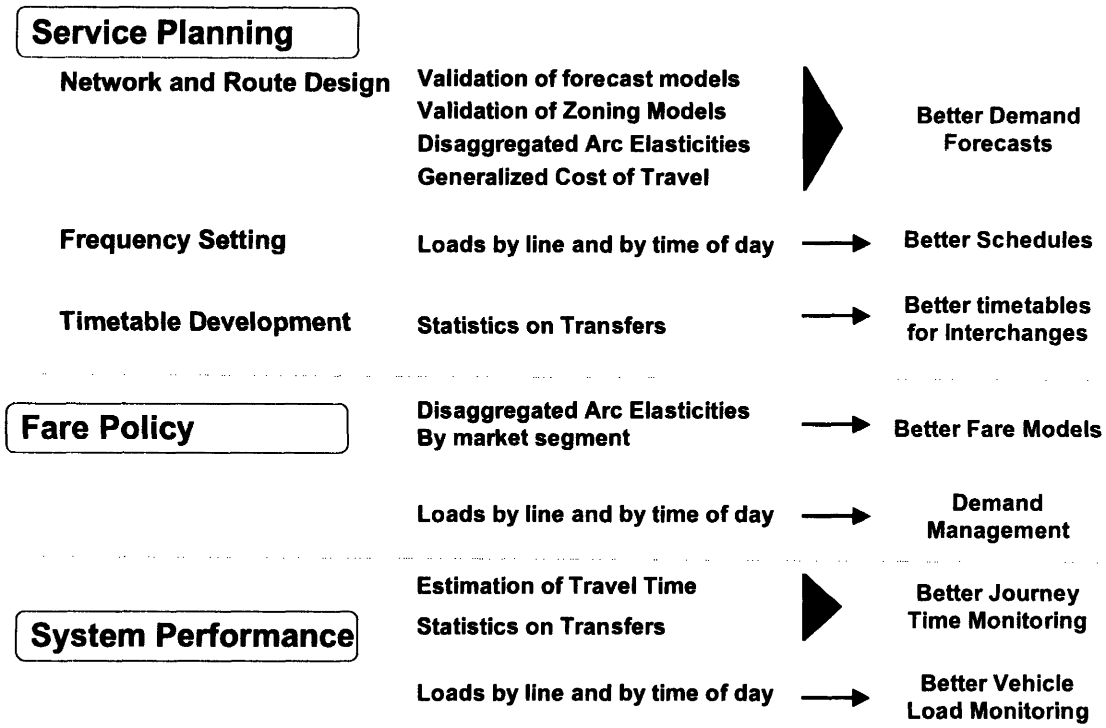

Figure 1-2: Applications of AFC Data

1.4.1. Service Planning

There are three functions within service planning where better estimates of travel patterns could contribute: network and route design, frequency setting and timetable development.

a) Network and Route Design

Network and route design is a complex planning function that addresses the question of which bus routes to operate, or which rail lines to build. Typically, at the core of this planning function there is a set of quantitative planning tools, or models. Transit agencies use these models to evaluate different scenarios and make informed decisions. There are many variations of these models, but all of them require some level of travel demand modelling. To build these demand models, transit agencies typically rely on extensive household surveys, counts and census information. Without going into the details of the demand modelling process, it is possible to identify four potential uses of improved estimates at the origin-destination level, which can lead to improvements in demand forecasts.

First, with a more accurate estimation of the origin-destination travel patterns, planners will have a more accurate basis for validating their demand forecasts, and this should result in better models.

Second, demand models typically require some level of zonal aggregation and so a good definition of zones is critical for having a good demand model. With better estimates at the origin-destination level, planners can obtain better insight into the travel patterns of transit users living in common geographical areas. The improved estimation could be used for validating existing zonal models, built from survey or census data. For instance, with more accurate origin-destination representations, linked to smart card personal data, transit planners could validate how homogeneous is a zone in terms of transit, or how intense is travel within that zone.

Third, the arc elasticity of demand is a useful analytical tool for predicting the impact on demand of changes in travel time, price and other variables. Nevertheless, as noted by Meyer and Miller: *"Elasticities are often computed from fairly aggregate statistics with little or no market segmentation. Thus considerable potential for "aggregation bias" exist in most elasticity calculations."* (Meyer and Miller)

With an improved origin-destination estimate planners can make a realistic segmentation of transit users by their travel patterns. In addition, with a set of origin-destination estimates that captures the temporal changes in demand, planners could analyze the changes on travel patters that result from changes in other variables. Moreover, by linking these estimates with personal data, planners could also analyze travel patterns by demographic groups. These segmentations of the market would be very helpful for calculating arc elasticities while minimizing aggregation bias.

Finally, a useful element in demand forecasting is the generalized cost of travel. This cost combines the out-of-pocket cost of transit with important non-monetary considerations, which passengers make implicitly every day, such as travel time. The generalized costs form the basis upon which citizens decide which journeys to make, on which transportation service, or mode, and over which path. With better origin-destination level estimates, planners can make better estimates of critical non-monetary variables such as travel time and number of transfers. Additionally, planners could use these improved origin-destination estimates to validate theoretical models using generalized cost of travel.

b) Frequency Setting

The second function in the service planning hierarchy is frequency setting. In this function, planners can use better origin-destination estimates to improve the frequency definition for common transit services like buses and trains.

Regarding buses, planners often use aggregate ticket sales combined with on-board and on-street counts to infer ridership. However, the estimates based on sales might not be very precise for transit agencies that sell pre-paid or period tickets, and counts are expensive and can be performed only infrequently. With improved estimates of origin-destination travel patterns, planners could obtain more precise estimates of ridership that could be accurately disaggregated by time of day, route and vehicle trip. With these estimates, planners would know, with unprecedented accuracy, how many passengers use a given bus route for each trip. This information should lead to better decisions on the frequency of a service by route and time period.

To set the frequencies on a rail system, planners need to have an estimate of the demand by line and by time of the day. To build these estimates, planners have to rely on their existing origin-destination estimates and use a path choice model, which assigns the OD flows to specific routes over the network. However, the accuracy of these estimates is hampered both by the precision of the survey-based origin-destination estimate, and by the assumption that such estimate is valid for an arbitrary timeframe. With a methodology for producing a more accurate estimate of travel patterns, which can also be updated for any timeframe, transit planners could improve greatly their estimates of loads by line. That is, planners would be able to measure the changes in train crowding, that result from changing weather conditions, sports events, musical events and seasonal factors, among others. With better estimates of loads by line, planners should be able to set better frequencies for the system, and better contingency plans for the events that affect the system in every day operation.

c) Timetable Development

The third function in the service planning hierarchy is the development of the timetable. With more accurate origin-destination level estimates, planners could make a number of adjustments to the timetable in order to match the needs of certain passengers. For instance, they could determine the time at which a bus service and a rail service should arrive and leave a connecting concourse, in order to minimize the expected waiting time for connecting passengers.

1.4.2. Fare Policy

The goals of fare policy vary across transit agencies, but generally relate to striking a balance between the conflicting goals of maximizing revenue and maximizing ridership. Additionally, some transit agencies concerned with capacity constraints, are now looking into innovative demand management strategies, that aim to promote a better use of transit capacity by creating appropriate financial incentives through fares. More accurate origin-destination estimations could assist transit agencies in making informed fare policy decisions.

First, to maximize ridership and revenue, transit agencies usually rely on models that estimate the price elasticity of demand, quantifying the impact on demand of changes in the fare. Today, it is possible to calculate this elasticity based on observations of aggregate changes in passenger volume. However, this kind of analysis does not show the nuances behind the change in demand. That is, which sets of passengers changed their travel behaviour or what effect the fare change had on the aggregate travel patterns.

Station passenger volumes might provide partial insight into the geographic distribution of the impact, but the analysis of changes in origin-destination travel patterns provides a deeper view of the consequences of a change in the fare. By using transactional data, planners can make such temporal comparisons. Further, by using personal data from AFC registration, planners could segment the analysis by groups sharing similar demographic characteristics.

Second, transit agencies could use more accurate estimates of loads by line to implement innovative demand management strategies based on pricing. That is, with more accurate estimates of loads by line, that can be updated for different timeframes, planners can learn which lines and stations have little demand, and which ones are overcrowded by time of the day, day of the week or month of the year. With this information in hand, they can develop pricing strategies to induce shifts in demand within the transit system.

1.4.3. System Performance

To measure transit performance, agencies have to carefully monitor service provision, demand for service and the interaction between these two variables. Improved origin-destination estimates provide transit agencies with new and valuable information on the second aspect: the demand for service. This section presents two examples of improvements to the measurement of service performance that can be attained thanks to the availability of better origin-destination estimates.

First, transit agencies that control both entry and exit could use improved origin-destination estimates, along with available data on entry and exit time, to make better estimates of the journey time distribution. Furthermore, planners could disaggregate these overarching performance indicators into partial estimates, which reflect the average journey time on different elements of the transit system.

In addition, with origin-destination estimates that can be updated for different timeframes, planners could estimate the crowding on their vehicles in different timeframes. Planners can also gain insight into the transfer time of passengers using multiple services such as bus and rail. This information could be used for estimating the overall journey time of passengers that use multiple services.

1.5. Different systems, Different approaches

AFC systems are configured differently to meet the particular needs of each transit system. From a broad perspective, two aspects of the configuration define the volume and type of data that can be collected from the AFC system to build origin-destination matrices: the access control method and the method for controlling payment. **Figure 1-3** illustrates the possible configurations of AFC systems with respect to these two aspects.

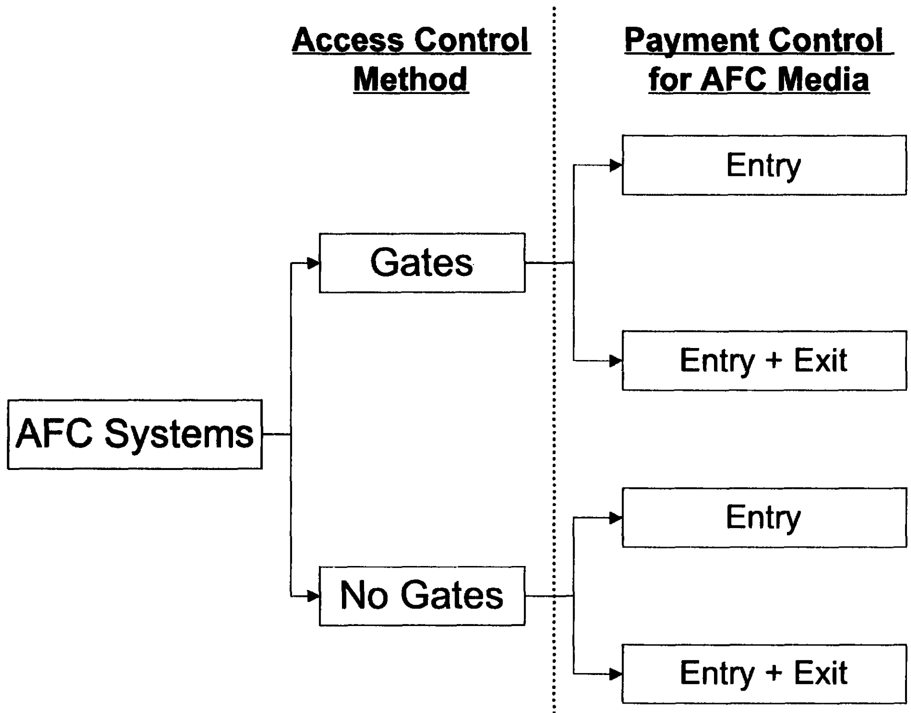

Figure 1-3: Basic Configurations of AFC Systems

Many transit systems use gates to control access, while others do not. Typically urban rail systems and many BRT systems use gates to control access to trains or buses, while regular buses and commuter rail systems typically do not use gates. The methodology developed in this thesis relies on the existence of entry and exit control totals for each location in the system, that is the existence of station level estimates for different timeframes. In the case of AFC systems on buses, this data might not be available unless one of the following conditions applies:

1) All passengers use electronic payment media and the AFC equipment on the vehicle is linked to an Automatic Vehicle Location (AVL) system that maps the boarding and alighting location for all customers

2) Buses are equipped with an Automatic Passenger Count (APC) system and an AVL system, from which it is possible to obtain an estimate of the number of customers boarding and alighting at each stop.

In the case of non-gated rail systems, the same principles apply, but with an APC system generally installed on the station platforms. Alternatively, transit agencies lacking these technologies could apply the approach presented here if they can develop data analysis techniques to overcome the lack of station level estimates for different timeframes.

The other relevant aspect for the implementation of the approach presented in this thesis is the method for controlling payment in the AFC system: while some transit systems control payment only on entry, others control payment at both entry and exit. Urban rail systems with distance-based fares as well as some bus systems with distance-based fares are common examples of systems that control payment at both entry and exit. On the other hand, many rail and bus systems with flat fares only require entry validation. Since the approach presented in this thesis relies on the existence of traceable entry and exit data for at least a portion of the users, it cannot be directly applied in those systems that lack either entry or exit data. For an approach to deal with the estimation of origin-destination travel patterns in those systems, refer to Rahbee (2002), Zhao (2004) and Wilson et al (2005).

Figure 1-4 presents the general configurations of AFC systems for which the approach presented in this thesis is intended.

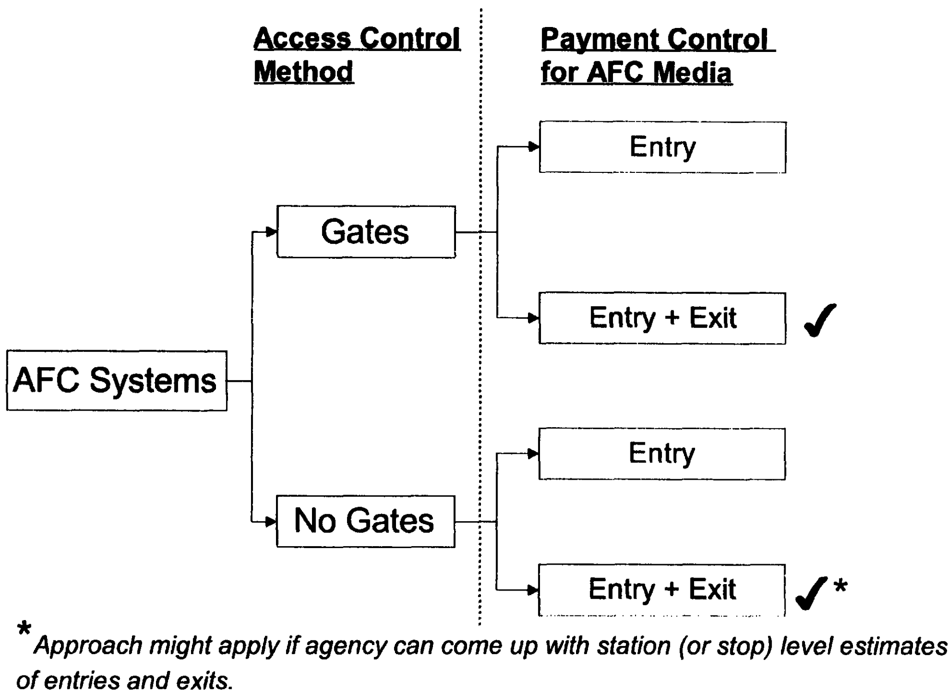

Figure 1-4: General AFC configurations for the proposed approach

1.6 Institutional Organization of Transport in London

Transport in London is under the responsibility of the Greater London Authority (GLA), which is a form of citywide government for London that consists of an elected Mayor and a 25-member Assembly. In 2000, GLA created Transport for London (TfL), to be the functional body responsible for implementing the Mayor's transport strategy and managing transport in London. GLA has assigned to TfL the following broad responsibilities over transport: (http://www.london.gov.uk/gla/)

1) *Managing London Buses, Croydon Tramlink, and the Docklands Light Railway*
2) *Managing the London Underground.*
3) *Managing a network of major roads, the Transport for London Road Network (TLRN).*
4) *Regulating taxis and minicabs.*
5) *Running London River Services, and promoting the safe use of the Thames for passenger and freight movement.*

6) *Helping co-ordinate the Dial-a-Ride and Taxicard schemes for door-to-door services for transport users with mobility problems.*
7) *Having responsibility for traffic lights across London.*

1.7 Thesis Organization

This thesis is organized into four chapters as shown in **Figure 1-5**. Chapter Two introduces the London case, beginning with a description of London's transit and AFC systems, and ending with a presentation of the existing method for estimating travel patterns on the London Underground. Chapter Three presents the proposed methodology based on the AFC data for building an origin destination matrix for the London Underground and evaluates the results. Chapter Four summarizes the research findings, and proposes next steps for research in this area.

Ch. 1 Introduction

Ch. 2 London Underground Background

Overview: Transit and AFC

Travel patterns: Existing process

Ch. 3 OD Matrix Estimation

Methodology

Analysis of Results

Ch. 4 Conclusions

Figure 1-5: Thesis Organization

Chapter Two: Background Information: AFC System and Survey Data In The London Underground

Planners at London Underground Limited (LUL) currently use surveys and gate counts to estimate the travel patterns on the Underground network. Recent advances in its AFC system and in particular, the implementation of a contactless smart card named Oyster, provide LUL planners with an extensive transactional dataset that could be used for improving their ridership estimates. This chapter presents background information that is relevant for the utilization of AFC transactional data for planning. It begins with a general overview of transit and fare collection in London in sections 2.1 and 2.2, and then presents and analyzes the current process for estimating travel patterns on the London Underground in section 2.3.

2.1 Overview of Transit in London

In Greater London, there are about 7 million inhabitants who make about 27 million journeys on the average weekday including 42 percent by car or motorcycle, 35 percent by transit and 22 walking or by bicycle. **Figure 2-1** shows the distribution of journeys in the Greater London area.

Greater London offers a wide portfolio of services including buses, heavy rail, light rail and trams. With an average of 4.8 million journeys per day, buses are the most widely used transit service in London, accounting for about half of all transit demand. To transport these many passengers, London has more than 8,000 buses, operating on a network of some 700 routes. There are three kinds of buses in London: traditional "double decker" buses, articulated buses (also known as bendy buses) and traditional 40-foot coaches.

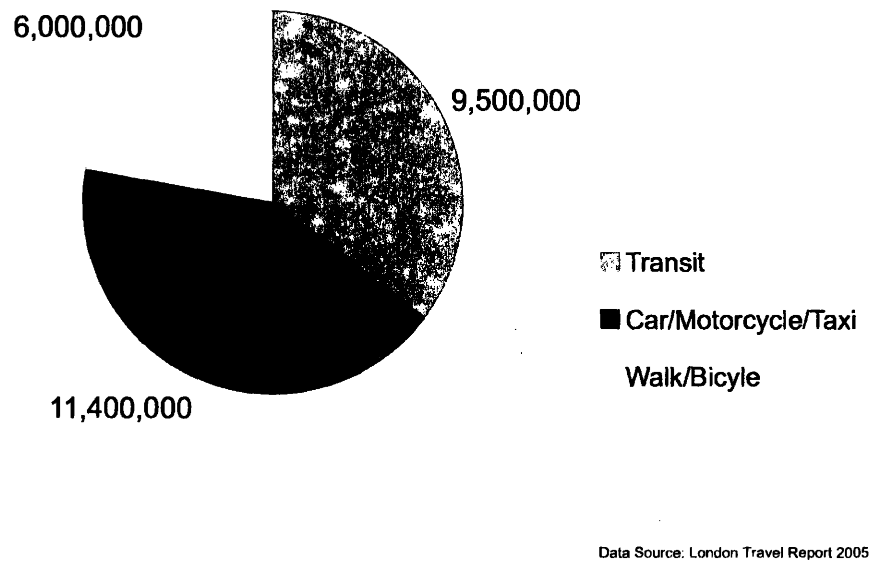

Figure 2-1: Distribution of Daily journeys in Greater London

The second most widely used transit service in Greater London is the Underground, which carries about 2.7 million journeys per day – 28 percent of all transit demand – across a network of 273 stations distributed along 12 lines.

Third is National Rail, with about 1.9 million daily journeys having their origin and/or their destination in Greater London. About half of these National Rail journeys (48 percent in 2004) start and end in London.

The transit portfolio of London is complemented by light rail and tram: the Docklands Light Rail (DLR) operates to the east of central London and carries an average of 0.1 million daily journeys and Tramlink operates in the south of greater London in the Croydon area and also carries about 0.1 million daily journeys.

Figure 2-2 shows the share of journeys for the different transit services available in Greater London.

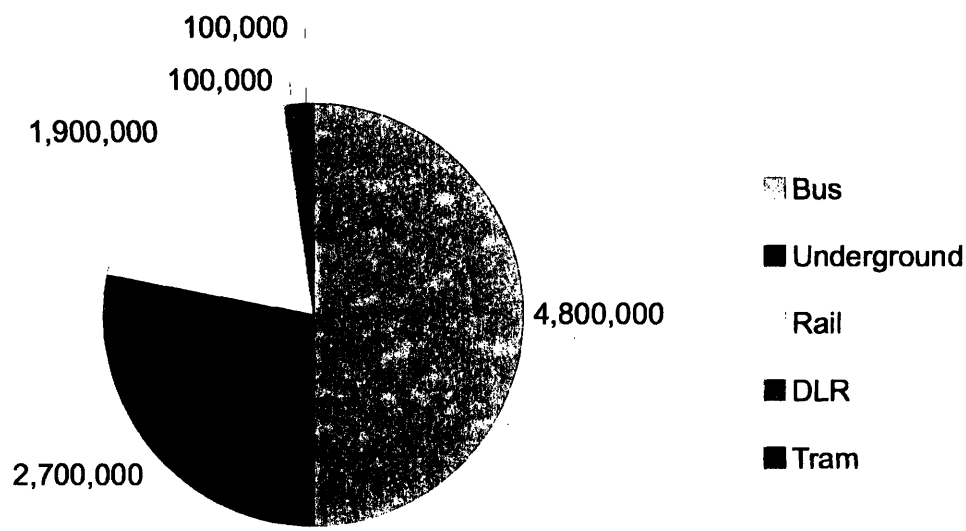

Figure 2-2: Distribution of Daily Transit journeys in Greater London

2.2 Overview of London AFC System

TfL offers three different fare payment media options: cash, printed tickets and Oyster cards. However, there are some differences in the fare payment media accepted on each transportation service. Oyster cards and printed tickets are universally accepted and cash is accepted only on buses. In addition, there are differences in the method for processing the payment media. Oyster cards are processed by the AFC system in all transportation services, while printed tickets are processed by the AFC system only in the Underground. In buses, DLR and trams printed tickets are accepted visually and are not processed by the AFC system. **Table 2-1** summarizes the fare payment media accepted on each of the transit services controlled by TfL.

	Cash	Printed Tickets	Oyster Card
BUSES	√	√	√*
UNDERGROUND	X	√*	√*
DLR	X	√	√*
TRAMS	X	√	√*

*** Processed by the AFC system**

Table 2-1 Media types accepted on TfL services

Oyster card allows customers to store two different types of fare products: prepay and ticket contracts. The following are the main characteristics of each one of these fare products:

1) Prepay allows customers to store on their Oyster card any amount of money, which they can later use to pay for transportation on any of TfL's services.

2) Ticket contracts are fare products with specific rules of validity by zone, transportation service and time. Ticket contracts include the following:
    a. Travelcards: These are unlimited ride period passes covering weekly, monthly, odd-period or annual durations.

b. Freedom passes - elderly: These are concession passes for senior citizens
c. Freedom passes - disabled: These are concession passes for persons with disabilities
d. Staff passes: These are concession passes for TfL employees.

TfL has taken a series of measures to encourage customers to use an Oyster card instead of printed tickets and cash. These measures include:

1) All travelcards are available only on Oyster card, except for the one-day and the three-day travelcards, which are still available on printed tickets.

2) Staff passes and freedom passes are available only on Oyster card.

3) Single ride and return tickets are also still available on printed media. However, Oyster customers using Prepay, pay a lower fare for single and return trips and have a guaranteed a cap on their daily spending on transit.

4) An extensive promotional campaign constantly publicizes the benefits of switching to Oyster card.

Subsections 2.2.1. to 2.2.5. describe the existing AFC system used in London by transit mode. Subsections 2.2.6. to 2.2.8. present the key characteristics of the supporting AFC data system.

2.2.1 Fare Collection on Buses

To pay for a bus ride, passengers in London can either purchase a fare product before boarding or pay cash to the driver as they board. Transport for London (TfL) aims to reduce the number of passengers paying as they board, by providing more and better ways to purchase tickets before boarding. As a result of a range of strategies, TfL can now ask all passengers in Central London to purchase tickets before boarding, although paying cash upon boarding remains an option outside of Central London.

In order to pre pay their bus fare, users can choose from a wide range of fare products including: single ride tickets, multiple ride tickets, period passes and concession passes. Some of these products are available on printed tickets, while others are available on Oyster Card and a few are available on either format.

When boarding, passengers holding a printed ticket have to present it to the driver and passengers with an Oyster Card have to tap in at the smart card reader. While cash payments and printed tickets are not processed by the AFC system, Oyster card transactions are: the AFC system records for each of these boarding transactions the serial number of the card, the date, time, ticket type, bus ID and a fare stage ID. Since passengers tap in only when boarding, the AFC system does not record any exit transaction.

The fare stage ID enables the AFC system to charge differential fares depending on the boarding location. To record the fare stage ID, Oyster readers are integrated into a console that the driver operates by indicating manually the location of the bus. However since bus fares are flat, this system is not currently in use. As a result, bus drivers are not required to identify the fare stage. TfL is in the process of implementing an Automated Vehicle Location (AVL) system, which would use satellite tracking technology and wireless communication to provide passengers with real time service information. The deployment of this new system is expected to begin in 2007. At this stage it is uncertain the degree of integration that will exist between that AVL system and the Oyster card platform.

2.2.2 Fare Collection on the London Underground

In the Underground, all passengers must pay their fare before entering any Underground station. As on buses, passengers can choose from a wide range of fare products, including: a single ride ticket, multiple ride tickets, period passes and concession passes. Nowadays most fare products are available only on Oyster and only a few still available only on printed tickets. All printed tickets in the Underground have a magnetic stripe on the back, which can be read by the gates. **Table 2-2** illustrates which products are available on each fare payment media type.

	Printed - Magnetic Stripe Ticket	Oyster Card
National Rail - Underground tickets	√	X
Group day tickets	√	X
Single and return tickets	√	√ **(Prepay)**
1 Day Travelcard	√	√ **(Prepay)**
3 Day Travelcard	√	X
7 Day or monthly Travelcard	X	√
3 Month, 6 month and odd period Travelcard	X	√
Annual period Travelcard	X	√
Elderly and disabled concession passes	X	√
Staff passes	X	√

Table 2-2: Underground fare products by fare payment media type

The Underground has a zonal fare, with a total of six zones covering Greater London. To enforce it, passengers have to validate their payment media at the gates installed at the entrances and exits of most Underground stations. At some entrances and exits however there are no gates. Because of this, it is helpful for this research to classify Underground stations into two groups:

1) Fully Gated (FG) stations, where all passengers have to pass through a gate to enter and exit the Underground platforms.

2) Non-Fully Gated (NFG) stations where some, or all, passengers can enter or exit the Underground without passing through a gate.

There are a total of 273 stations on the Underground, of which, 225 stations are Fully Gated (FG) and the remaining 48 are Non Fully Gated (NFG). **Appendix A** has a table listing all stations with their classification.

At FG stations all passengers must use a valid payment media, to pass through the gate, while at NFG stations, only passengers with Oyster card must validate at stand-alone card readers. At NFG stations, passengers with a printed ticket can enter and exit the Underground without validating. London Underground Limited has a team of inspectors that control fare evasion at these stations, by asking passengers on board a sample of trains to produce their tickets. Passengers that fail to produce a valid ticket are charged a penalty of 20 pound sterling.

In every entry and exit transaction with an Oyster card – both at FG and NFG stations – the AFC system creates a transaction record that includes the unique ID of the card, the ticket type, the station code and the date and time of the transaction. In contrast, the AFC system does not produce a record for every transaction with a printed ticket. Instead every fifteen minutes it produces a summary with the number of printed ticket transactions at each gate. Each summary includes the count of transactions for each of the fare products available on printed tickets.

2.2.3 Fare Collection on National Rail

Fare Collection on National Rail is outside the jurisdiction of Transport for London. Nevertheless, National Rail and the Underground share a number of stations where passengers can interchange between services. In this thesis the analysis of fare collection on National Rail will be limited to this set of shared stations. At shared stations, passengers can interchange between National Rail and the Underground using printed tickets that have a fare product valid on both networks. Also, they can use Oyster card Prepay at selected stations and lines.

There are 63 stations where passengers can transfer between National Rail and the Underground of which 44 are in the FG set of stations and the remaining 19 are in the NFG set. **Appendix A** presents a list of these interchange stations. As discussed before, at FG Stations, connecting passengers have to pass through a gate in order to enter or exit the controlled Underground area. **Figure 2-3** illustrates possible fare collection layouts at these FG stations. Since all passengers have to pass through a gate, the AFC system records data on all Underground entry and exit transactions. As mentioned above, most connecting passengers use printed tickets with a magnetic stripe. As with regular printed tickets in the Underground, the AFC system maintains a summary with total entries and exits at each gate by fifteen minute time period.

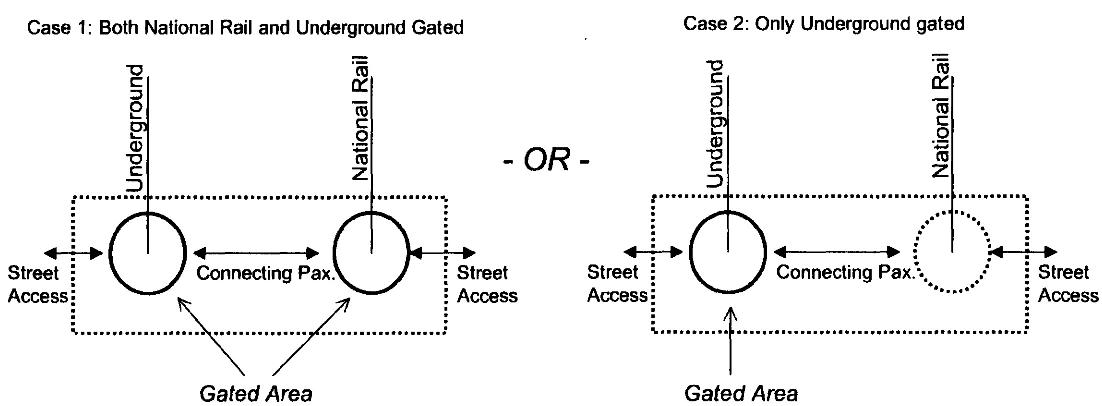

Figure 2-3: Layouts of FG Stations with National Rail Connections.

For those connecting stations that are also NFG stations, passengers connecting between National Rail and the Underground do not validate at gates. For this reason, at these stations the AFC system does not have a record for all entry and exit transactions. **Figure 2-4** illustrates two possible layouts for these NFG stations.

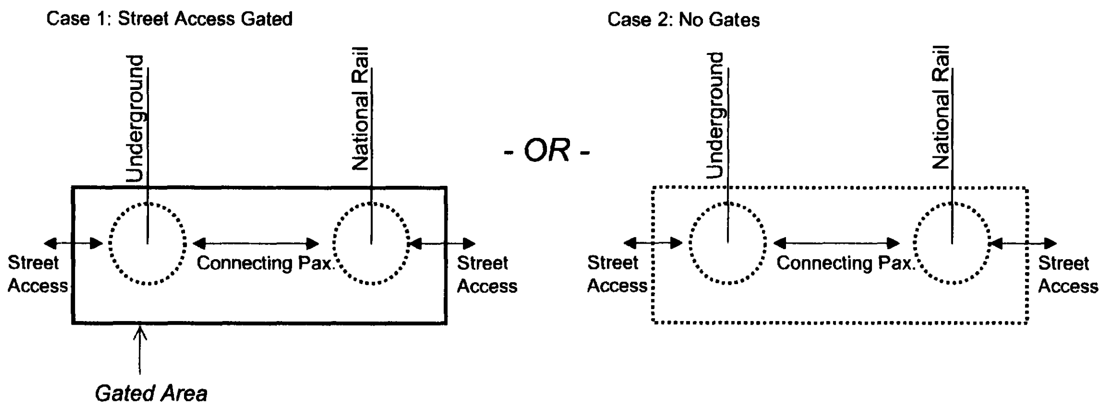

Figure 2-4: Layouts of NFG stations with National Rail Connections

2.2.4 Fare Collection on the DLR

To pay for a DLR ride, all passengers have to purchase a fare product before boarding. In order to pre-pay their fare, users can choose from a wide range of fare products including: single ride tickets, multiple ride tickets, period passes and concession passes. Some of these products are available on printed tickets, others are available on Oyster Card.

Like the Underground, DLR has a zonal fare, but unlike the Underground, most DLR stations are non gated –in fact, 35 out of the 38 DLR stations have no gates at all. At these stations, the AFC system records both entry and exit data from Oyster card transactions, but does not record any data from passengers using printed tickets. Passengers using an Oyster card have to validate at stand-alone smart card readers installed on the station platforms. The data obtained from Oyster entry and exit transactions is the same as on the Underground.

Only 3 DLR stations, which share facilities with the London Underground, have gates. At these stations, the AFC system records data for all entry and exit transactions, both from printed tickets with magnetic stripe and Oyster Cards. The data obtained from printed tickets is the same as for Underground transactions with this media type. To control fare payment in this mostly non-gated system, inspectors perform random checks on board a sample of trains. Inspectors examine printed tickets visually and Oyster Cards using a special handheld device.

Besides the AFC data, DLR stations are equipped with Automatic Passenger Counters that register entries and exits at each station. This system is managed independently from the AFC system.

2.2.5 Fare Collection on Tramlink

Tramlink is a tram service with 3 lines and 38 stops that operates in the Croydon area, south of Central London. To use Tramlink, passengers must purchase a fare product before boarding. In order to purchase a ticket, users can choose from a wide range of products including single ride tickets, multiple ride tickets, period passes and concession passes. A few of these products are available on printed tickets and most are now available only on Oyster card.

Tramlink has a flat fare and non-gated stations. In this system, passengers with an Oyster card have to tap in – only when boarding – at the stand-alone smart card readers installed at the tram stops. The data obtained from these Oyster entry transactions is the same as for Oyster entry transactions on the Underground. The AFC system does not record data for passengers traveling with printed tickets.

2.2.6 Transactional Data Summary

Table 2-3 lists the data available from Oyster card transactions on buses, the Underground, DLR and Tramlink. As mentioned before, Oyster card records entry and exit data for the Underground and DLR, while for Buses and Tramlink the system only records entry data.

	Card ID	Ticket Type	Entry Location	Entry Time	Exit Location	Exit Time
BUSES	√	√	√ *	√	X	X
UNDERGROUND	√	√	√	√	√	√
DLR	√	√	√	√	√	√
TRAMS	√	√	√	√	X	X

*** Driver intervention required**

Table 2-3: Data available from Oyster card transactions

2.2.7 Personal Data

In addition to transactional data, personal data is collected from registered Oyster card users. Registration takes place either when a card is issued, when customers wish to make on-line purchases, or when customers wish to get balance protection. To register, customers must fill in a form that contains the fields summarized in **Table 2-4**.

DATA FIELD	MANDATORY?
Title	Yes
Forename	Yes
Middle Initial	No
Surname	Yes
House Name	No
House Building Number	No
Street	Yes
Town	Yes
Country	No
Postcode	Yes
Home phone	Yes
Mobile Phone	No
E-mail address	Yes

Table 2-4: Oyster Card Registration Data

Currently, all Oyster card users with concession and period passes must register their card at the time of issuance. All other Oyster users can choose not to register at the time of issuance, but must register their personal data if they wish to receive balance protection or use the online sales portal.

2.2.8 Central Data System

All Oyster card transactions and personal data and all printed ticket counts are sent electronically to a Central Data System. For Oyster card data, this system has capacity to store 'live' records for the most recent eight weeks. Every week the oldest week of data in this eight-week set is overwritten with the new week of data, although the oldest week of data then stored on tape. To comply with existing privacy protection policies, the unique serial number of the card, present in each transaction record, is corrupted when it is transferred to tape.

The transactional data in the eight-week database is arranged in tables by transportation subsystem: for bus entries, for Underground and DLR entries, for Underground and DLR exits and for Tramlink validations. The personal data, along with sales information and "hotlisted" Oyster Cards (cards that have been reported as lost or stolen) is stored in the Card Management System (CMS).

From the transactional data and the personal data, the Central Data System administrators develop summary tables that provide information that TfL needs for planning and operations analysis. For instance, a simple summary table can have the total number of entries per station per day in the underground, or the number of journeys by passengers living in each Postal Area.

Summary tables are kept 'live' in the system for a customisable period of time. In fact, most summaries that exist today in the Central Data System have information dating to the beginning of operations. **Figure 2-5** illustrates the data process for Oyster records in the Central Data System.

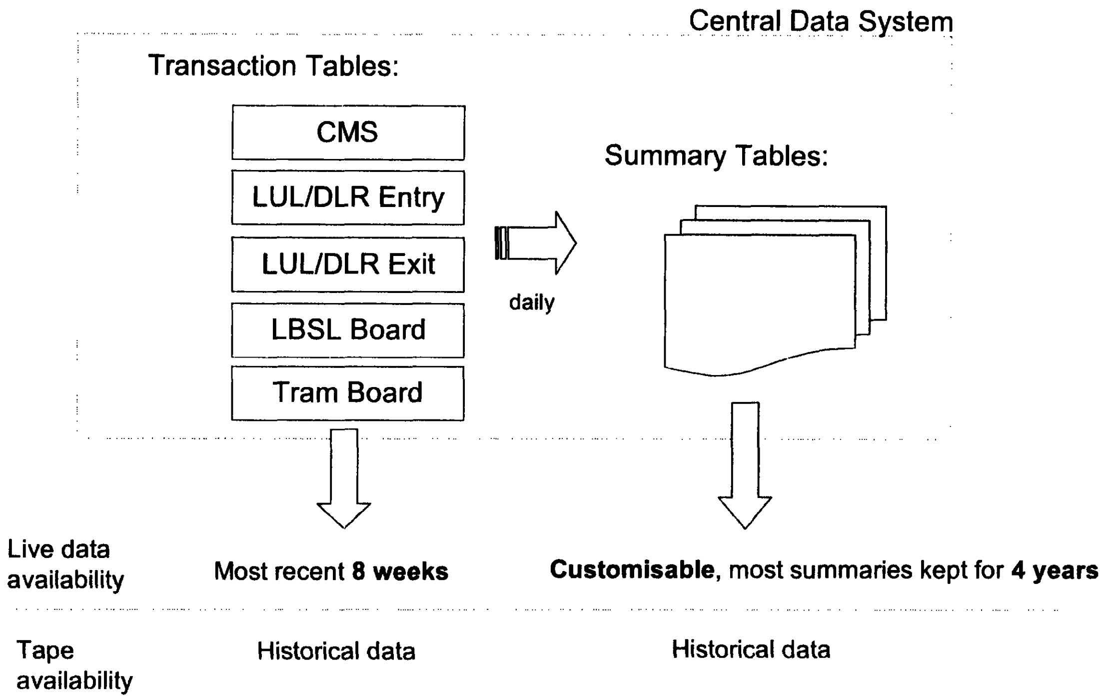

Figure 2-5: Handling of Data in the Central System

Although historical data stored on tape can be restored back into a special segment of the 'live' system, in practice its availability is limited both by the space available for restores on the 'live' system and by the time it takes to upload the data: The 'live' system has a stack of memory that can store up to four weeks of old transactional data at any given time. It takes one day to upload a week of data. That means that to upload one year of transactions would take 52 days, or more than two calendar months: in practice, uploading large amounts of transactional data is operationally infeasible.

In addition, since the card serial number is corrupted as transactions are transferred onto tape, it is impossible to link old transactional data with personal data available on the Card Management System. Further, for the same reason, it becomes impossible to track the transactions of a given Oyster Card. As a result, it becomes impossible to use restored historical data for some applications that require a follow-up on the behaviour of segments of the market, defined by customer personal data. Examples of those applications are: the price elasticity of demand for customers of a given postcode and the Origin Destination Matrix, for customers of a given postcode. To overcome these challenges, the system administrators can define summary tables. These tables can be updated automatically and maintained 'live' on the system for long periods of time.

2.3 Overview of OD Estimation at the London Underground

Planners at London Underground Limited (LUL) make origin-destination estimates using the Rolling Origin Destination Survey (RODS). RODS is a ten-year rolling survey program that begun in 1998 whose main output is an annual estimate of the origin-destination matrix for a typical day on the Underground.

Apart from its use to estimate the general origin-destination matrix, the RODS survey is used to produce a series of reports on travel patterns including but not limited to: initial origin and final destination of customers using each underground station, other transportation modes used before and after taking the underground, purpose of travel to each underground station, and origin-destination matrix for different demographic groups. **Figure 2-6** presents a summary of the main applications of RODS.

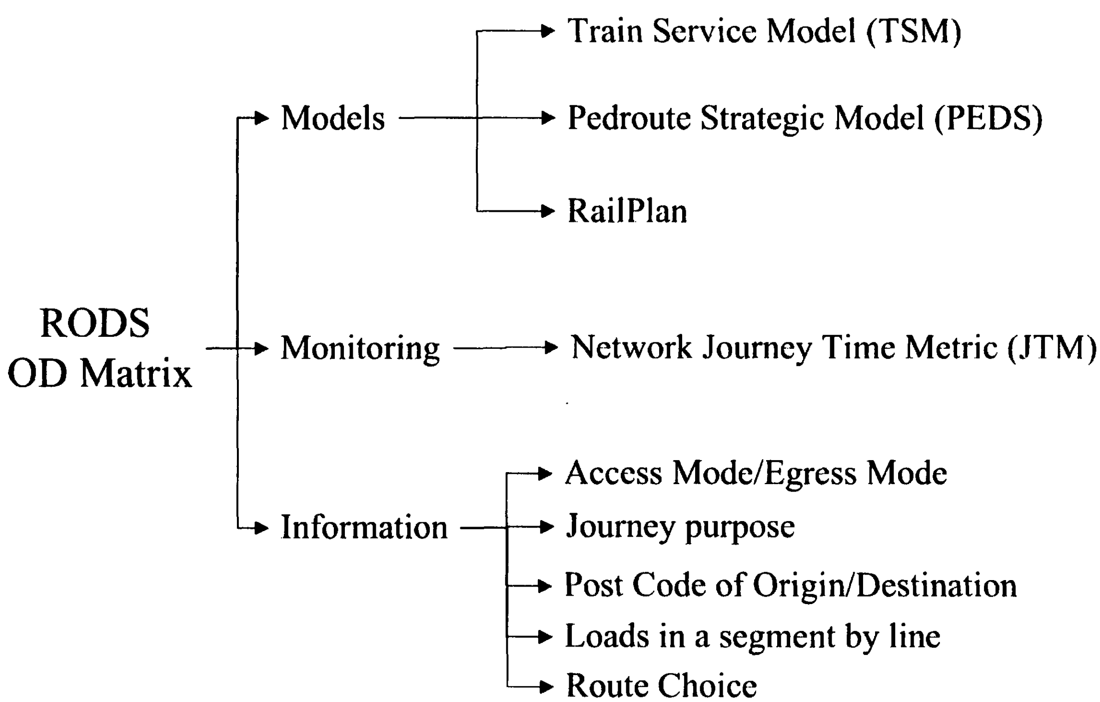

Figure 2-6: Main applications of RODS

The Train Service Model (TSM) is a computer model designed to simulate London Underground operations. This model is used to help assess the impact of all sorts of changes including timetable changes, reliability projects and line upgrades and extensions. The main inputs to this model are passenger origins and destinations obtained from RODS, train capacity and schedule. TSM currently uses RODS as input for demand, which is scaled to average November counts. That is, TSM doesn't capture seasonal variations in demand.

The Pedroute Strategic Model (PEDS) is a model that assesses the delay and congestion at any, or all, of the entrances and exits of Underground stations. A software application converts RODS passenger flows into flows to each specific entrance and exit.

The Network Journey Time Metric (JTM) is a measure of how long the average customer's journey takes compared to how long the journey would take if the service ran perfectly to schedule. This model uses RODS to weight the impact of a delay at a particular node, and gate counts to assess demand volume in the period of interest.

LUL planners receive on average 1 to 2 information requests per week both from within and from outside TfL. Such requests include:

1) Access mode and journey purpose to a particular set of underground stations.
2) Post Code of the origin for passengers who enter at a particular station.
3) Post Code of the destination for passengers who exit at a particular station.
4) Loads in segments of a particular Underground line, in a given direction, distinguishing demand between lines that might run in parallel.

Finally, RAILPLAN is the model that TfL planners use for network and route design. This model uses RODS origin-destination Matrix for validating demand forecasts.

2.3.1 Description of the RODS process

There are 273 stations in the Underground, serving about 2.7 million passengers daily. To build a representative dataset for this large and complex system, LUL implemented a rolling, multi-year survey program in which planners select each autumn a set of 30 to 40 stations to survey. The selection of stations is based on where important changes in ridership and/or service have occurred subject to a budget constraint. Each station on the survey set is assigned a survey date. During that day, field workers hand out survey questionnaires to random passengers starting their journey from that station. Respondents are then expected to complete the surveys and return them by mail.

To establish the number of questionnaires to hand out at each station, LUL planners first determine a target sample size by hour at each station. This number is estimated using the hourly control totals for each station and the desired level of accuracy for the survey. Then, planners multiply the target sample sizes by the inverse of the expected response rate, which for RODS hovers between 20 and 30 percent.

In the questionnaire, included in **Appendix D**, passengers are asked about the details of the specific journey they are making. In particular, they are asked:

1) Initial origin and final destination for that particular trip.
2) Underground stations used to complete that trip, including interchange stations.
3) Other transportation modes involved in that trip.
4) Purpose of the trip.
5) Ticket type.
6) Frequency of that trip.
7) Gender and age.

Using the survey data obtained throughout the years of the RODS program, LUL creates a seed origin-destination matrix, which serves as the base for inferring the full origin-destination matrix. A critical input for the inference process is the total number of trips starting and ending at each Underground station. To come up with this estimates, LUL planners differentiate between Fully Gated (FG) and Non Fully Gated (NFG) stations. At FG stations, planners use the average of November entry and exit gate counts, obtained with the AFC system, while at NFG stations, planners use a combination of November manual counts plus average November gate counts where available. There are a handful of FG stations where LUL planners consider that AFC data is not reliable, or where some adjustments maybe needed. At these stations LUL planners estimate control totals using a combination of manual counts and corrected AFC data. **Figure 2-7** illustrates the methods used to estimate the control totals for the different kinds of Underground stations. **Appendix A** has a detailed classification of all Underground stations.

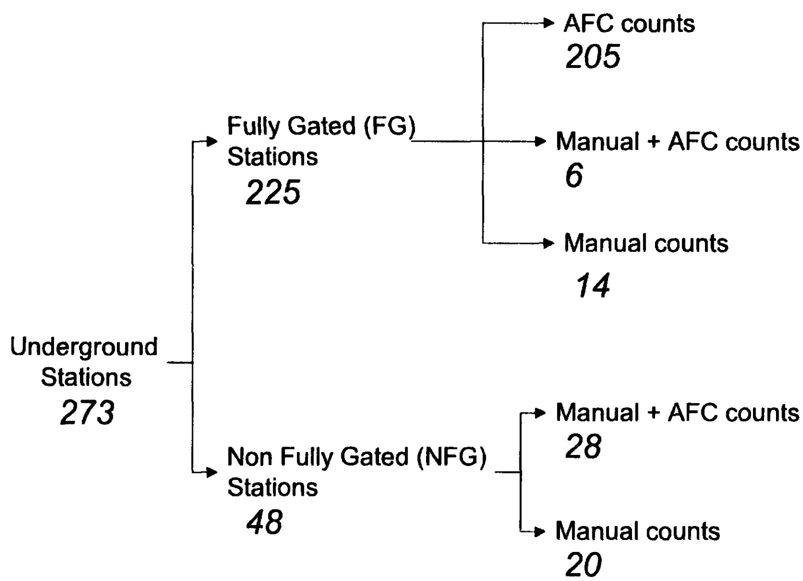

Figure 2-7: Method for determining control totals at Underground Stations

Survey data and station entry and exit control totals are the main inputs in the estimation of the full origin-destination matrix. The following is a broad outline of the steps in the RODS process.

1) **Set up:** The day is divided into fifteen-minute time segments and all survey responses are assigned to the appropriate time segment. For time segments with too few survey responses, planners create duplicates of survey records obtained for adjacent time segments.

2) **Calculation of expansion factors:** Expansion factors are the number of journeys that each survey record represents. This number is calculated by dividing the control total for each time segment by the number of survey responses within that time segment. To illustrate this process, assume that between 8:00AM and 8:15 AM there were 1,000 entries at Picadilly Circus Station and there are 200 survey responses for journeys beginning at Picadilly Circus between 8:00AM and 8:15AM. In this example, each survey response represents 5 journeys (1,000/200).

3) **Expansion:** The origin-destination matrix matching station entry totals (singly constrained OD matrix) is obtained by multiplying each survey record by the corresponding expansion factor.

4) **Adjustment:** An iterative adjustment routine seeks to match the distributions of age, sex, journey purpose and ticket type in the OD Matrix to the distributions observed in the Underground User Survey, which is a face-to-face survey of random passengers on station platforms. This iterative adjustment routine also seeks to produce an origin-destination matrix that matches both station entry and exit control totals (doubly constrained OD matrix).

Figure 2-8 summarizes the general procedure for estimating the Origin-Destination Matrix.

By June 2004, there were 193,249 survey records in the aggregate RODS dataset. **Figure 2-9** shows the number of records in the current dataset by year obtained. It is important to note that while RODS started in 1998, the dataset also includes some records dating from 1990. These older records, which correspond to a previous survey program, provide data on travel patterns from stations where there is little or no more recent RODS survey data available.

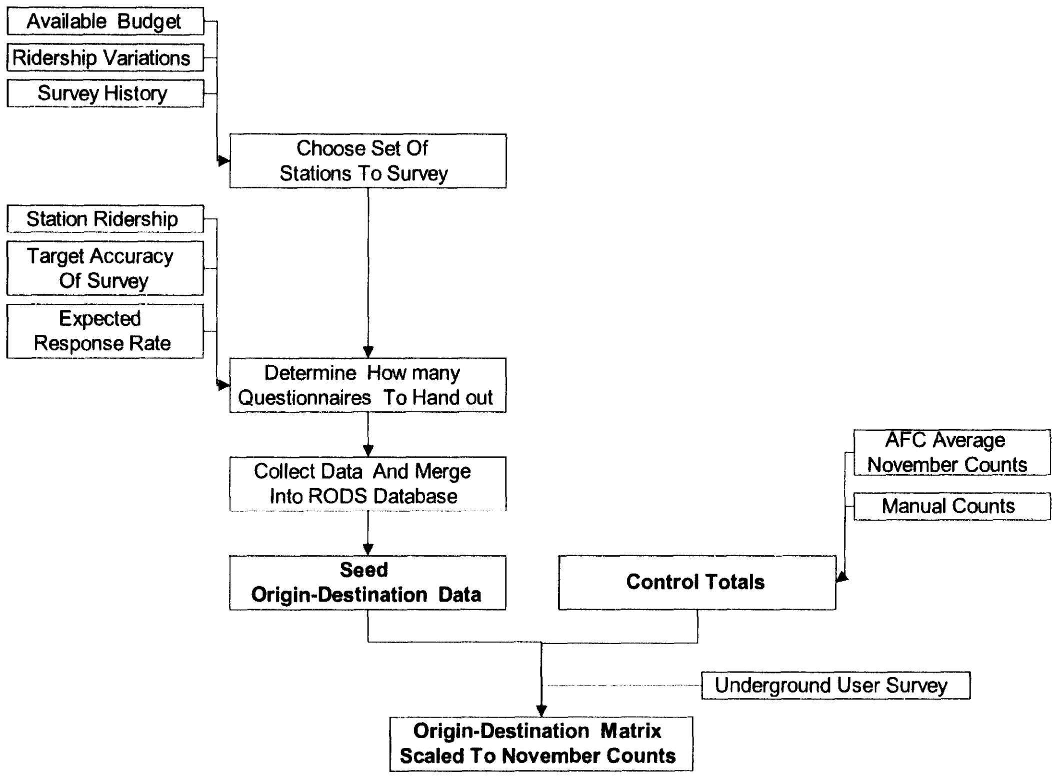

Figure 2-8: Process for obtaining the O-D Matrix using RODS

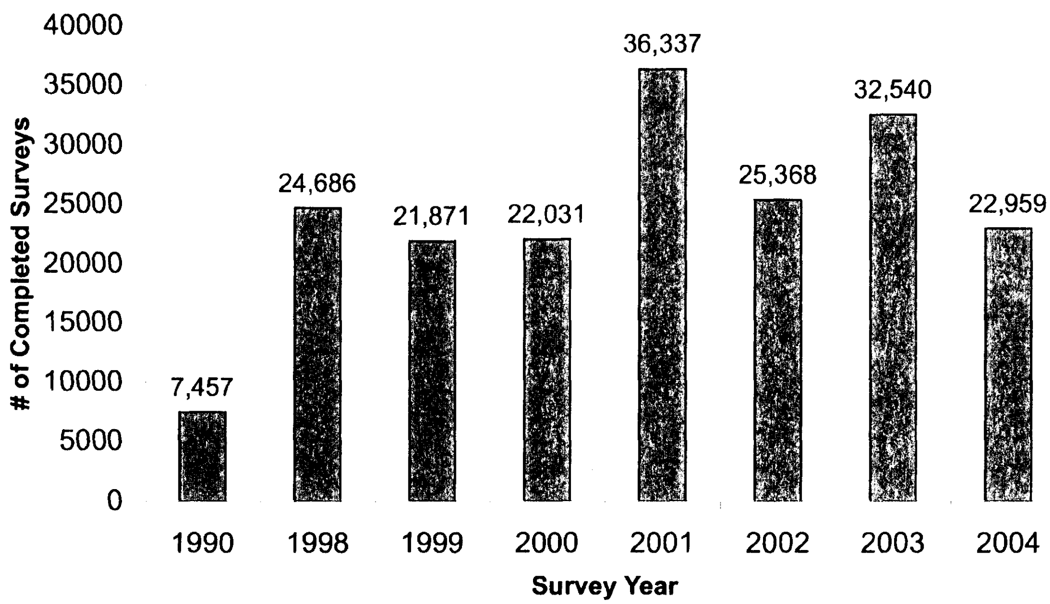

Figure 2-9: Number of Records in RODS Dataset by Year

As mentioned before, each survey record is assigned to a time segment, and then expanded to match the control totals. **Figure 2-10** illustrates the number of survey records and the entry control totals for each time segment. Note that in the survey there is no data on journeys before 7:00AM and after midnight.

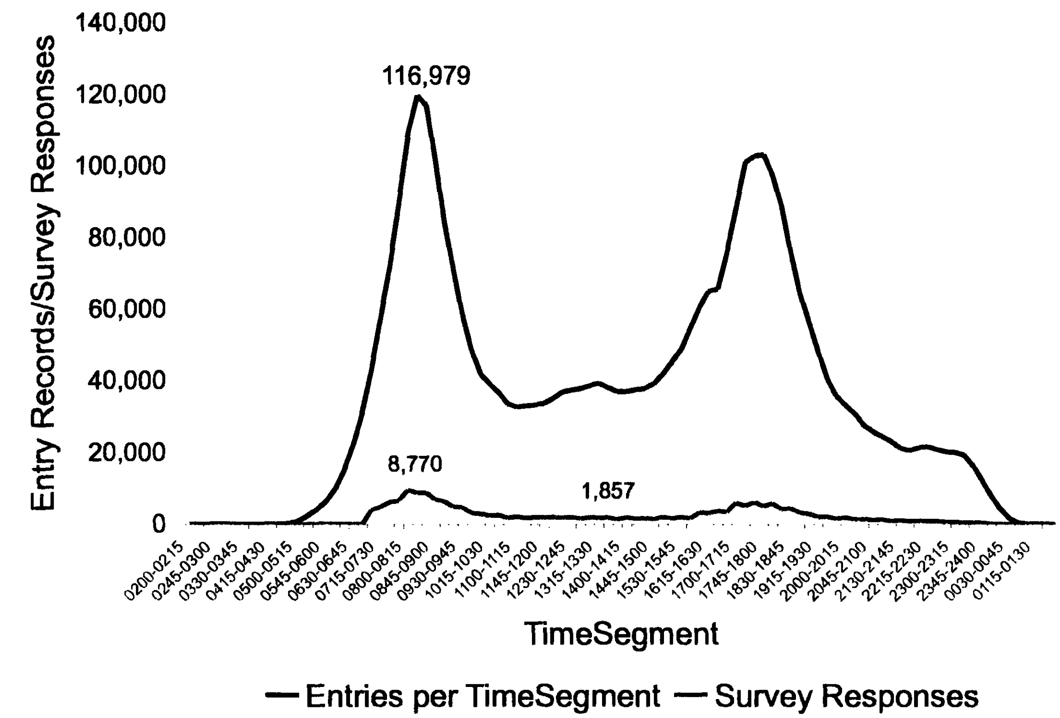

Figure 2-10: Entry Control Totals and Survey Responses Per Time Segment

In each time segment, the survey responses corresponding to each station are expanded to match the corresponding fifteen-minute entry and exit control totals. **Figure 2-11** illustrates the expansion factors of RODS using as an example the 8:00-8:15 AM time segment. The figure shows, on a logarithmic scale, the number of journeys that each survey response represents – or expansion factor – along with the corresponding station entry control total. The stations in the figure are ranked by (decreasing) expansion factor. This figure shows that within this fifteen-minute time segment there is a large variation in the number of journeys that each survey response represents. In fact, this expansion factor ranges between 3 and 44 Underground journeys per survey, with a median of 10.5. The figure also shows that both the expansion factors and the entry control totals follow broadly the same decreasing pattern, indicating some correlation between the expansion factors and the number of entries per station. However, the figure also shows that between Underground stations with similar expansion factors, there are significant variations in the number of entries.

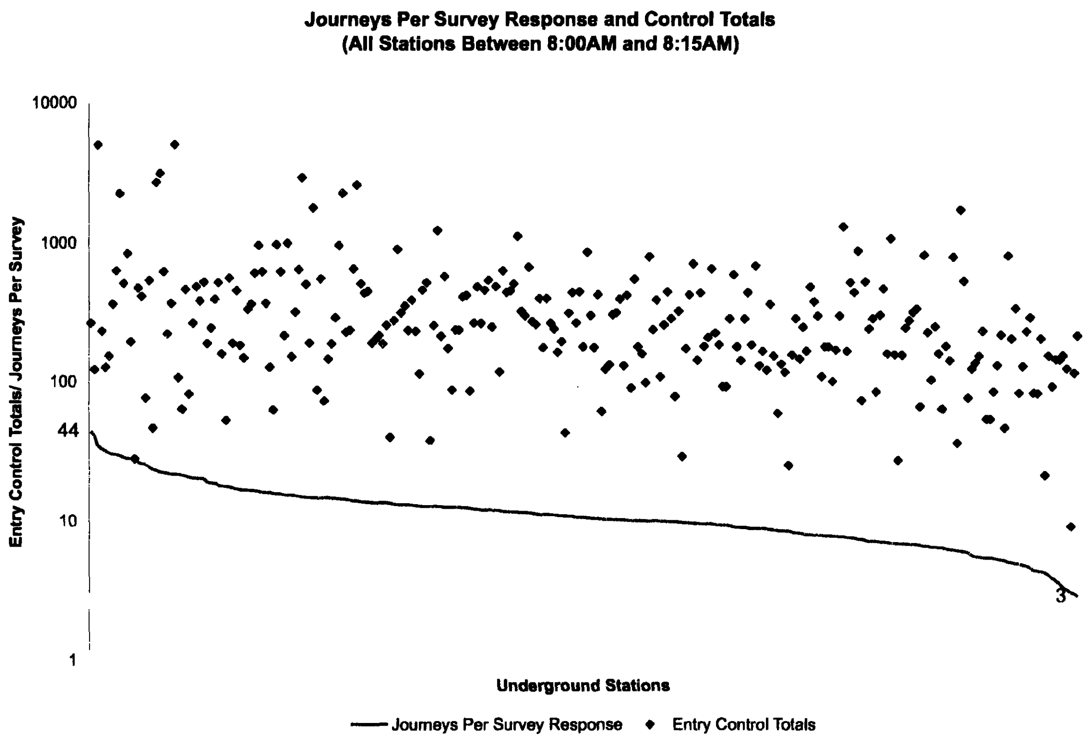

Figure 2-11: Journeys Per Survey Record and Control Totals (8:00-8:15AM)

For the entire day, **Figure 2-12** illustrates the median expansion factor for each time segment. It ranges between 10, early in the morning, and 35 journeys per survey response in the middle of the day. The median expansion factor for the whole day dataset is 17 journeys per survey response. The pattern in the figure shows that the relative coverage of the survey, represented by these expansion factors, is higher in the AM peak, and weakest on the middle of the day and during the evening. This pattern is somewhat the opposite of the pattern of demand. This inverse pattern is somewhat surprising and the large difference in coverage between the AM and PM peak periods is particularly striking.

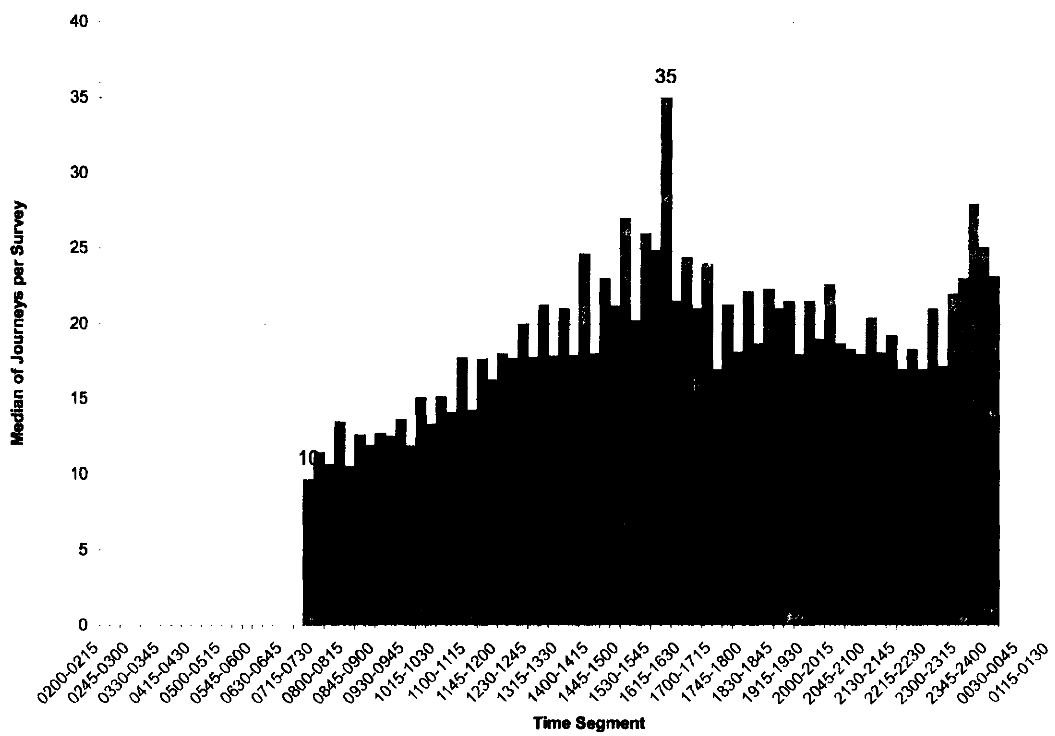

Figure 2-12: Median expansion factor by time segment

2.3.2 Assessment of RODS

There are at least four issues that negatively affect the quality of the origin-destination matrix that is obtained through the RODS process.

First, expanding the RODS survey data by fifteen-minute intervals is inadequate, and can lead to errors in the resulting origin-destination matrix. Usually, the required sampling rate –number of survey respondents divided by the size of the target population – can be quite small, as long as the target population is large. However, for small target populations, the sampling rate must be high. Otherwise, the sample may not represent the target population. By dividing the day into independent fifteen-minute intervals, the target populations are very small, which requires high sampling rates. **Figure 2-13** illustrates this issue. It shows for each time segment, the median entries to all Underground stations. Note that the target population in each time segment is quite small. In fact, the median for the whole day is just 58 entries per station, while the median for the peak hour is less than 250 entries per station (the median of the medians presented in the figure is 67). Using a survey with small sample rates to understand the travel patterns of small target population is not correct, as the sample may not be representative and therefore can lead to inaccurate origin-destination matrices.

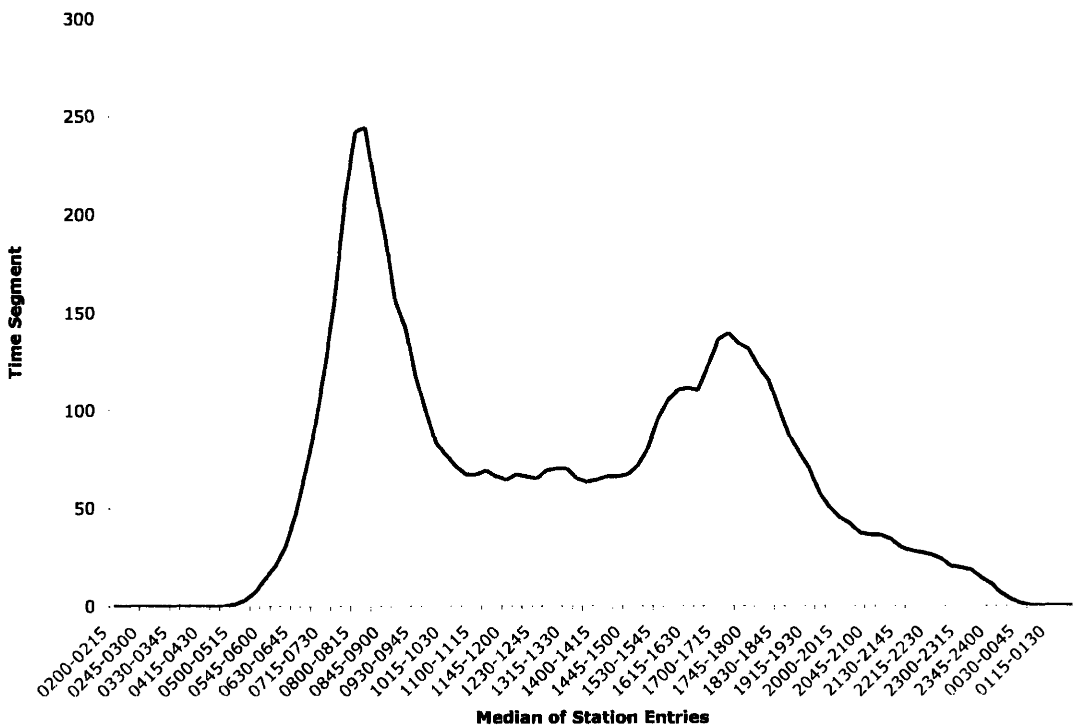

Figure 2-13: Median Entries per Station by Time Segment

A second issue with RODS is the high non-response rate – defined as the number of non-returned survey responses divided by the total number of surveys handed out – which hovers between 70 and 80 percent. A low non-response rate would provide confidence that the survey results are representative of the target population, but the high non-response rate raises concern about non-response bias in the sample. In the particular case of RODS, the high non-response rate is an indication of potential bias in the sample, which can result from certain segments of passengers, with characteristic travel patterns, consistently not returning the questionnaires.

The third issue is the rolling method used for conducting the survey. Although this methodology represents an improvement over the previous one used by TfL in which a single survey was conducted every 10 years, with the rolling methodology it is still not possible to accurately capture changes in travel patterns over time. Today, the RODS dataset includes survey responses from eight different years, and therefore the survey produces an eight-year "rolling" average, rather than a true annual estimate of travel patterns.

Finally, since the surveys are handed out only between 7:00AM and midnight the dataset does not capture the travel patterns of all customers, particularly those who begin their journeys early in the morning. This can result in a significant bias in the dataset, as these customers are more likely to have longer commutes than customers traveling later in the morning.

Chapter Three: Integrating AFC Data and Survey Data: Estimating the Origin-Destination Matrix for the Underground

Oyster entry and exit transactions provide TfL planners with a large origin-destination dataset for all days of operation. The goal of this chapter is to develop a new methodology that combines available Oyster origin-destination data with estimated station entries and exits and with RODS, to build a more precise period-level origin-destination matrix. The chapter is divided into three parts: Section 3.1 presents an analysis of the origin-destination data available from Oyster, Section 3.2 presents the proposed methodology and section 3.3 presents the results of the methodology, compared with the RODS 2004 OD matrix.

3.1 Overview Of Oyster Origin-Destination Data

For purposes of analysis, TfL planners divide the year into thirteen four-week periods, with the first period always beginning on April 1st. The analyses in this chapter are for period 1, 2006 (or simply, period 1) which runs from April 1st to April 29, 2006. **Figure 3-1** shows the daily Underground entry transactions made with Oyster cards for period 1.

This Oyster dataset includes Completely Documented (CD) Oyster records, in which both the entry and exit stations are fully identified, but it also includes the following records:

1) Incompletely Documented Journeys (IDJ) that result from passengers tapping in but not tapping out at the smart card readers (these are generally referred to as unfinished Oyster journey records).

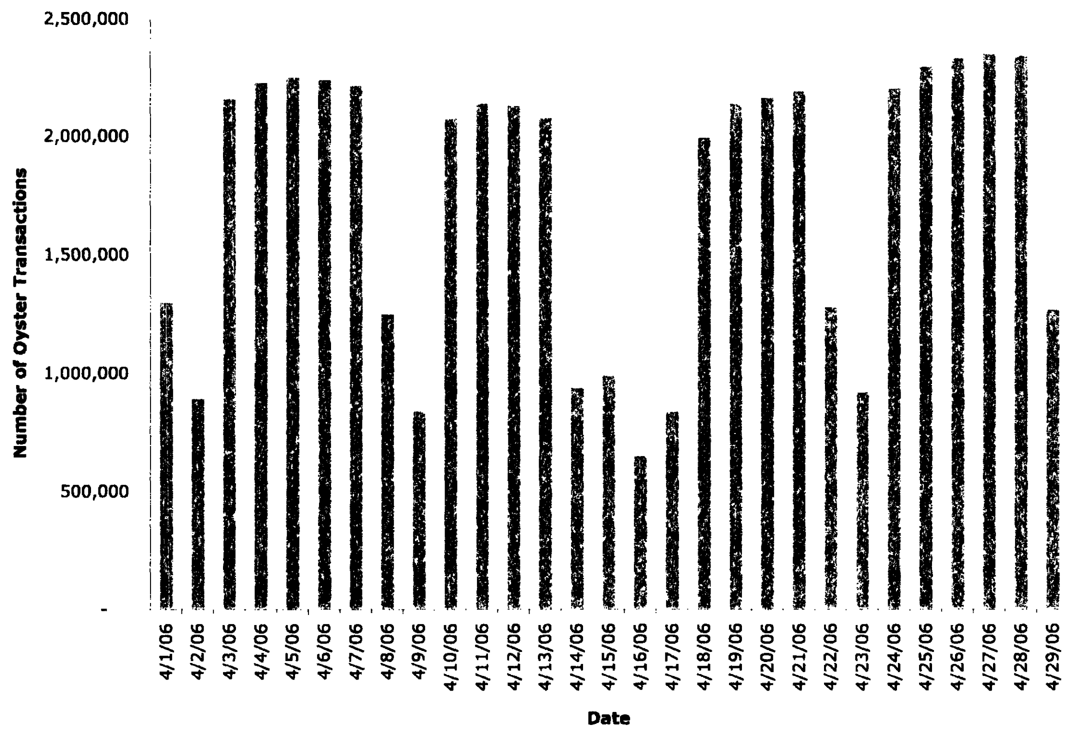

Figure 3-1: Daily Oyster Transactions From April 1st To April 29, 2006

2) Incompletely Documented Journeys (IDJ) from passengers tapping out but not tapping in at the readers (these are generally referred to as unstarted Oyster journey records).

3) "No travel" records, that correspond to Oyster cards used to enter and exit at the same station within a short period of time. Most of the times, "no travel" records correspond to staff passes used to let people in and out of stations.

In Period 1 the number of IDJ and no travel records is quite uniform relative to the total CD Oyster records, as illustrated in **Figure 3-2.**

In Period 1 there are 5 Saturdays, 4 Sundays, 2 holidays (Good Friday on April 14 and Easter Monday on April 17) and 18 weekdays. All analyses in this research are based on the average of the 18 weekdays of period 1. **Figure 3-3** shows the percentage of CD, IDJ and "no-travel" records for the average weekday in this period.

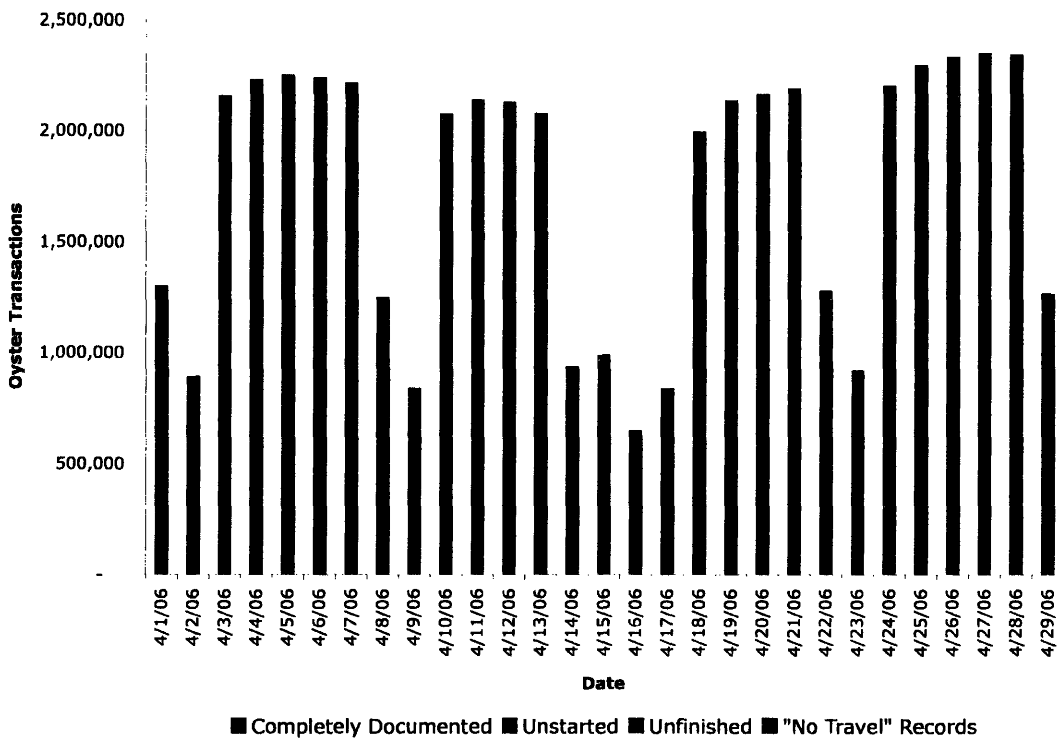

Figure 3-2: IDJ, No-Travel And Completely Documented Journeys

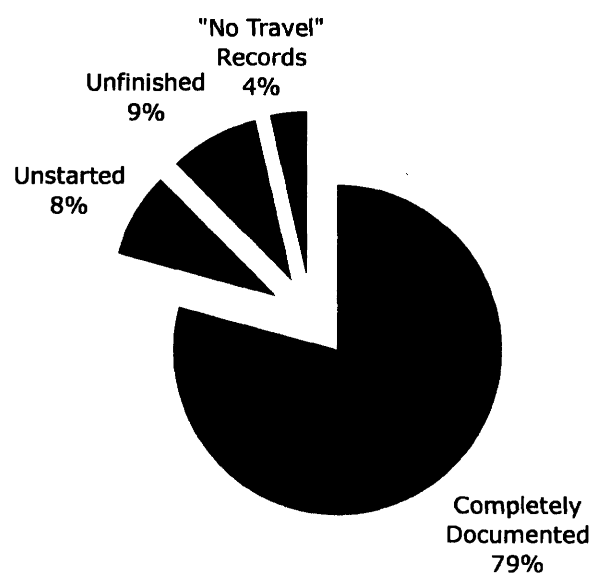

Figure 3-3: Percentage of IDJ, No-Travel and Completely Documented Records

3.2 Methodology for Estimating the OD Matrix

The dataset of CD Oyster journeys provides a complete OD matrix for a large subset of Underground customers. This section identifies the challenges of expanding the travel patterns of this subset of customers to represent all Underground customers, and presents a methodology to overcome them. In essence, the methodology used to build the full OD matrix is similar to that used in RODS: the journey records in the seed OD matrix are multiplied by expansion factors to match station entry totals. Then, using an iterative process, the OD matrix is adjusted to meet bots the station entry and exit control totals. However, there are two important differences in the proposed method:

1) The seed matrix is obtained directly from the Oyster dataset instead of from survey data

2) The expansion factors are estimated using RODS, to correct for biases that might exist in the Oyster seed matrix.

There are three major steps in this methodology.

1) Estimate entry and exit ridership at each underground station (station level estimate) for the average weekday in the analysis period.

2) Estimate the number of journeys – or expansion factor – for each CD Oyster journey record to obtain an OD matrix that matches the station entry totals.

3) Using a Furness process, adjust the OD matrix to meet both station entry and exit control totals.

Each step is presented in detail in the following sections.

3.2.1 Estimating Station entries and Exits

This section presents the estimates of station entries and exits for the average weekday in Period 1, 2006. Two cases are considered: Fully Gated (FG) stations and Non-Fully Gated (NFG) stations (see **Appendix A).** This section ends with a summary of the estimates.

a) Entries and exits at FG stations

At FG stations all customers have to use either an Oyster card or a printed ticket with magnetic stripe to pass through the gates. For these 205 stations, entry and exit totals can be estimated directly from AFC data, as is done for the RODS 2004 estimates. **Figure 3-4** illustrates the relationship used in this research to estimate station entries and exits using AFC data.

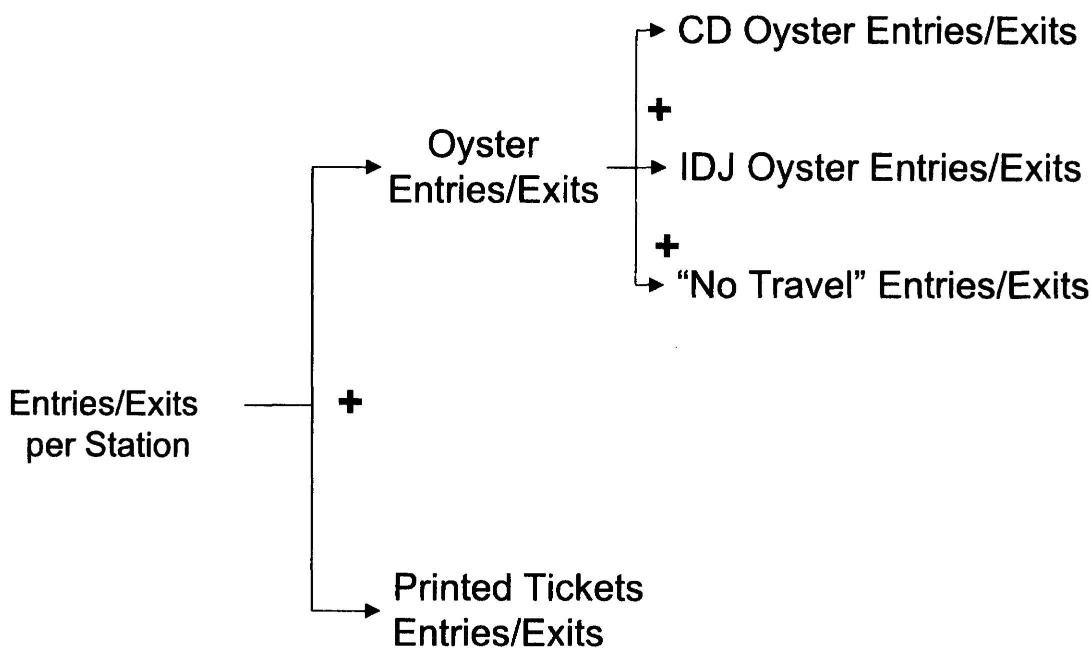

Figure 3-4: Formula to estimate Entries and Exits at FG stations

The application of this relationship is straightforward and results in a set of entry and exit estimates for FG stations in weekdays of Period 1, 2006. Additionally, estimates of entries and exits in RODS 2004 provide a baseline for validating the Period 1 estimates. **Figures 3-5** and **3-6** compare these entry and exit estimates for RODS 2004 and the AFC system for period 1, 2006.

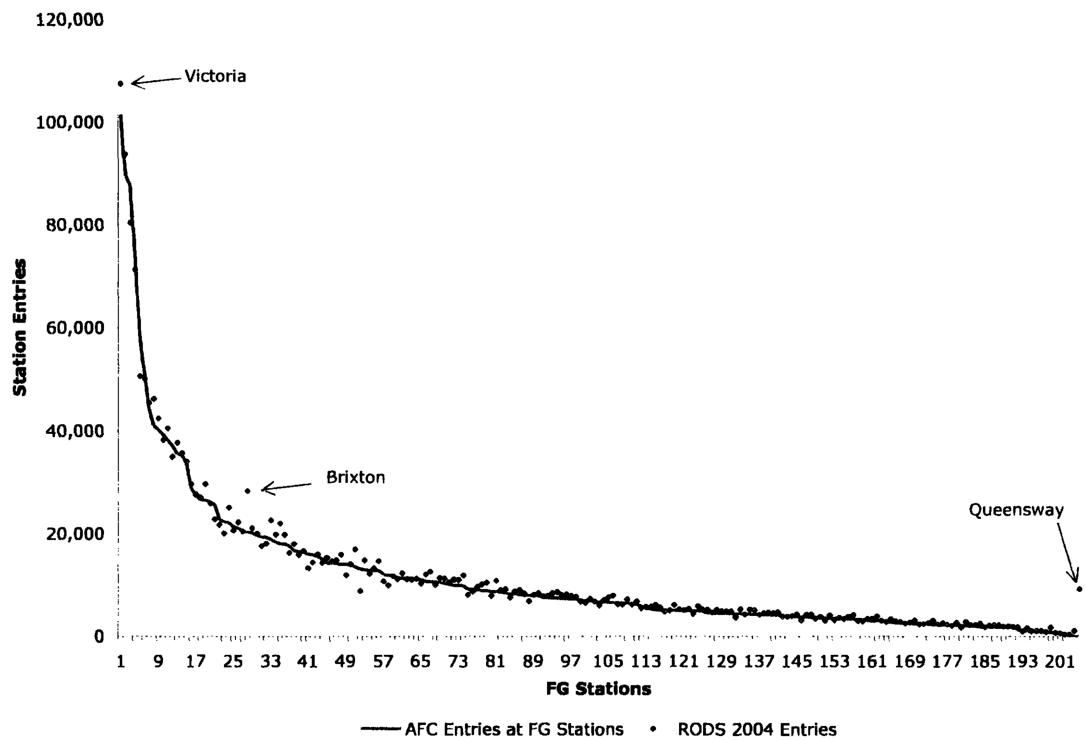

Figure 3-5: FG station entries for period 1, 2006 and RODS 2004

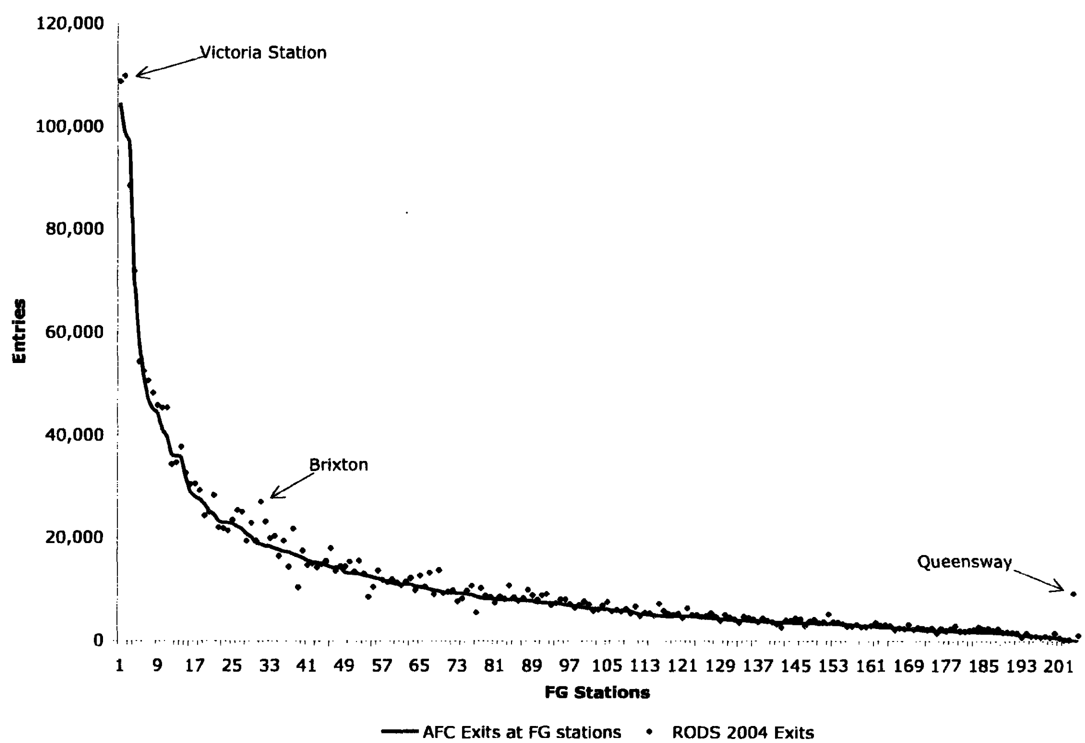

Figure 3-6: FG station exits for Period 1, 2006 and RODS 2004

The visual evidence presented in the figures above, shows great similarity between the estimates for period 1, 2006 and for RODS 2004. The Percentage Root Mean Square Error (%RMSE) provides a quantitative assessment of this visual evidence: %RMSE values of 15% and 17% corroborate the similarity between these estimates. **Table 3-1** summarizes the %RMSE values.

	FG Entries	FG Exits
n	205	205
MSE	2,896,524	4,076,414
RMSE	1,702	2,019
% RMSE	**15%**	**17%**

Table 3-1: % RMSE for FG estimates (RODS 2004 v. Period 1, 2006)

Victoria, Brixton and Queensway stations that are highlighted on the figures, have the highest differences between the two estimates. In the case of Queensway, which has been closed for major maintenance since 2004, the RODS 2004 estimate is not a credible basis for comparison, since the Period 1, 2006 ridership at this station is zero. Further research could explain the large differences for the other two stations.

b) Entries and exits at NFG stations

At NFG stations some, or all, passengers can enter or exit without creating an AFC transaction. At these stations it is necessary to use manual counts to account for those entries and exits. The estimate for these stations results from adding AFC counts and manual counts, as shown in **figure 3-7**.

In this research, the calculation of AFC entries and exits is straightforward, and follows the same relationship described above, for FG stations. However, the estimation of manual counts requires some additional attention. Specifically the following three issues need to be addressed:

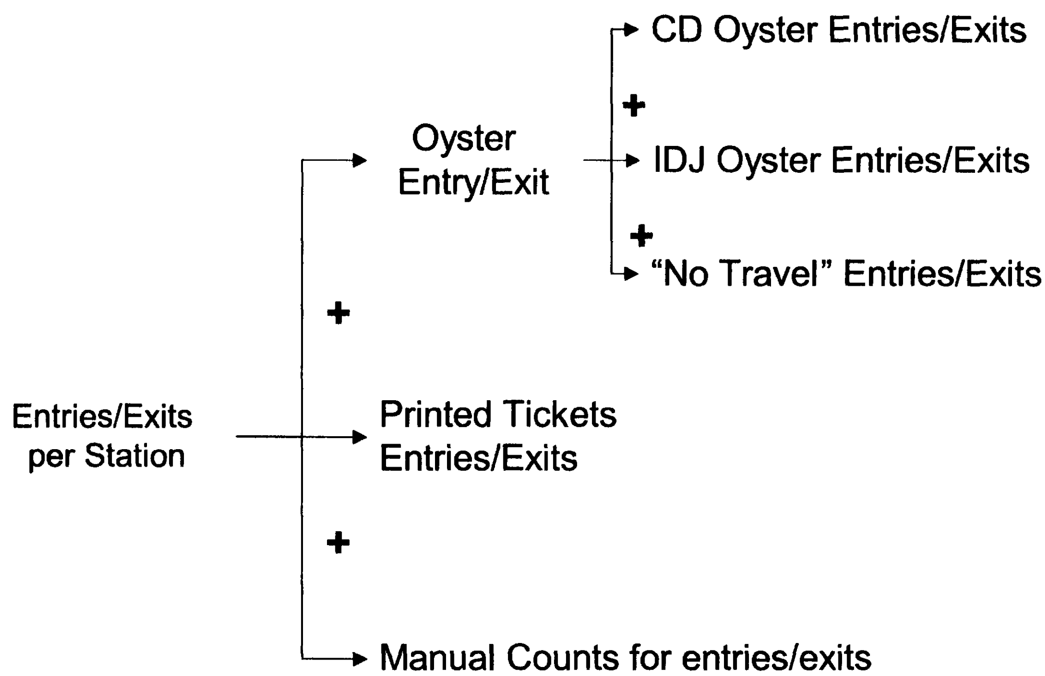

Figure 3-7: Relationship to estimate entries and exits at NFG stations

1) While there are AFC counts available for period 1, 2006, there are no manual counts for this period. In fact, TfL only performs manual counts once every year, always in November.

2) The manual counts that are available do not differentiate between entries and exits to the Underground and National Rail at joint stations and therefore using them directly would overestimate Underground ridership.

3) The manual counts include passengers that have an Oyster card and that tap in and out at the stand-alone card readers, and so adding AFC data and manual counts could result in double counting.

The estimates for FG stations presented above provide useful insight into these issues and suggest a solution. In the FG case period 1, 2006 estimates were very similar to estimates from RODS 2004. Therefore, it is reasonable to assume that this would also be the case for NFG stations. Following this assumption, the fraction of manual counts to assign at

each station should be such that, when added to the observed AFC counts for Period 1, yields the best possible approximation to the station estimate from RODS 2004.
Equation 3.1 summarizes the method for estimating the fraction of manual entry counts that should be assigned to NFG stations:

$$MC\_Entries(i) = \max\left(\min\left(RODS\_Entries(i) - AFC\_Entries(i), MC\_Entries(i)\right), 0\right) \quad \textbf{(3.1)}$$

Where,

MC_Entries(i) are the manual entry counts that will be assigned to station i.
RODS_Entries(i) are the total entries at station i from RODS 2004
AFC_Entries(i) is the average AFC entries at station i during weekdays in period 1
MC_Entries(i) are the total manual entry counts for November 2004

Figure 3-8 shows, for all 68 NFG stations, the estimate that results from applying the relationship of **figure 3-7** along with **equation 3.1.**, to period 1 entry data. It also shows the corresponding estimate of entries from RODS 2004.

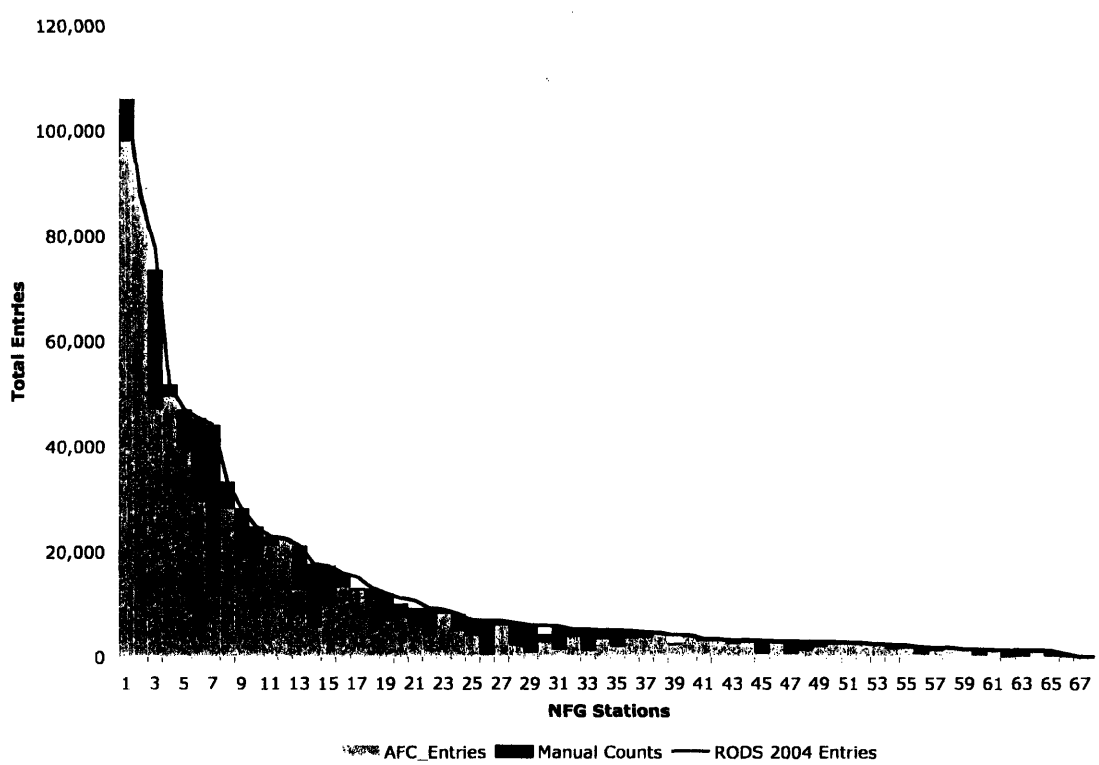

Figure 3-8: Estimates of entries at NFG stations

Exits per station are estimated through a similar procedure, but using **equation 3.2**.

$$MC\_Exits(i) = \max\left(\min\left(RODS\_Exits(i) - AFC\_Exits(i), MC\_Exits(i)\right), 0\right) \quad \textbf{(3.2)}$$

Where,

MC_Exits(i) are the manual exit counts that will be assigned to station i.

RODS_Exits(i) are the total exits at station I from RODS 2004

AFC_Exits(i) is the average AFC exits at station I during weekdays in period 1

MC_Exits(i) are the total manual exit counts for November 2004

Figure 3-9 shows the resulting estimates for exits at NFG stations. In this case there are two stations where the estimate for period 1, 2006 is well above the estimate from RODS 2004: King's Cross/St. Pancras and Stratford. At both of these stations the number of exit records in the AFC systems is above the estimate from RODS 2004. Again, further research on these station level estimates could clarify the circumstances.

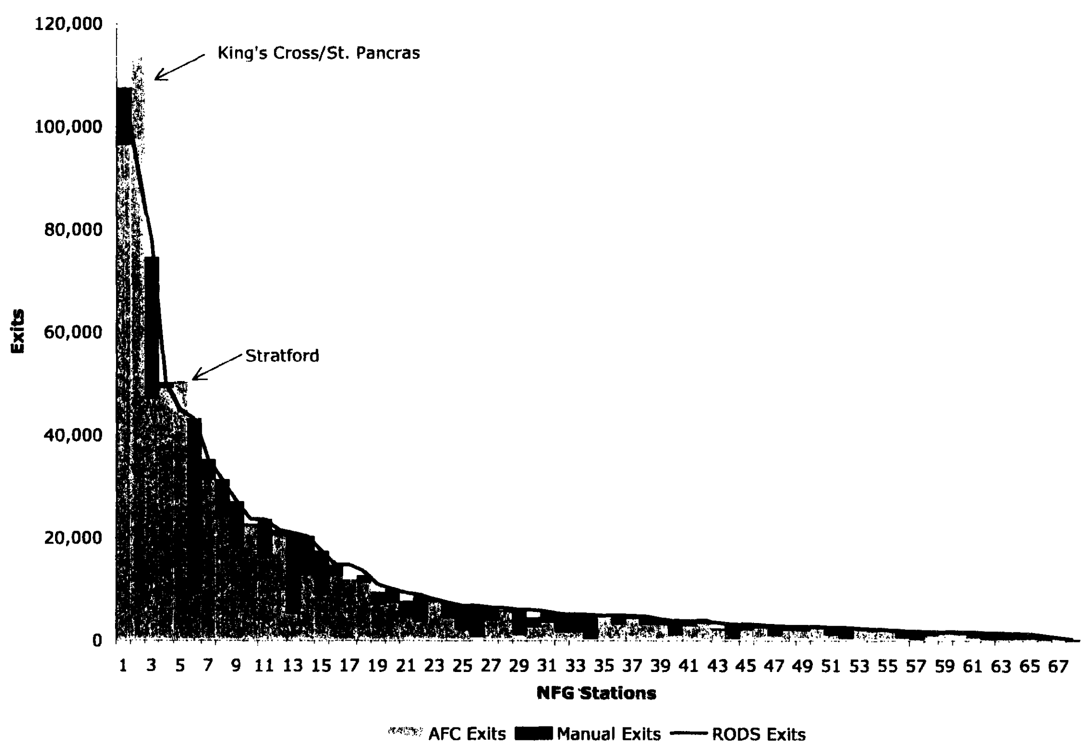

Figure 3-9: Estimates of exits at NFG stations

Table 3-2 summarizes the %RMSE values for both entries and exits at NFG stations. For entries the 5% RMSE shows that, the estimates for period 1 are very similar to the estimates in RODS 2004. In contrast, for the exits, a 21% RMSE reflects a much larger difference between the two estimates. However, most of the difference is explained by differences in two stations: King's Cross/St. Pancras and Stratford. If these two stations are excluded from the calculations, the % RMSE is reduced to just 6%.

	NFG Entries	NFG Exits	NFG Exits **
n	68	68	66
MSE	463,544	7,714,794	423,211
RMSE	681	2,778	651
% RMSE	**5%**	**21%**	**6%**

** Excluding King's Cross St. Pancras and Stratford

Table 3-2: % RMSE for NFG estimates (RODS 2004 v. Period 1, 2006)

c) Summary of entries and exits

Table 3-3 summarizes the %RMSE for the estimates of entries and exits. On aggregate, the %RMSE for entries is 12%, while for exits it is 18%, including King's Cross/St. Pancras and Stratford, and 15% excluding these stations. As these percentages indicate, the overall station level estimates for period 1, 2006 are quite similar to station level estimates in RODS 2004.

SUMMARY OF ENTRIES

	FG Entries	NFG Entries	Total Entries
n	205	68	273
MSE	2,896,524	463,544	2,290,507
RMSE	1,702	681	1,513
% RMSE	**15%**	**5%**	**12%**

SUMMARY OF EXITS

	FG Exits	NFG Exits	Total Exits
n	205	68	273
MSE	4,076,414	7,714,794	4,982,677
RMSE	2,019	2,778	2,232
% RMSE	**17%**	**21%**	**18%**

	FG Exits	NFG Exits **	Total Exits **
n	205	66	271
MSE	4,076,414	423,211	3,186,704
RMSE	2,019	651	1,785
% RMSE	**17%**	**6%**	**15%**

**** Excluding King's Cross St. Pancras and Stratford**

Table 3-3: % RMSE for entry and exit estimates (RODS 2004 v. Period 1, 2006)

Figure 3-10 puts together the entry estimates obtained in the previous section and shows, for weekdays in Period 1, 2006 the 100 stations with the highest number of entries ranked by decreasing order (**Table B-1** in **Appendix B** includes the estimated entries for all Underground stations). The figure also shows that the entry estimates result from adding together completely documented journey records (CD Oyster) with non-documented journey records (ND), where the non-documented records are either incompletely documented (ID) Oyster entries, Oyster "no travel" records, entries with printed tickets, and entries from manual counts. The methodology presented in **section 3.2.2.** allows inferring the destination for these ND entry records, based on the known CD Oyster records available for each station.

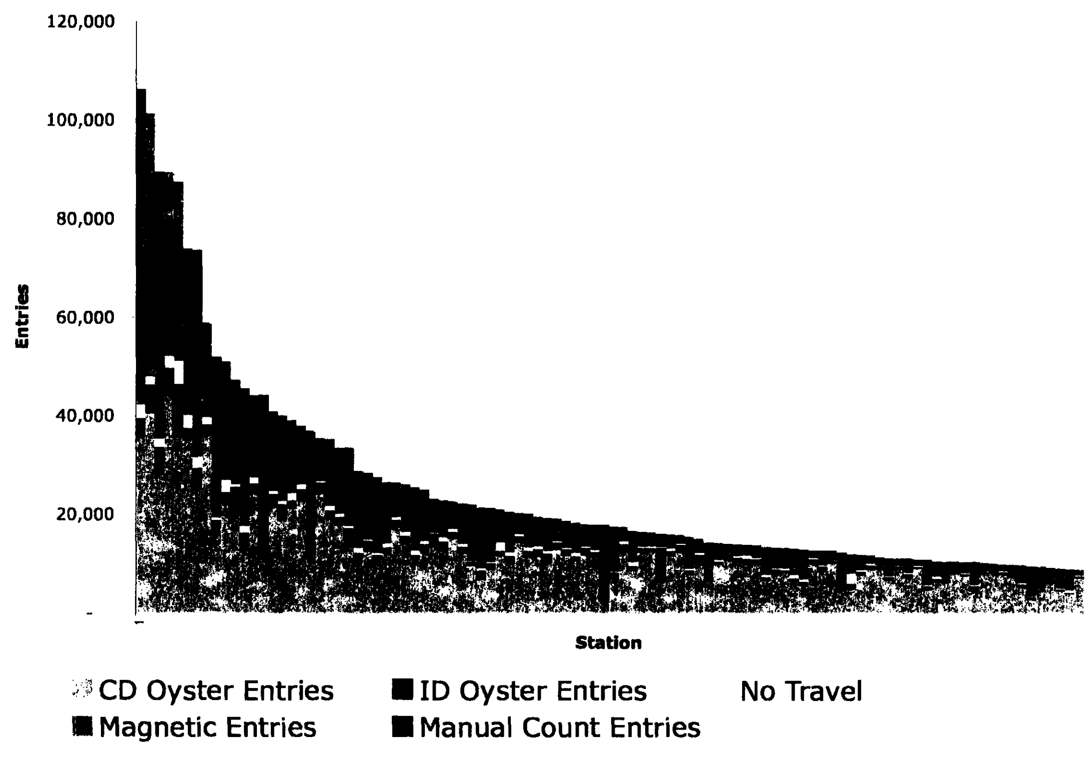

Figure 3-10: 100 stations with the highest estimates of entries

Figure 3-11 illustrates the parallel case but this time for the 100 stations with the highest number of exits. (**Table B-2** in **Appendix B** includes the estimated exits for all Underground stations).

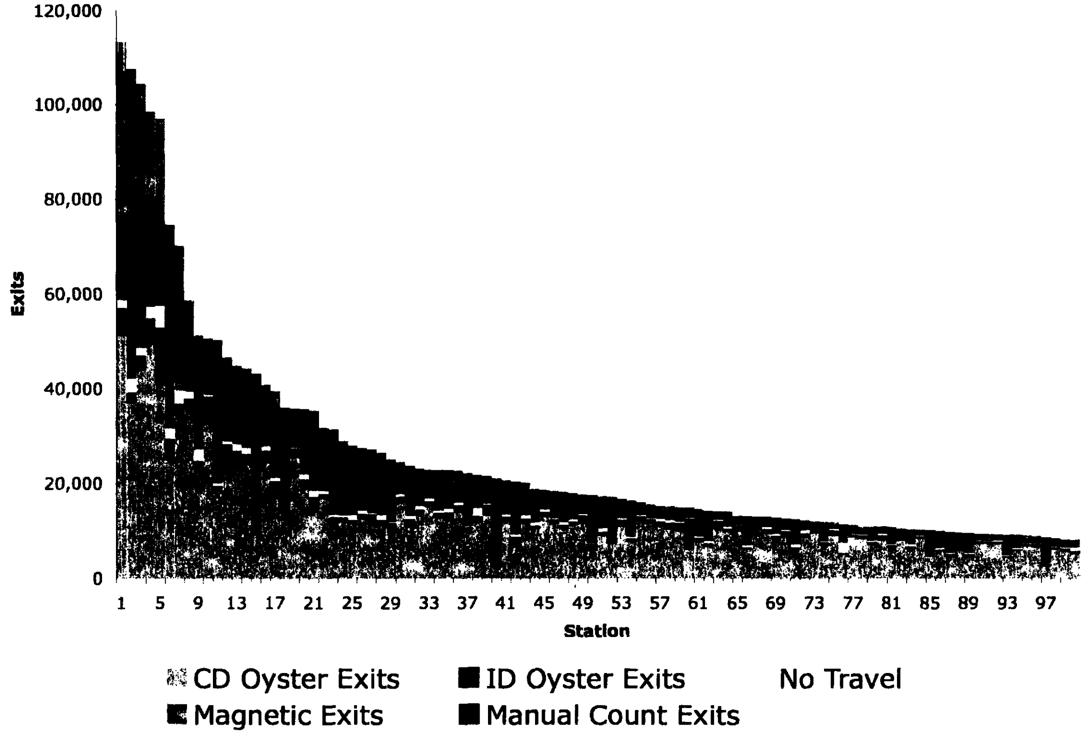

Figure 3-11: 100 stations with highest estimated exits

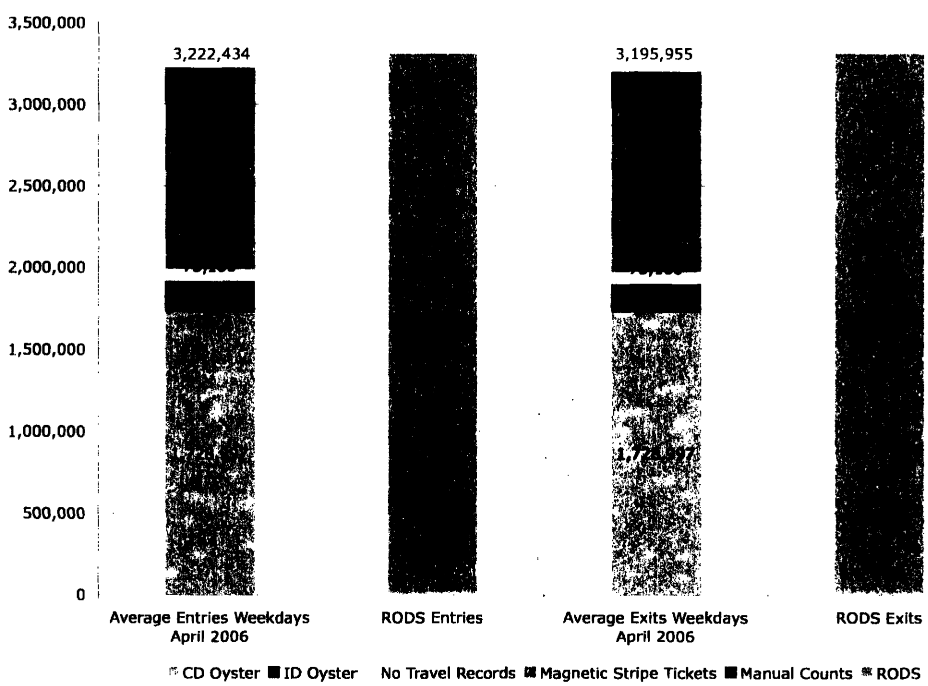

Figure 3-12: System level estimates (Period 1, 2006 v. RODS 2004)

With the station estimates obtained so far, it is possible to build a system level estimate of ridership for the average period 1 weekday. This estimate is simply the sum of all station ridership estimates. **Figure 3-12** compares the system level estimates for period 1, 2006 with those from RODS 2004.

Three conclusions can be drawn from these system level comparisons:

1) In period 1, 2006 there are an estimated 26,458 more entries than exits. This small difference (0.8%) is explained by asymmetries in the number of incompletely documented journeys and magnetic stripe tickets.

2) Ridership in period 1, 2006 is 3% less than in November 2004. This can be explained by seasonal variations and Easter holidays in April.

3) More than half of the journeys in the Underground (54%) have completely documented Oyster data on origins and destinations.

The next task is to expand the CD Oyster travel patterns to reflect the remaining 46% of Underground users.

3.2.2 Estimation of Expansion Factors

This section is divided into two parts. The first part discusses the issues that need to be dealt with in expanding the CD Oyster dataset to all Underground customers. The second part, building on the first, presents the methodology for expanding the CD Oyster dataset.

a) Characterization of the CD Oyster dataset

Before expanding the CD Oyster dataset to entry and exit totals, it is necessary to establish if the CD Oyster dataset is representative of travel patterns for the whole set of Underground customers. The main problem in conducting this evaluation is that the travel patterns of the CD Oyster dataset can only be compared to the travel patterns from RODS, which is itself an estimate and, as discussed before, is not a perfect reflection of reality. Keeping this important issue in mind, this research evaluates the CD Oyster dataset by comparing it with RODS 2004, to establish: (a) the differences in travel patterns between the two datasets and (b) travel patterns that are over or under represented in the CD Oyster dataset.

Travel Patterns included in the CD Oyster dataset

Figure 3-13 compares the number of Origin-Destination combinations captured by RODS 2004 and by the CD Oyster dataset, for period 1, 2006. For comparison purposes the total number of O-D pairs is also shown. The RODS estimate is that there are journeys between less than half (41%) of all possible origin-destination pairs, while Oyster documents journeys between almost three quarters of all potential pairs (73%).

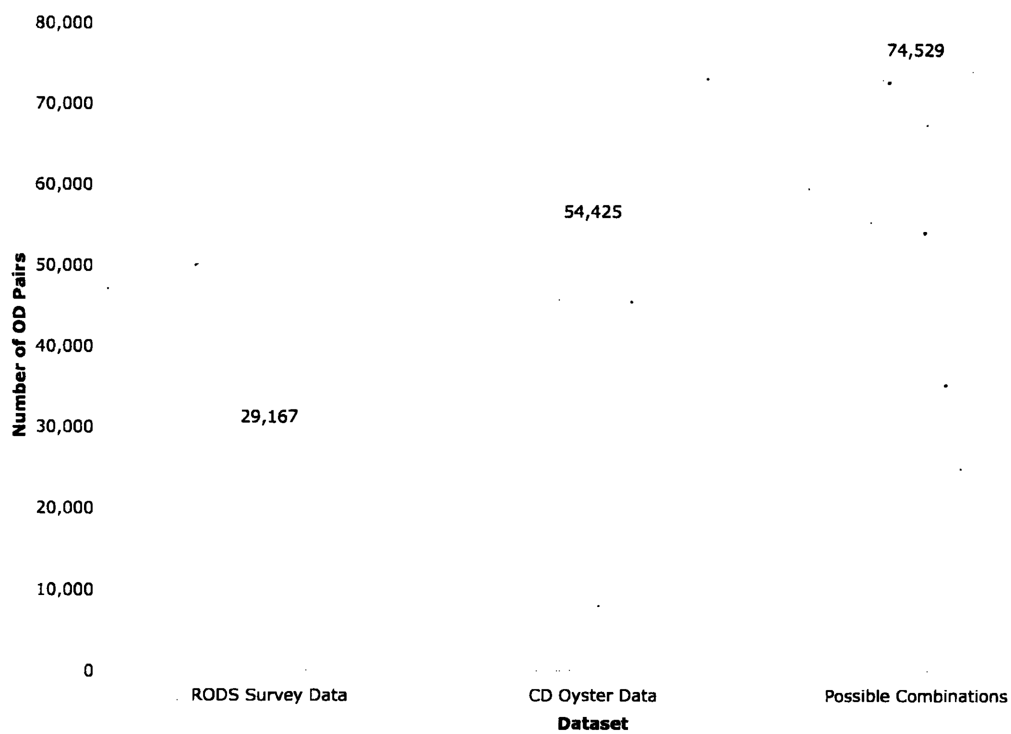

Figure 3-13: Comparison of OD pairs with travel from RODS and Oyster

Oyster captures 25,258 OD pairs that are not captured in RODS, that is, almost twice the number of OD pairs that are captured by the multiyear survey. This result clearly shows that travel patterns in the Underground are much more diverse than that revealed by the survey. Further, the large difference in OD pairs highlights the need to use Oyster card data to accurately characterize travel patterns on the London Underground.

Furthermore, a comparison of the CD Oyster dataset to the original RODS survey dataset, consisting of 193,249 survey records from 8 different years, shows the journey combinations captured by RODS survey are practically a subset of the journey combinations captured on Oyster: there are only 1,018 pairs captured on RODS that are not captured by Oyster, while there are 26,549 OD combinations that are captured by Oyster but not by the RODS survey, as illustrated in **Figure 3-14**.

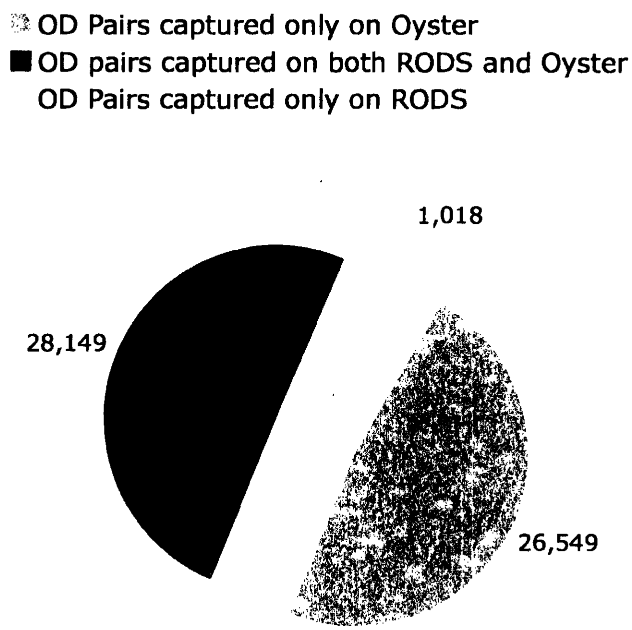

Figure 3-14: Non-zero OD pairs per Dataset

In terms of journeys, only 0.83% (1,613 out of 193,249) of the RODS journeys are between OD pairs captured only by RODS. However, 43% (700 out of 1,613) of these journeys are in OD pairs that involve either Heathrow Terminal 4 or Queensway, which are currently closed. It is clear that these journeys should not be included in the OD matrix. However, they are included in the RODS dataset. If these pairs are omitted, then only 0.47% (913 out of 193,249) of the RODS journeys are between OD pairs captured only by RODS. On the other hand, 9% (155,042 out of 1,728,022) of the Oyster documented journeys are between OD pairs captured only by Oyster. **Figure 3-15** illustrates this with a Venn diagram.

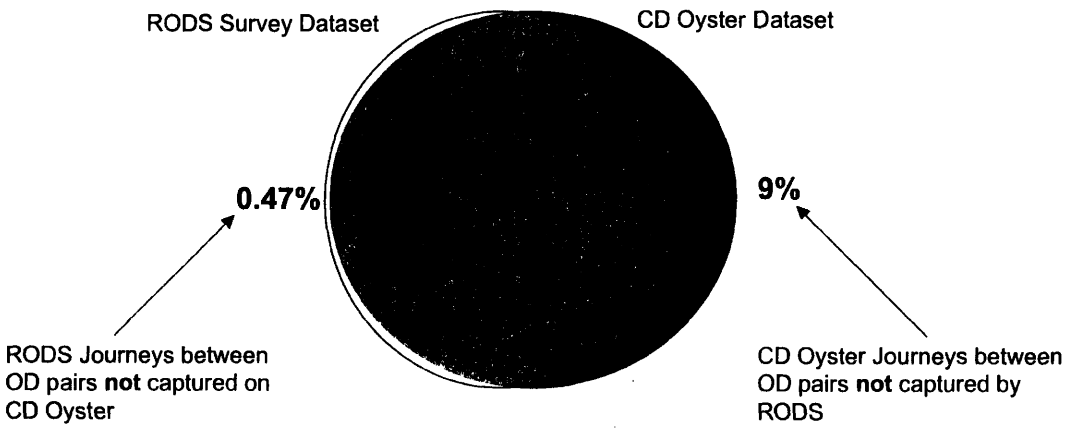

Figure 3-15: Differences in Journeys by OD pair between RODS and Oyster

There are two main conclusions from this analysis:

1) The CD Oyster dataset captures virtually all journeys captured by RODS, plus a large number of journeys that are not captured by RODS and

2) RODS is biased towards the largest OD pairs, as demonstrated by the large number of combinations that are captured only on Oyster and which represent 9% of all journeys. As a result, RODS underestimates the number of journeys between many less popular origin destination pairs and overestimates the journeys between more popular pairs.

Proportionality of CD Oyster to entire population

While it has been demonstrated that Oyster captures virtually all OD pairs that are measured in RODS, the number of journeys on some OD pairs is likely to be underrepresented for the following reasons:

1) Oyster Incompletely Documented Journeys are more likely to occur when one end is an NFG station, since passengers do not have to pass through a gate. Therefore journeys that involve NFG stations are systematically less likely to be included in the CD Oyster Dataset.

2) Since NFG stations typically offer National Rail services where the Oyster card is not yet accepted, customers traveling with magnetic stripe tickets are more likely than Oyster users to begin or end their trips at an NFG station.

Both these issues suggest that the proportion of journeys to NFG stations in Oyster is lower than it should be. This is confirmed by comparing the Oyster and RODS datasets. As **Figure 3-16** shows, while 29% of all RODS entries are bound to NFG stations, in the CD Oyster dataset this figure is only 21%.

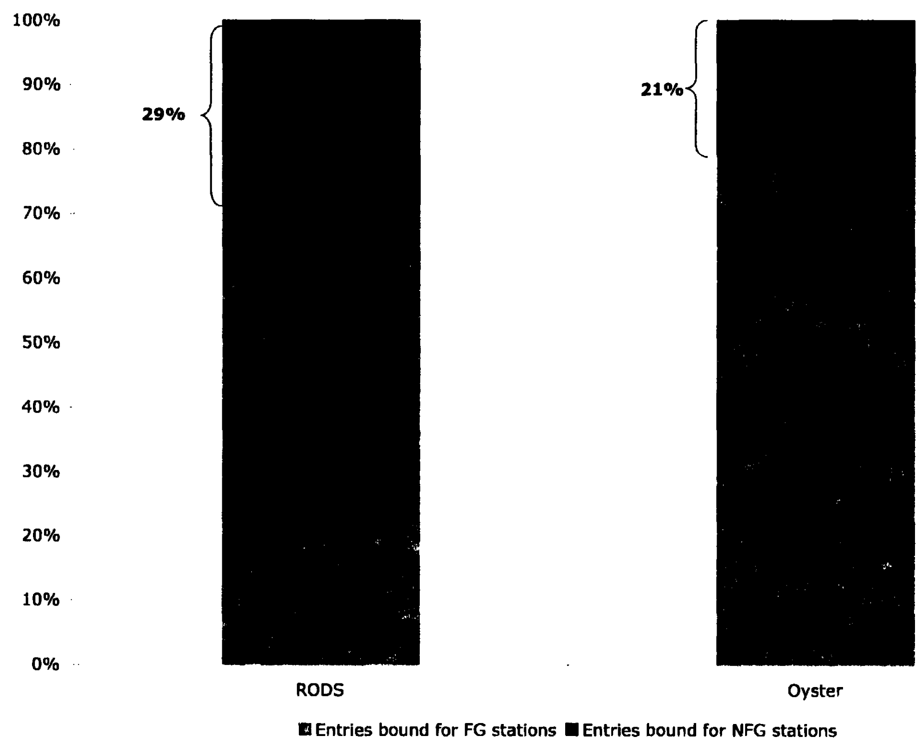

Figure 3-16: Percentage of journeys bound to FG and NFG stations

This difference also exists at the station level. **Figure 3-17** shows for each Underground station, the percentage of journeys bound to NFG stations in RODS 204 and in Oyster, ranked by (descending) order. The figure shows that for most stations (202 out of 273), the percentage of Oyster journeys bound to NFG stations is lower than the corresponding RODS 2004 estimate.

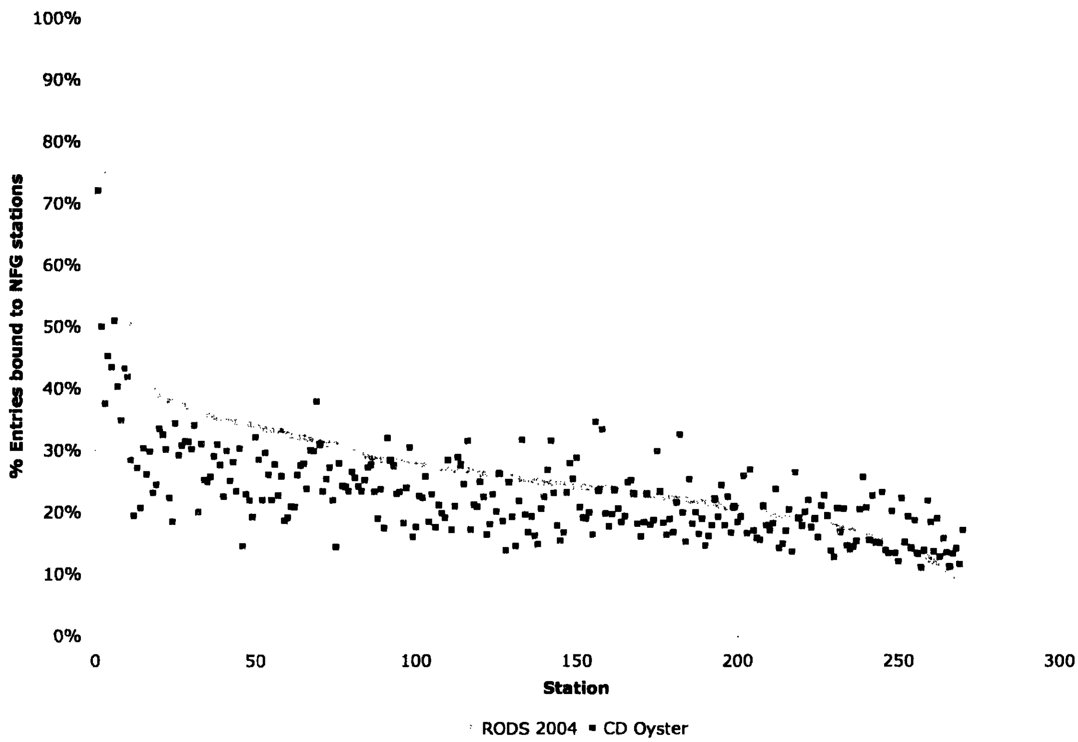

Figure 3-17: Percentage of journeys bound for NFG stations

However, figure 3-17 also shows that for stations with low percentages of journeys bound to NFG stations (at the right of the figure), Oyster estimates tend to be above RODS. An initial examination of these stations, scattered above the RODS 2004 line in the figure, does not suggest any easy explanation. **Table 3-4** compares this set of stations to all Underground stations and as the results suggest, these stations are quite similar to all Underground stations although they tend to be a bit smaller and have a slightly higher penetration of Oyster card. Also, among these stations there are both FG and NFG stations in almost the same proportion as in the whole set of Underground stations.

	Median of RODS Entries	Median of Oyster penetration	%NFG stations
All Stations	6,360	68%	33%
Selected stations	5,154	71%	31%

Table 3-4: Characteristics of stations above RODS line in figure 3-17

In summary and for the reasons presented in this section, the assumption in this research is that RODS proportions in figure 3-17 more accurately reflect reality than Oyster proportions in the same figure. To resolve this issue, the research presents a methodology that incorporates RODS proportions into the calculation of the expansion factors for the Oyster dataset. The %RMSE between the Oyster and RODS datasets is 31%: we will come back to this value, and to figure 3-17 when evaluating the results of the methodology.

b) Estimation of Expansion Factors

The expansion factors presented in this section are designed to correct for the bias identified above, and allow the expansion of the CD Oyster dataset to represent all travel patterns. The outcome of this process is a singly constrained OD matrix. That is, a matrix that matches the station entry totals, but not necessarily the station exit totals. The next section presents an implementation of an Iterative Proportional Fitting (IPF) process that transforms this singly constrained OD matrix into a doubly constrained OD matrix, which matches both station entry and exit totals.

Equation 3.3 below presents the basic equation for the expansion of the CD Oyster dataset to station entry totals.

$$\sum_{i=1}^{273}\left[CD(A,i)\times RowFactor(A,i)\right]=E(A) \qquad \textbf{(3.3)}$$

Where,

CD(A,i) is the total number of CD Oyster journeys from station A to station i

RowFactor(A,i) is the row expansion factor for journeys from station A to station i

E(A) is the total number of entries at station A.

CD(A,i) is obtained directly from the CD Oyster dataset, ***E(A)*** was estimated as in section **3.1.1** and summarized for all stations in **Table B-1** in **Appendix B.** The expansion factors – ***RowFactor(A,i)*** – are calculated for all pairs (A,i) using **Equation 3.4** below. This equation corrects the bias in the Oyster dataset by calculating different expansion factors for journeys to FG stations and journeys to NFG stations.

$$RowFactor\,(A,i) = \begin{cases} \dfrac{CD_{FG}(A) + ND_{FG}(A)}{CD_{FG}(A)} & \text{if } i \in FG \\ \\ \dfrac{CD_{NFG}(A) + ND_{NFG}(A)}{CD_{NFG}(A)} & \text{if } i \in NFG \end{cases} \qquad \textbf{(3.4)}$$

Where,

FG = {Set of Fully Gated Stations} = {S1, S2, S3 ,..., S205}

NFG = {Set of Non Fully Gated Stations} = {S206, S207, S208 ,..., S273}

$CD_{FG}(A)$ is the number of Completely Documented Oyster records from station A to FG stations.

$CD_{NFG}(A)$ is the number of Completely Documented Oyster records from station A to NFG stations.

$ND_{FG}(A)$ is the number of Non Documented records from station A to FG stations.

$ND_{NFG}(A)$ is the number of Non Documented records from station A to NFG stations.

The sets ***FG*** and ***NFG*** are summarized in **Appendix A**. The variables $CD_{FG}(A)$ and $CD_{NFG}(A)$ represent the number of Completely Documented journeys to FG and NFG stations respectively. The values of these variables can be obtained directly from the CD Oyster dataset and are summarized in **Table B-3** of **Appendix B**. The variables: $ND_{FG}(A)$ and $ND_{NFG}(A)$ represent the number of Non Documented Journeys from Station A that are bound to FG and NFG stations respectively. The values of these variables are unknown but, from the bias on the Oyster dataset, we know that they are not necessarily proportional to the available CD journeys. To correct this bias, we use the proportions observed on RODS for journeys to FG and NFG stations using **Equations 3.5** and **3.6** below

$$ND_{FG}(A) = \min\left[\left(\frac{RODS_{FG}(A)}{RODS(A)} \times E(A)\right) - CD_{FG}(A), \quad E(A) - CD(A)\right] \quad \textbf{(3.5)}$$

and

$$ND_{NFG}(A) = E(A) - CD(A) - ND_{FG}(A) \quad \textbf{(3.6)}$$

Where,

$RODS_{FG}(A)$ is the number of journeys from RODS 2004 from station A to FG stations
RODS(A) is the number of journeys from RODS 2004 from station A.
CD(A) is the total number of CD Oyster journeys from station A

The variables $RODS_{FG}(A)$ and RODS(A) represent the number of RODS journeys from station A to FG stations and to all stations respectively. The ratio of these variables is the percentage of journeys on RODS that are bound to FG stations. The values of the RODS proportions are summarized in **Table B-3** in **Appendix B.** CD(A) represent the total number of Completely Documented Journeys from station A, which is obtained directly from the CD Oyster dataset. **Table B-3** in **Appendix B** summarizes its values. The resulting values for $ND_{FG}(A)$ and $ND_{NFG}(A)$ are used in **Equation 3.4** to obtain the row expansion factors with the results summarized in **TABLE B-3** of **Appendix B**. Finally, the CD Oyster records are multiplied by the corresponding row factors to obtain the singly constrained OD Matrix.

3.2.3 Row-Column Balancing

The singly constrained OD matrix obtained in the previous section matches station entry totals, but does not necessarily match station exit totals. By running an Iterative Proportional Fitting (IPF) process, it is possible to transform that matrix into a doubly constrained OD matrix, which matches both station entry and exit totals. The following is a brief description of the IPF process (Dowling el Al. Pgs. 23-24).

1) Each cell of the OD matrix is multiplied by station specific column correction factors. This produces a new OD matrix matching station exit control totals (columns), but not necessarily the station entry (row) totals.

2) The cells in this OD matrix are multiplied by station specific row correction factors, to obtain a new OD matrix matching station entry totals but again, not necessarily station exit totals.

3) The process is repeated, until the OD matrix is balanced for both columns and rows, or until there are only small differences with the target values.

The column correction factors are calculated by dividing the target exit control total of each station, by the most current value of station exits. Similarly, the row correction factors are calculated by dividing the target entry control total of each station, by the most current value of station entries. For this research, the IPF algorithm was implemented in Visual Basic for Excel, and is included in **Appendix C** for reference. Five iterations are enough to obtain a close approximation to the estimated station entry and exit control totals.

3.3 Analysis of Results

The output of the methodology presented in section 3.2.2 is a doubly constrained OD matrix, which uses origin-destination data from Oyster and adjustment proportions from RODS 2004. This section analyzes the results of applying this methodology to weekdays in period 1, 2006, by comparing the new OD matrix to RODS 2004. In particular this section considers two issues: the correction in the proportion of journeys to NFG stations and the differences in travel patterns.

a) Correction in the proportion of journeys to NFG stations

Figure 3-18 shows that the proportion of journeys to NFG stations in the doubly constrained OD matrix is very similar to the proportion observed in RODS 2004. A small difference persists because the methodology for correcting the proportions affects only non-documented Oyster journey records, and not completely documented Oyster journey records.

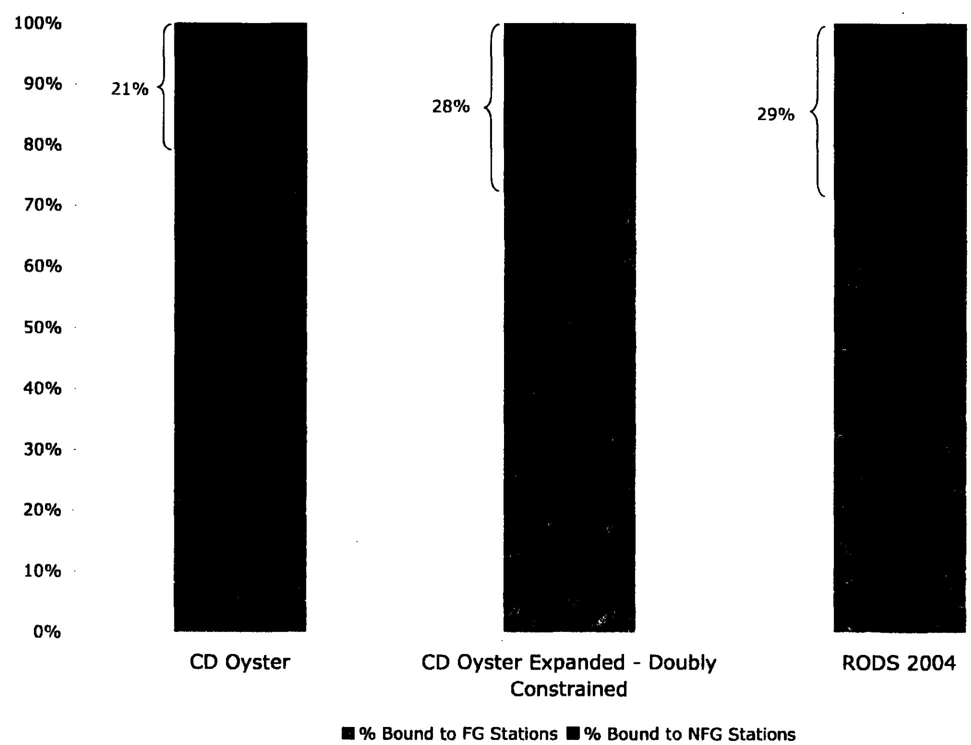

Figure 3-18: Percentage of Journeys bound to FG and NFG stations

Station proportions are also corrected. **Figure 3-19** is an update of **figure 3-17**. It now compares for each Underground station the percentage of journeys bound to NFG stations in RODS and in the doubly constrained OD matrix. This figure shows that for most stations there is great similarity in the percentage of journeys bound to NFG stations. This similarity is further confirmed by comparing the change in %RMSE: originally at 31%, now after the expansion and correction, it stands at just 13%. Differences between the two datasets are also the result of irreconcilable differences between RODS and the completely documented journey records.

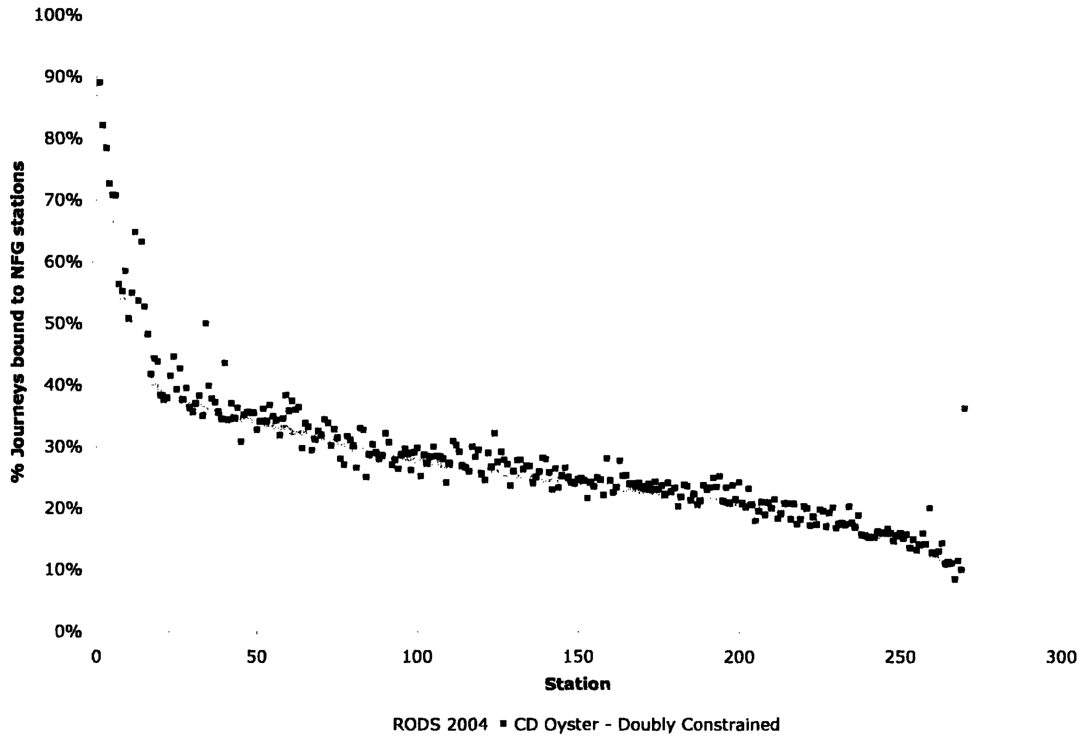

Figure 3-19: Percentage of journeys per station bound to NFG stations

b) Differences in travel patterns

Figure 3-20 shows the top 200 OD pairs in the doubly constrained OD matrix and compares these values with the corresponding RODS 2004 estimates. The figure shows that the Oyster and the RODS estimates follow broadly the same pattern, although there are significant differences between the two OD matrix estimates. The figure also shows two characteristics that support the value of Oyster based estimates.

1) In RODS 2004 there are a large number of journeys between Waterloo and Bank & Monument, far greater than the estimate from Oyster. However, in April 2006 the Waterloo and City line that directly connects these two stations was closed for maintenance. As a result, many passengers who used these two stations because

of the direct train link probably switched to neighboring stations where they can find a better route for their trips.

2) There are a number of OD pairs for which the RODS estimates appear far below even the unexpanded CD Oyster values. As an example, the figure highlights the estimate of journeys from King's Cross/St. Pancras to Stratford. These cases are strong evidence that RODS underestimates the number of journeys between some OD pairs, and it also suggests that it is likely that in other cases the RODS estimates are as far off in the other direction.

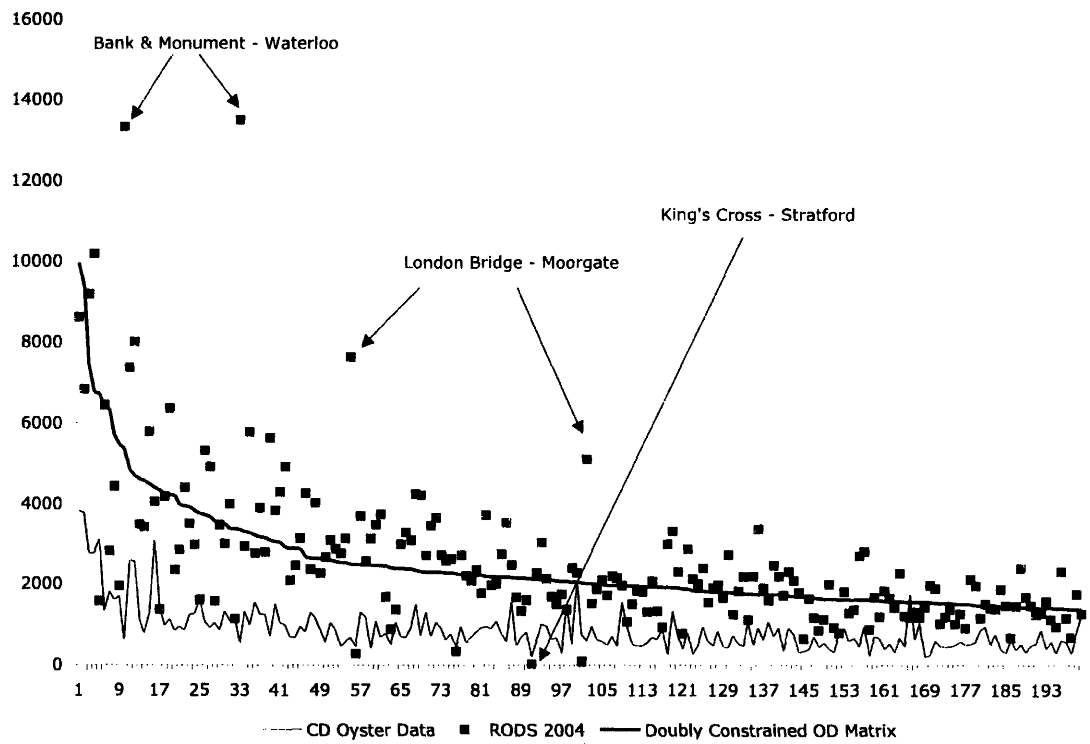

Figure 3-20: 200 OD pairs with highest ridership

It is also worth mentioning again, that the number of OD pairs in the resulting OD matrix is well above the number of OD pairs in RODS 2004. Also, 9% of the journeys in the resulting OD matrix are between these OD pairs not captured by RODS 2004. This evidence strongly suggests that RODS 2004 wrongly assigns this percentage of journeys to the OD pairs that it captures, overestimating by that much the number of journeys between these OD pairs.

Chapter Four: Conclusions

Traditionally, transit agencies have had only a broad understanding of the demand they serve. Today, with the implementation of AFC systems, they have the potential to shift to a more detailed and precise understanding of demand and associated travel behavior. This thesis shows that by making that shift, transit agencies have the potential to improve their decision-making and carry out service improvements. The first step for realizing this potential is to have a coherent and easy to update set of current ridership estimates based on AFC data. The second step is to build on top of these estimates the planning and decision-making tools that would exploit the new information. This thesis addresses part of the first step. In particular, it develops a methodology for building an easy to update rail origin-destination matrix using AFC data.

Section 4.1 summarizes the research findings; Section 4.2 points out the limitations in this research; and Section 4.3 proposes future research directions.

4.1 Overview of Research Findings

This research proposed a methodology for estimating an origin destination matrix for an urban rail system (the London Underground) that has AFC control at entries and exits for most stations. This methodology enables transit agencies to use origin destination data from smart cards as the foundation for travel pattern estimation, by correcting the potential biases in the smart card dataset through the use of existing travel pattern estimates.

Smart card data offers many advantages over survey data. The following are the main advantages observed for the particular case of the London Underground:

1) While the traditional passenger survey captures travel between 29,167 different OD pairs on the network, the AFC system in one 4-week period records travel between 54,425 different OD pairs. That is, in the smart card dataset there are 26,549 additional OD pairs represented, 87% more than in the survey dataset.

2) 9 % of all Underground journeys are between the 26,459 OD pairs that are not represented in the survey dataset. This highlights a significant bias in the survey, because it wrongly assigns 9% of the total journeys to more popular OD pairs.

3) AFC data continuously captures the impact on travel patterns of many ongoing operational changes, while the survey conducted once a year for a small set (~15%) of stations on a very limited timeframe (during November) is not responsive to such events.

4) Although planners at the London Underground produce one origin destination matrix per year, the output they get from this annual process actually represents an 8-year "rolling" average rather than a current estimate. In contrast, by adopting the proposed methodology, transit planners can build not one, but many origin destination matrices per year, and use them to analyze in detail variations in travel patterns.

In addition to the above advantages of the methodology, the research highlighted two issues that negatively affect the estimates obtained with the current survey program:

1) There is a high non-response rate (78%), which provides a strong indication that there may be a significant non-response bias in the existing survey. That is, the survey could be systematically missing the trips of certain groups of passengers that refuse to complete the questionnaires.

2) Although the Underground starts running at 5:00 AM, there are no survey records for journeys starting before 7:00 AM. Approximately 3% of the Underground journeys

begin before 7:00AM and this may well include a larger proportion of long trips, when compared to the length of the journeys in the following time periods.

4.2 Limitations and Challenges

There are two main limitations on this study, and one key challenge. The limitations are the accuracy of the station level entry and exit estimates, and the expansion of the data to daily rather than hourly totals. The main challenge is the implementation of the methodology.

First, the focus on this thesis has been on the origin destination level. However, to build an accurate estimate at this level it is necessary to have a reliable estimate of ridership, both entries and exits, at the station level. This research presented a methodology for building an acceptable station level estimate using AFC data and manual counts. Still, there are some concerns that need to be addressed which may lead to improved estimates:

1) There are certain Non Fully Gated (NFG) stations with a higher proportion of Incompletely Documented Journeys (IDJ). These journeys, which are part of the gate counts, include both travel within the Underground and travel between the Underground and National Rail, DLR and Tramlink. The distinction between these flows is beyond the scope of this research but needs further attention.

2) 82 % of all "no travel" records, correspond to staff passes. Many of these transactions probably correspond to station staff letting passengers in and out of stations when card or gate failures occur. However, "no travel" transactions probably also include staff entries and exits that do not correspond to actual journeys and u-turns from passengers deciding not to take the Underground, for example when they see that the platform is very crowded.

3) There are probably a number of non-documented journeys with magnetic tickets, resulting from gate or ticket failures that should also be taken into account.

4) Manual counts are available only for November and include journeys to and from other services such as National Rail. To manage this issue the research set the number of manual counts to match the values of RODS 2004, but more precise estimation may be possible with more in depth knowledge of the manual counting process.

Second, survey data from RODS is expanded to fifteen-minute entry and exit totals, resulting in estimates of travel patterns by time of the day. Although this research identified some issues with the expansion of small samples to fifteen-minute intervals, there is value in having origin destination matrices for different time periods of the day. This research produces an origin destination matrix for the full day. However, the same methodology proposed here could easily be applied to build origin destination matrices for different time periods during the day.

Finally, the main challenge for this research is its implementation. It requires a shift from well-established routines, to new processes that would result in outputs with significant differences from to today's outputs. The following are some suggestions:

1) Planners at TfL should analyze and validate the methodology proposed here and finally, assume a lead role in its implementation.

2) The RODS survey should target stations where smart card data is weakest. That is, RODS should be refocused to target stations where there is a lower proportion of Oyster card users, which generally coincide with Non-Fully Gated (NFG) stations. With better data for these stations, planners could update the percentage of journeys bound to NFG stations, which is required for the methodology presented in this research.

4.3 Future Research Directions

Chapter one identified a host of applications for more accurate and easy to update origin-destination matrices. Also, this research identified some areas for improvement of the ridership estimates in general. The following are directions for future research in the area.

a) Research to make use of more accurate and easy to update OD matrices

1) **Loads by line, by time of the day:** As mentioned in Chapter one, more accurate loads by line, that can easily be updated to reflect operational and ridership changes, can be useful for network and route design, fare policy and system performance. This research already has shown significant differences between the RODS 2004 and Period 1, 2006 origin-destination matrix. It also shows that RODS 2004 does not capture the effects on travel patterns of most operational changes, nor does it reflect seasonal variations of any kind. However, it is important to analyze how these differences in the OD matrices translate into the estimates of loads by line and by time of day.

2) **Journey Time Metrics:** Chapter one also shows that better estimates of travel time can be useful for network and route design, and system performance. With better measures of travel time it is possible to calculate better estimates of the generalized cost of travel and improve monitoring of trends. The Oyster origin destination dataset provides detailed information on the real journey time for passengers on the Underground. Using the techniques presented in this research it should be possible to produce Oyster-based estimates of the journey time for the whole population of Underground users.

3) **Disaggregate arc elasticities:** Chapter one shows that with better and easy to update origin-destination matrices, planners can estimate more accurate arc-elasticities that measure the impact of fare or operational changes for different segments of customers. These arc elasticities should help improve the network and route design models as well as the fare policy models.

4) **Statistics on transfers:** Chapter one shows that better statistics on transfers can be used for network and route design and system performance. With more accurate origin-destination level estimates planners could make a number of adjustments to the timetable in order to match the needs of certain passengers. For

instance, they could determine the time at which a bus service and a rail service should arrive and leave a connecting concourse, in order to minimize the expected waiting time for connecting passengers. They could also improve the monitoring of the total travel time, for passengers that use different transportation services.

b) Research to further improve ridership estimates

1) Improve station level ridership estimates: The research shows that station level ridership estimates are critical for having reliable estimates at the three network levels: system level, station level and origin-destination level. Therefore improving station level estimates is an important step to make to most out of AFC data.

2) **Inferring Incompletely Documented Journeys (IDJ):** IDJ records fall into two categories. First, those systematically missing from the dataset, such as passengers transferring to or from National Rail at NFG stations and second, IDJ corresponding to gate or card failures. For the journeys in the latter set, it should be possible to use an inference technique similar to that presented by Zhao and Rahbee. The application of this methodology should also enable planners to isolate systematic occurrence of IDJ records and help improve the station level estimates.

3) **Personal Data:** With personal data it could be possible to learn the home address of passengers and this would open a host of research avenues (Utsonomiya et al, 2006). For instance it could be possible to identify the OD matrix for passengers living in a certain geographic area. Personal data linked to origin destination level estimates could provide a rich source of data for planners.

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APPENDIX A – CLASSIFICATION OF UNDERGROUND STATIONS

Station Name	Station Code	Fully Gated (FG)	Non Fully Gated (NFG)	National Rail	RODS 2004 counting Method	Grouping for current research
Acton Town	500	YES	-	-	AFC counts	FG
Aldgate	502	YES	-	-	AFC counts	FG
Aldgate East	503	YES	-	-	AFC counts	FG
Alperton	505	YES	-	-	AFC counts	FG
Amersham	506	-	YES	YES	Manual + AFC counts	NFG
Angel	507	YES	-	-	AFC counts	FG
Archway	508	YES	-	-	AFC counts	FG
Arnos Grove	509	YES	-	-	AFC counts	FG
Arsenal	510	YES	-	-	AFC counts	FG
Baker Street	511	YES	-	-	AFC counts	FG
Balham	512	YES	-	YES	AFC counts	FG
Bank & Monument	513	-	YES	-	Manual + AFC counts	NFG
Barbican	501	-	YES	YES	Manual + AFC counts	NFG
Barking	514	-	YES	YES	Manual + AFC counts	NFG
Barkingside	515	YES	-	-	AFC counts	FG
Barons Court	516	YES	-	-	AFC counts	FG
Bayswater	517	YES	-	-	AFC counts	FG
Becontree	518	YES	-	-	Manual counts	NFG
Belsize Park	519	YES	-	-	AFC counts	FG
Bermondsey	787	YES	-	-	AFC counts	FG
Bethnal Green	520	YES	-	-	AFC counts	FG
Blackfriars	521	YES	-	YES	AFC counts	FG
Blackhorse Road	522	-	YES	YES	Manual + AFC counts	NFG
Bond Street	524	YES	-	-	AFC counts	FG
Borough	525	YES	-	-	AFC counts	FG
Boston Manor	526	YES	-	-	AFC counts	FG
Bounds Green	527	YES	-	-	AFC counts	FG
Bow Road	528	YES	-	-	AFC counts	FG
Brent Cross	529	YES	-	-	Manual counts	NFG
Brixton	778	YES	-	YES	AFC counts	FG
Bromley-by-Bow	530	YES	-	-	AFC counts	FG
Buckhurst Hill	531	YES	-	-	AFC counts	FG
Burnt Oak	532	YES	-	-	Manual counts	NFG
Caledonian Road	534	YES	-	-	AFC counts	FG
Camden Town	535	YES	-	-	AFC counts	FG

Canada Water	788	YES	-	-	AFC counts	FG
Canary Wharf	852	YES	-	-	AFC counts	FG
Canning Town	884	-	YES	YES	Manual + AFC counts	NFG
Cannon Street	536	YES	-	YES	AFC counts	FG
Canons Park	537	YES	-	-	AFC counts	FG
Chalfont & Latimer	539	-	YES	YES	Manual + AFC counts	NFG
Chalk Farm	540	YES	-	-	AFC counts	FG
Chancery Lane	541	YES	-	-	AFC counts	FG
Charing Cross	718	YES	-	YES	AFC counts	FG
Chesham	543	YES	-	-	AFC counts	FG
Chigwell	544	YES	-	-	AFC counts	FG
Chiswick Park	545	YES	-	-	AFC counts	FG
Chorleywood	546	-	YES	YES	Manual counts	NFG
Clapham Common	547	YES	-	-	AFC counts	FG
Clapham North	548	YES	-	YES	AFC counts	FG
Clapham South	549	YES	-	-	AFC counts	FG
Cockfosters	550	YES	-	-	AFC counts	FG
Colindale	551	YES	-	-	Manual counts	NFG
Colliers Wood	552	YES	-	-	AFC counts	FG
Covent Garden	553	YES	-	-	AFC counts	FG
Croxley	554	YES	-	-	AFC counts	FG
Dagenham East	555	YES	-	-	AFC counts	FG
Dagenham Heathway	556	YES	-	-	Manual counts	NFG
Debden	557	YES	-	-	AFC counts	FG
Dollis Hill	558	YES	-	-	AFC counts	FG
Ealing Broadway	560	-	YES	YES	Manual + AFC counts	NFG
Ealing Common	561	YES	-	-	AFC counts	FG
Earl's Court	562	YES	-	-	AFC counts	FG
East Acton	563	YES	-	-	AFC counts	FG
East Finchley	565	YES	-	-	AFC counts	FG
East Ham	566	YES	-	-	AFC counts	FG
East Putney	567	YES	-	-	AFC counts	FG
Eastcote	564	YES	-	-	AFC counts	FG
Edgware	568	YES	-	-	Manual counts	NFG
Edgware Road (Bak)	774	YES	-	-	AFC counts	FG
Edgware Road (Cir)	569	YES	-	-	AFC counts	FG
Elephant & Castle	570	YES	-	YES	AFC counts	FG
Elm Park	571	YES	-	-	AFC counts	FG
Embankment	542	YES	-	-	AFC counts	FG
Epping	572	YES	-	-	AFC counts	FG
Euston	574	YES	-	YES	AFC counts	FG
Euston Square	575	YES	-	-	AFC counts	FG
Fairlop	576	YES	-	-	AFC counts	FG
Farringdon	577	-	YES	YES	Manual + AFC counts	NFG
Finchley Central	578	YES	-	-	Manual counts	NFG
Finchley Road	579	YES	-	-	AFC counts	FG
Finsbury Park	580	-	YES	YES	Manual counts	NFG

Fulham Broadway	581	YES	-	-	AFC counts	FG
Gants Hill	582	YES	-	-	AFC counts	FG
Gloucester Road	583	YES	-	-	AFC counts	FG
Golders Green	584	YES	-	-	AFC counts	FG
Goldhawk Road	585	YES	-	-	AFC counts	FG
Goodge Street	586	YES	-	-	AFC counts	FG
Grange Hill	587	YES	-	-	AFC counts	FG
Great Portland Street	588	YES	-	-	AFC counts	FG
Green Park	590	YES	-	-	AFC counts	FG
Greenford	589	-	YES	YES	Manual + AFC counts	NFG
Gunnersbury	591	-	YES	YES	Manual + AFC counts	NFG
Hainault	592	YES	-	-	AFC counts	FG
Hammersmith (Dis)	593	YES	-	-	AFC counts	FG
Hammersmith (H&C)	773	YES	-	-	AFC counts	FG
Hampstead	594	YES	-	-	AFC counts	FG
Hanger Lane	595	YES	-	-	AFC counts	FG
Harlesden	596	-	YES	YES	Manual counts	NFG
Harrow & Wealdstone	597	-	YES	YES	Manual counts	NFG
Harrow-on-the-Hill	598	-	YES	YES	Manual + AFC counts	NFG
Hatton Cross	779	YES	-	-	AFC counts	FG
Heathrow Terminal 4	781	YES	-	-	AFC counts	FG
Heathrow Terminals 123	780	YES	-	-	Manual counts	NFG
Hendon Central	601	YES	-	-	Manual counts	NFG
High Barnet	602	YES	-	-	Manual counts	NFG
High Street Kensington	605	YES	-	-	AFC counts	FG
Highbury & Islington	603	-	YES	YES	Manual + AFC counts	NFG
Highgate	604	YES	-	-	AFC counts	FG
Hillingdon	606	YES	-	-	AFC counts	FG
Holborn	607	YES	-	-	AFC counts	FG
Holland Park	608	YES	-	-	AFC counts	FG
Holloway Road	609	YES	-	-	AFC counts	FG
Hornchurch	610	YES	-	-	AFC counts	FG
Hounslow Central	611	YES	-	-	AFC counts	FG
Hounslow East	612	YES	-	-	Manual + AFC counts	NFG
Hounslow West	613	YES	-	-	AFC counts	FG
Hyde Park Corner	614	YES	-	-	AFC counts	FG
Ickenham	615	YES	-	-	AFC counts	FG
Kennington	616	YES	-	-	AFC counts	FG
Kensal Green	617	-	YES	YES	Manual + AFC counts	NFG
Kensington (Olympia)	618	-	YES	YES	Manual counts	NFG
Kentish Town	619	-	YES	YES	Manual + AFC counts	NFG
Kenton	620	-	YES	YES	Manual counts	NFG
Kew Gardens	621	-	YES	YES	Manual + AFC counts	NFG
Kilburn	622	YES	-	-	AFC counts	FG
Kilburn Park	623	YES	-	-	AFC counts	FG
King's Cross St. Pancras	625	-	YES	YES	Manual + AFC counts	NFG
Kingsbury	624	YES	-	-	AFC counts	FG

Knightsbridge	626	YES	-	-	AFC counts	FG
Ladbroke Grove	627	YES	-	-	AFC counts	FG
Lambeth North	628	YES	-	-	AFC counts	FG
Lancaster Gate	629	YES	-	-	AFC counts	FG
Latimer Road	630	YES	-	-	AFC counts	FG
Leicester Square	631	YES	-	-	AFC counts	FG
Leyton	632	YES	-	-	AFC counts	FG
Leytonstone	633	YES	-	-	AFC counts	FG
Liverpool Street	634	YES	-	YES	AFC counts	FG
London Bridge	635	YES	-	YES	AFC counts	FG
Loughton	636	YES	-	-	AFC counts	FG
Maida Vale	637	YES	-	-	AFC counts	FG
Manor House	638	YES	-	-	AFC counts	FG
Mansion House	639	YES	-	-	AFC counts	FG
Marble Arch	640	YES	-	-	AFC counts	FG
Marylebone	641	YES	-	YES	AFC counts	FG
Mile End	642	YES	-	-	AFC counts	FG
Mill Hill East	643	-	YES	-	Manual counts	NFG
Moor Park	646	YES	-	-	AFC counts	FG
Moorgate	645	-	YES	YES	Manual + AFC counts	NFG
Morden	647	YES	-	-	AFC counts	FG
Mornington Crescent	648	YES	-	-	AFC counts	FG
Neasden	649	YES	-	-	AFC counts	FG
New Cross	651	-	YES	YES	Manual counts	NFG
New Cross Gate	652	-	YES	YES	Manual counts	NFG
Newbury Park	650	YES	-	-	AFC counts	FG
North Acton	653	YES	-	-	AFC counts	FG
North Ealing	654	YES	-	-	AFC counts	FG
North Greenwich	789	YES	-	-	AFC counts	FG
North Harrow	656	YES	-	-	AFC counts	FG
North Wembley	659	-	YES	YES	Manual counts	NFG
Northfields	655	YES	-	-	AFC counts	FG
Northolt	657	YES	-	-	AFC counts	FG
Northwick Park	660	YES	-	-	AFC counts	FG
Northwood	661	YES	-	-	AFC counts	FG
Northwood Hills	662	YES	-	-	AFC counts	FG
Notting Hill Gate	663	YES	-	-	AFC counts	FG
Oakwood	664	YES	-	-	AFC counts	FG
Old Street	665	-	YES	YES	Manual + AFC counts	NFG
Osterley	667	YES	-	-	AFC counts	FG
Oval	668	YES	-	-	AFC counts	FG
Oxford Circus	669	YES	-	-	AFC counts	FG
Paddington	670	-	YES	YES	Manual + AFC counts	NFG
Park Royal	671	YES	-	-	AFC counts	FG
Parsons Green	672	YES	-	-	AFC counts	FG
Perivale	673	YES	-	-	AFC counts	FG
Piccadilly Circus	674	YES	-	-	AFC counts	FG

Pimlico	776	YES	-	-	AFC counts	FG
Pinner	675	YES	-	-	Manual + AFC counts	NFG
Plaistow	676	YES	-	-	AFC counts	FG
Preston Road	677	YES	-	-	AFC counts	FG
Putney Bridge	678	YES	-	-	AFC counts	FG
Queen's Park	680	-	YES	YES	Manual + AFC counts	NFG
Queensbury	679	YES	-	-	AFC counts	FG
Queensway	681	YES	-	-	AFC counts	FG
Ravenscourt Park	682	YES	-	-	AFC counts	FG
Rayners Lane	683	YES	-	-	AFC counts	FG
Redbridge	684	YES	-	-	AFC counts	FG
Regent's Park	685	YES	-	-	AFC counts	FG
Richmond	686	-	YES	YES	Manual counts	NFG
Rickmansworth	687	-	YES	YES	Manual + AFC counts	NFG
Roding Valley	688	-	YES	-	Manual counts	NFG
Rotherhithe	689	YES	-	-	AFC counts	FG
Royal Oak	690	YES	-	-	AFC counts	FG
Ruislip	691	YES	-	-	AFC counts	FG
Ruislip Gardens	692	YES	-	-	AFC counts	FG
Ruislip Manor	693	YES	-	-	AFC counts	FG
Russell Square	694	YES	-	-	AFC counts	FG
Seven Sisters	698	-	YES	YES	Manual + AFC counts	NFG
Shadwell	699	YES	-	-	AFC counts	FG
Shepherd's Bush (Cen)	700	YES	-	-	AFC counts	FG
Shepherd's Bush (H&C)	775	YES	-	-	AFC counts	FG
Shoreditch	701	-	YES	-	Manual counts	NFG
Sloane Square	702	YES	-	-	AFC counts	FG
Snaresbrook	703	YES	-	-	Manual + AFC counts	NFG
South Ealing	704	YES	-	-	AFC counts	FG
South Harrow	707	YES	-	-	AFC counts	FG
South Kensington	708	YES	-	-	AFC counts	FG
South Kenton	709	-	YES	YES	Manual counts	NFG
South Ruislip	710	-	YES	YES	Manual + AFC counts	NFG
South Wimbledon	711	YES	-	-	AFC counts	FG
South Woodford	712	YES	-	-	AFC counts	FG
Southfields	705	YES	-	-	AFC counts	FG
Southgate	706	YES	-	-	AFC counts	FG
Southwark	784	YES	-	-	AFC counts	FG
St. James's Park	695	YES	-	-	AFC counts	FG
St. John's Wood	696	YES	-	-	AFC counts	FG
St. Paul's	697	YES	-	-	AFC counts	FG
Stamford Brook	713	YES	-	-	AFC counts	FG
Stanmore	714	YES	-	-	AFC counts	FG
Stepney Green	715	YES	-	-	AFC counts	FG
Stockwell	716	YES	-	-	AFC counts	FG
Stonebridge Park	717	-	YES	YES	Manual counts	NFG
Stratford	719	-	YES	YES	Manual + AFC counts	NFG

Sudbury Hill	720	YES	-	YES	AFC counts	FG
Sudbury Town	721	YES	-	-	Manual + AFC counts	NFG
Surrey Quays	722	YES	-	-	AFC counts	FG
Swiss Cottage	723	YES	-	-	AFC counts	FG
Temple	724	YES	-	-	AFC counts	FG
Theydon Bois	725	YES	-	-	AFC counts	FG
Tooting Bec	726	YES	-	-	AFC counts	FG
Tooting Broadway	727	YES	-	-	AFC counts	FG
Tottenham Court Road	728	YES	-	-	AFC counts	FG
Tottenham Hale	729	YES	-	YES	AFC counts	FG
Totteridge & Whetstone	730	YES	-	-	Manual counts	NFG
Tower Hill	731	YES	-	YES	AFC counts	FG
Tufnell Park	733	YES	-	-	AFC counts	FG
Turnham Green	734	YES	-	-	AFC counts	FG
Turnpike Lane	735	YES	-	-	AFC counts	FG
Upminster	736	-	YES	YES	Manual counts	NFG
Upminster Bridge	737	YES	-	-	AFC counts	FG
Upney	738	YES	-	-	Manual counts	NFG
Upton Park	739	YES	-	-	AFC counts	FG
Uxbridge	740	YES	-	-	AFC counts	FG
Vauxhall	777	YES	-	YES	AFC counts	FG
Victoria	741	YES	-	YES	AFC counts	FG
Walthamstow Central	742	YES	-	YES	AFC counts	FG
Wanstead	743	YES	-	-	AFC counts	FG
Wapping	744	YES	-	-	AFC counts	FG
Warren Street	745	YES	-	-	AFC counts	FG
Warwick Avenue	746	YES	-	-	AFC counts	FG
Waterloo	747	-	YES	YES	Manual + AFC counts	NFG
Watford	748	YES	-	-	AFC counts	FG
Wembley Central	751	-	YES	YES	Manual counts	NFG
Wembley Park	752	YES	-	-	AFC counts	FG
West Acton	753	YES	-	-	AFC counts	FG
West Brompton	755	-	YES	YES	Manual + AFC counts	NFG
West Finchley	756	YES	-	-	Manual counts	NFG
West Ham	757	-	YES	YES	Manual + AFC counts	NFG
West Hampstead	758	YES	-	YES	AFC counts	FG
West Harrow	759	YES	-	-	Manual + AFC counts	NFG
West Kensington	760	YES	-	-	Manual + AFC counts	NFG
West Ruislip	762	-	YES	YES	Manual counts	NFG
Westbourne Park	754	YES	-	-	AFC counts	FG
Westminster	761	YES	-	YES	AFC counts	FG
White City	764	YES	-	-	AFC counts	FG
Whitechapel	763	YES	-	-	AFC counts	FG
Willesden Green	765	YES	-	-	AFC counts	FG
Willesden Junction	766	-	YES	YES	Manual counts	NFG
Wimbledon	767	-	YES	YES	Manual counts	NFG
Wimbledon Park	768	YES	-	-	AFC counts	FG

Wood Green	770	YES	-	-	AFC counts	FG
Woodford	769	YES	-	-	AFC counts	FG
Woodside Park	771	YES	-	-	Manual counts	NFG

APPENDIX B – OD MATRIX ESTIMATION PARAMETERS

TABLE B-1: Estimated Entries per station

Station Name	Type	CD Oyster Entries	ID Oyster Entries	"No Travel" Entries	Printed Ticket Entries	Manual Counts	Estimated Entries Period 1	RODS 2004 Entries
Acton Town	FG	5,966	477	149	1,190	0	**7,782**	**8,334**
Aldgate	FG	3,771	445	166	2,903	0	**7,285**	**8,153**
Aldgate East	FG	6,819	542	178	3,658	0	**11,196**	**12,281**
Alperton	FG	2,602	170	32	537	0	**3,341**	**3,798**
Amersham	NFG	1,751	91	316	878	0	**3,036**	**2,986**
Angel	FG	11,715	1,243	260	5,588	0	**18,806**	**22,570**
Archway	FG	7,421	540	64	1,858	0	**9,883**	**11,011**
Arnos Grove	FG	3,823	268	89	1,112	0	**5,292**	**5,746**
Arsenal	FG	2,460	157	61	885	0	**3,563**	**3,362**
Baker Street	FG	17,900	1,611	639	13,477	0	**33,627**	**34,045**
Balham	FG	9,903	460	440	3,449	0	**14,252**	**14,638**
Bank & Monument	NFG	25,046	4,398	2,182	15,721	26,331	**73,677**	**77,544**
Barbican	NFG	7,937	937	191	3,880	321	**13,267**	**15,364**
Barking	NFG	6,770	1,745	493	4,111	8,244	**21,363**	**21,363**
Barkingside	FG	648	54	21	198	0	**920**	**980**
Barons Court	FG	7,019	315	75	1,372	0	**8,782**	**10,451**
Bayswater	FG	6,574	575	616	5,307	0	**13,072**	**8,836**
Becontree	NFG	1,272	122	8	160	1,600	**3,162**	**3,162**
Belsize Park	FG	5,531	369	72	1,470	0	**7,441**	**8,341**
Bermondsey	FG	6,385	371	212	1,218	0	**8,186**	**7,532**
Bethnal Green	FG	12,520	1,422	525	3,046	0	**17,512**	**16,243**
Blackfriars	FG	10,317	1,189	736	8,286	0	**20,529**	**20,434**
Blackhorse Road	NFG	6,201	803	95	1,514	611	**9,224**	**9,224**
Bond Street	FG	24,208	1,998	1,346	16,721	0	**44,273**	**45,383**
Borough	FG	3,066	277	293	1,311	0	**4,946**	**5,038**
Boston Manor	FG	1,585	72	22	460	0	**2,138**	**2,557**
Bounds Green	FG	5,951	378	83	1,053	0	**7,465**	**7,895**
Bow Road	FG	4,088	238	38	710	0	**5,074**	**5,566**
Brent Cross	NFG	1,653	122	28	437	851	**3,090**	**3,090**
Brixton	FG	14,306	1,178	509	4,306	0	**20,298**	**28,333**
Bromley-by-Bow	FG	2,587	258	44	558	0	**3,447**	**4,028**
Buckhurst Hill	FG	1,710	98	16	528	0	**2,352**	**2,266**
Burnt Oak	NFG	2,704	244	45	650	1,610	**5,253**	**5,253**

Caledonian Road	FG	4,976	356	62	1,254	0	**6,648**	**6,749**
Camden Town	FG	12,165	1,229	572	8,303	0	**22,270**	**20,051**
Canada Water	FG	8,928	556	104	1,802	0	**11,389**	**11,178**
Canary Wharf	FG	36,175	2,008	1,434	19,373	0	**58,990**	**50,518**
Canning Town	NFG	6,966	1,172	189	1,677	7,532	**17,535**	**17,535**
Cannon Street	FG	4,151	190	337	4,392	0	**9,070**	**8,679**
Canons Park	FG	1,358	46	16	312	0	**1,732**	**1,946**
Chalfont & Latimer	NFG	773	16	15	36	1,232	**2,073**	**2,121**
Chalk Farm	FG	3,798	291	80	1,196	0	**5,365**	**5,641**
Chancery Lane	FG	11,572	1,388	591	6,059	0	**19,610**	**20,030**
Charing Cross	FG	11,250	906	1,024	15,653	0	**28,833**	**29,683**
Chesham	FG	380	25	3	196	0	**604**	**637**
Chigwell	FG	256	18	18	75	0	**367**	**403**
Chiswick Park	FG	2,600	162	23	673	0	**3,456**	**2,990**
Chorleywood	NFG	836	22	10	270	358	**1,497**	**1,497**
Clapham Common	FG	7,992	381	127	1,726	0	**10,225**	**11,287**
Clapham North	FG	5,353	235	201	1,108	0	**6,897**	**6,709**
Clapham South	FG	7,986	316	250	1,344	0	**9,895**	**11,115**
Cockfosters	FG	1,076	84	15	617	0	**1,792**	**2,443**
Colindale	NFG	2,918	222	23	987	1,267	**5,417**	**5,417**
Colliers Wood	FG	5,529	238	44	1,060	0	**6,871**	**6,464**
Covent Garden	FG	8,760	1,245	231	11,113	0	**21,348**	**20,577**
Croxley	FG	656	18	5	200	0	**879**	**1,108**
Dagenham East	FG	1,499	183	12	360	0	**2,055**	**2,623**
Dagenham Heathway	NFG	1,807	196	10	182	3,000	**5,195**	**5,195**
Debden	FG	1,446	125	79	541	0	**2,192**	**2,395**
Dollis Hill	FG	3,560	109	21	590	0	**4,280**	**5,172**
Ealing Broadway	NFG	13,449	2,603	212	5,144	1,745	**23,153**	**23,153**
Ealing Common	FG	3,241	187	55	624	0	**4,107**	**4,614**
Earl's Court	FG	17,529	1,355	514	7,076	0	**26,473**	**29,615**
East Acton	FG	3,481	181	36	712	0	**4,410**	**4,924**
East Finchley	FG	5,519	328	159	1,165	0	**7,171**	**7,642**
East Ham	FG	10,788	1,185	92	2,004	0	**14,068**	**14,807**
East Putney	FG	5,481	479	39	1,475	0	**7,474**	**7,767**
Eastcote	FG	2,594	89	23	469	0	**3,174**	**3,436**
Edgware	NFG	2,559	241	121	824	1,351	**5,096**	**5,096**
Edgware Road (Bak)	FG	2,680	289	89	1,498	0	**4,556**	**5,128**
Edgware Road (Cir)	FG	5,015	488	197	2,358	0	**8,057**	**9,032**
Elephant & Castle	FG	11,701	1,421	275	4,629	0	**18,026**	**22,015**
Elm Park	FG	2,137	228	17	598	0	**2,980**	**3,477**
Embankment	FG	12,157	1,115	794	12,505	0	**26,571**	**26,998**
Epping	FG	2,216	144	111	944	0	**3,416**	**3,159**
Euston	FG	11,922	2,563	176	22,394	0	**37,055**	**35,008**
Euston Square	FG	5,847	564	448	6,076	0	**12,935**	**14,809**
Fairlop	FG	485	46	33	161	0	**724**	**681**
Farringdon	NFG	13,456	3,722	486	10,793	5,087	**33,545**	**33,545**
Finchley Central	NFG	3,404	188	31	678	2,789	**7,090**	**7,090**

Finchley Road	FG	10,198	412	82	2,065	0	**12,756**	**14,595**
Finsbury Park	NFG	11,115	618	1	0	32,524	**44,258**	**44,258**
Fulham Broadway	FG	8,548	994	97	3,145	0	**12,784**	**13,282**
Gants Hill	FG	4,711	359	141	1,187	0	**6,398**	**6,092**
Gloucester Road	FG	10,769	645	622	6,274	0	**18,311**	**19,850**
Golders Green	FG	6,136	434	177	1,357	0	**8,105**	**8,765**
Goldhawk Road	FG	1,785	112	38	383	0	**2,317**	**2,586**
Goodge Street	FG	6,394	451	68	3,654	0	**10,567**	**12,555**
Grange Hill	FG	317	23	14	82	0	**435**	**420**
Great Portland Street	FG	5,054	544	182	2,859	0	**8,639**	**10,800**
Green Park	FG	21,357	1,476	1,482	14,883	0	**39,198**	**38,185**
Greenford	NFG	3,445	238	75	828	0	**4,585**	**4,345**
Gunnersbury	NFG	1,652	525	23	867	1,413	**4,479**	**6,133**
Hainault	FG	2,188	256	241	522	0	**3,207**	**2,967**
Hammersmith (Dis)	FG	24,245	2,169	323	8,742	0	**35,479**	**37,748**
Hammersmith (H&C)	FG	5,244	436	75	2,216	0	**7,971**	**6,814**
Hampstead	FG	3,628	285	119	949	0	**4,981**	**6,074**
Hanger Lane	FG	2,952	136	33	663	0	**3,784**	**3,104**
Harlesden	NFG	719	204	2	0	2,369	**3,294**	**3,294**
Harrow & Wealdstone	NFG	598	120	0	0	6,353	**7,070**	**7,070**
Harrow-on-the-Hill	NFG	8,284	461	273	2,237	1,936	**13,191**	**13,338**
Hatton Cross	FG	2,765	175	8	1,071	0	**4,019**	**3,830**
Heathrow Terminal 4	FG	- 0	1	0	0	0	**1**	**1,143**
Heathrow Terminals 123	NFG	4,774	573	14	1,797	5,150	**12,308**	**12,308**
Hendon Central	NFG	4,122	243	48	845	3,164	**8,421**	**8,421**
High Barnet	NFG	2,154	181	81	870	412	**3,698**	**3,698**
High Street Kensington	FG	8,809	697	720	6,449	0	**16,675**	**18,000**
Highbury & Islington	NFG	12,558	2,087	292	4,214	9,321	**28,472**	**28,472**
Highgate	FG	5,024	295	92	1,140	0	**6,551**	**6,944**
Hillingdon	FG	1,153	48	12	494	0	**1,707**	**2,022**
Holborn	FG	22,780	2,257	1,022	12,016	0	**38,074**	**40,510**
Holland Park	FG	3,387	227	147	1,167	0	**4,928**	**5,296**
Holloway Road	FG	6,263	532	137	1,878	0	**8,809**	**10,082**
Hornchurch	FG	1,456	144	9	417	0	**2,026**	**2,795**
Hounslow Central	FG	3,062	166	23	931	0	**4,182**	**4,171**
Hounslow East	NFG	3,501	206	36	962	0	**4,706**	**4,838**
Hounslow West	FG	2,392	150	59	928	0	**3,528**	**3,755**
Hyde Park Corner	FG	3,107	240	288	2,978	0	**6,614**	**5,989**
Ickenham	FG	921	40	13	199	0	**1,173**	**1,673**
Kennington	FG	3,452	222	203	943	0	**4,819**	**5,227**
Kensal Green	NFG	2,020	205	12	566	118	**2,921**	**2,921**
Kensington (Olympia)	NFG	326	15	0	0	1,217	**1,558**	**1,558**
Kentish Town	NFG	4,726	752	262	1,950	2,664	**10,355**	**11,428**
Kenton	NFG	351	74	1	0	956	**1,381**	**1,381**
Kew Gardens	NFG	1,420	286	32	809	273	**2,819**	**4,347**
Kilburn	FG	8,215	304	50	1,541	0	**10,111**	**10,596**
Kilburn Park	FG	2,979	387	122	884	0	**4,372**	**4,869**

King's Cross St. Pancras	NFG	28,157	5,521	1,687	54,170	0	**89,535**	**87,678**
Kingsbury	FG	2,999	120	94	645	0	**3,859**	**3,983**
Knightsbridge	FG	9,708	673	187	11,581	0	**22,149**	**25,148**
Ladbroke Grove	FG	4,537	289	48	1,248	0	**6,121**	**6,742**
Lambeth North	FG	2,189	154	33	1,466	0	**3,842**	**4,266**
Lancaster Gate	FG	4,700	294	23	4,116	0	**9,132**	**8,032**
Latimer Road	FG	2,008	146	31	414	0	**2,599**	**2,874**
Leicester Square	FG	18,901	3,176	769	17,360	0	**40,206**	**42,456**
Leyton	FG	12,305	1,440	262	1,824	0	**15,831**	**14,395**
Leytonstone	FG	10,026	945	232	1,623	0	**12,825**	**12,211**
Liverpool Street	FG	35,907	10,545	4,694	36,376	0	**87,522**	**80,312**
London Bridge	FG	35,132	2,336	2,771	33,853	0	**74,091**	**71,149**
Loughton	FG	2,292	143	64	861	0	**3,359**	**3,407**
Maida Vale	FG	3,329	210	91	718	0	**4,348**	**4,906**
Manor House	FG	9,008	515	73	1,593	0	**11,190**	**11,117**
Mansion House	FG	5,341	290	120	2,931	0	**8,681**	**7,814**
Marble Arch	FG	7,898	752	292	6,558	0	**15,500**	**15,986**
Marylebone	FG	5,347	719	78	8,133	0	**14,277**	**15,347**
Mile End	FG	10,392	871	344	2,360	0	**13,967**	**15,830**
Mill Hill East	NFG	392	19	1	0	1,101	**1,513**	**1,513**
Moor Park	FG	637	23	13	227	0	**899**	**1,072**
Moorgate	NFG	13,813	2,414	1,437	12,263	15,652	**45,577**	**45,577**
Morden	FG	5,670	319	642	1,861	0	**8,492**	**8,994**
Mornington Crescent	FG	2,684	229	49	1,179	0	**4,141**	**4,510**
Neasden	FG	2,895	129	51	585	0	**3,660**	**4,196**
New Cross	NFG	807	599	44	0	3,956	**5,405**	**5,405**
New Cross Gate	NFG	1,040	100	1	0	5,114	**6,255**	**6,255**
Newbury Park	FG	3,566	259	55	1,028	0	**4,908**	**4,308**
North Acton	FG	4,808	356	29	1,164	0	**6,357**	**6,161**
North Ealing	FG	786	32	5	135	0	**958**	**1,533**
North Greenwich	FG	11,630	830	604	2,876	0	**15,940**	**13,227**
North Harrow	FG	1,550	46	21	317	0	**1,933**	**2,215**
North Wembley	NFG	497	123	1	0	1,049	**1,670**	**1,670**
Northfields	FG	4,095	236	138	656	0	**5,125**	**6,104**
Northolt	FG	3,237	174	51	799	0	**4,260**	**4,223**
Northwick Park	FG	3,161	114	19	763	0	**4,057**	**4,644**
Northwood	FG	1,836	71	73	549	0	**2,529**	**2,729**
Northwood Hills	FG	1,315	43	19	276	0	**1,653**	**1,871**
Notting Hill Gate	FG	15,165	1,200	713	5,635	0	**22,713**	**21,715**
Oakwood	FG	1,949	150	67	811	0	**2,977**	**3,851**
Old Street	NFG	12,725	1,754	884	7,621	0	**22,983**	**22,752**
Osterley	FG	1,920	82	29	671	0	**2,701**	**3,284**
Oval	FG	5,214	552	102	1,439	0	**7,307**	**8,055**
Oxford Circus	FG	44,293	5,355	2,466	37,307	0	**89,421**	**93,650**
Paddington	NFG	17,233	1,553	559	30,443	2,103	**51,891**	**51,891**
Park Royal	FG	1,399	89	15	382	0	**1,885**	**2,248**
Parsons Green	FG	5,155	378	112	1,218	0	**6,863**	**7,307**

Perivale	FG	1,930	103	24	460	0	**2,517**	**2,436**
Piccadilly Circus	FG	22,165	2,309	2,501	24,122	0	**51,097**	**49,973**
Pimlico	FG	6,652	420	408	3,180	0	**10,660**	**12,039**
Pinner	NFG	2,255	75	60	487	275	**3,153**	**3,239**
Plaistow	FG	5,200	404	46	807	0	**6,457**	**7,894**
Preston Road	FG	3,328	100	41	591	0	**4,060**	**4,542**
Putney Bridge	FG	4,601	399	127	1,398	0	**6,525**	**7,493**
Queen's Park	NFG	4,557	401	40	1,168	3,232	**9,398**	**10,901**
Queensbury	FG	3,090	115	75	582	0	**3,862**	**3,802**
Queensway	FG	- 0	0	0	0	0	**0**	**9,135**
Ravenscourt Park	FG	2,410	169	59	699	0	**3,337**	**4,162**
Rayners Lane	FG	4,055	160	101	658	0	**4,974**	**5,172**
Redbridge	FG	2,168	170	136	731	0	**3,205**	**2,882**
Regent's Park	FG	2,239	134	78	2,026	0	**4,477**	**4,596**
Richmond	NFG	2,541	3,288	83	0	12,033	**17,945**	**17,945**
Rickmansworth	NFG	1,716	84	103	597	210	**2,710**	**2,710**
Roding Valley	NFG	112	5	0	0	214	**331**	**331**
Rotherhithe	FG	1,286	162	19	299	0	**1,766**	**1,772**
Royal Oak	FG	- 0	0	0	368	1,979	**2,347**	**2,347**
Ruislip	FG	1,413	53	49	227	0	**1,741**	**2,208**
Ruislip Gardens	FG	838	46	14	202	0	**1,100**	**900**
Ruislip Manor	FG	1,406	53	14	263	0	**1,736**	**2,183**
Russell Square	FG	6,721	582	468	5,681	0	**13,452**	**16,933**
Seven Sisters	NFG	12,120	1,813	636	3,362	7,086	**25,017**	**25,017**
Shadwell	FG	1,314	293	77	389	0	**2,073**	**1,968**
Shepherd's Bush (Cen)	FG	12,384	792	226	3,045	0	**16,448**	**15,842**
Shepherd's Bush (H&C)	FG	3,108	223	85	771	0	**4,187**	**5,053**
Shoreditch	NFG	435	35	0	0	0	**470**	**229**
Sloane Square	FG	11,439	791	507	5,209	0	**17,947**	**19,733**
Snaresbrook	NFG	2,064	134	68	545	572	**3,383**	**3,383**
South Ealing	FG	3,391	143	42	631	0	**4,207**	**5,145**
South Harrow	FG	1,933	90	31	419	0	**2,473**	**2,677**
South Kensington	FG	19,202	1,497	1,061	13,550	0	**35,310**	**35,711**
South Kenton	NFG	282	43	0	0	555	**880**	**880**
South Ruislip	NFG	1,439	78	31	355	77	**1,980**	**1,980**
South Wimbledon	FG	3,902	182	138	825	0	**5,047**	**4,816**
South Woodford	FG	3,822	239	136	806	0	**5,002**	**5,055**
Southfields	FG	5,577	704	36	910	0	**7,227**	**7,921**
Southgate	FG	4,595	314	62	1,380	0	**6,352**	**7,139**
Southwark	FG	5,002	990	2,081	3,956	0	**12,030**	**10,736**
St. James's Park	FG	11,566	903	1,795	6,819	0	**21,083**	**22,278**
St. John's Wood	FG	6,064	228	30	1,658	0	**7,979**	**8,351**
St. Paul's	FG	10,912	1,074	531	6,850	0	**19,367**	**17,640**
Stamford Brook	FG	2,639	164	48	753	0	**3,604**	**4,240**
Stanmore	FG	2,205	128	52	1,003	0	**3,387**	**3,599**
Stepney Green	FG	3,491	390	55	945	0	**4,881**	**5,814**
Stockwell	FG	10,394	632	682	2,207	0	**13,915**	**11,899**

Stonebridge Park	NFG	720	210	1	0	2,278	**3,209**	**3,209**
Stratford	NFG	20,166	5,442	453	13,592	7,586	**47,239**	**47,239**
Sudbury Hill	FG	1,896	85	23	363	0	**2,367**	**3,069**
Sudbury Town	NFG	2,169	123	48	333	396	**3,069**	**3,069**
Surrey Quays	FG	2,028	302	33	369	0	**2,732**	**2,721**
Swiss Cottage	FG	6,426	235	68	1,623	0	**8,352**	**9,078**
Temple	FG	5,425	507	249	3,617	0	**9,798**	**11,847**
Theydon Bois	FG	627	40	10	201	0	**877**	**828**
Tooting Bec	FG	7,301	267	75	1,326	0	**8,970**	**9,601**
Tooting Broadway	FG	12,598	603	317	2,888	0	**16,406**	**16,599**
Tottenham Court Road	FG	21,603	2,531	656	16,240	0	**41,030**	**46,207**
Tottenham Hale	FG	4,857	620	248	5,207	0	**10,932**	**10,236**
Totteridge & Whetstone	NFG	1,447	84	11	477	440	**2,459**	**2,459**
Tower Hill	FG	10,887	854	413	15,508	0	**27,661**	**27,674**
Tufnell Park	FG	3,435	219	31	741	0	**4,425**	**5,163**
Turnham Green	FG	5,930	315	52	1,502	0	**7,799**	**8,100**
Turnpike Lane	FG	8,920	784	253	1,828	0	**11,785**	**11,683**
Upminster	NFG	1,313	294	30	0	4,378	**6,015**	**6,015**
Upminster Bridge	FG	528	64	5	185	0	**782**	**1,703**
Upney	NFG	1,291	134	10	356	731	**2,521**	**2,521**
Upton Park	FG	8,110	881	69	1,488	0	**10,548**	**9,967**
Uxbridge	FG	5,156	365	280	1,557	0	**7,358**	**8,548**
Vauxhall	FG	14,029	1,598	733	9,807	0	**26,167**	**25,851**
Victoria	FG	40,519	5,807	1,588	53,449	0	**101,363**	**107,473**
Walthamstow Central	FG	12,939	1,298	339	4,665	0	**19,241**	**18,083**
Wanstead	FG	2,198	140	55	554	0	**2,947**	**2,992**
Wapping	FG	1,461	145	76	362	0	**2,044**	**1,627**
Warren Street	FG	11,351	1,213	702	6,963	0	**20,229**	**21,170**
Warwick Avenue	FG	4,437	241	130	1,004	0	**5,812**	**5,443**
Waterloo	NFG	35,714	3,683	2,925	55,891	7,934	**106,147**	**106,147**
Watford	FG	1,208	64	47	423	0	**1,742**	**2,115**
Wembley Central	NFG	1,460	925	29	892	377	**3,682**	**3,682**
Wembley Park	FG	7,837	535	314	3,129	0	**11,815**	**9,961**
West Acton	FG	1,684	91	20	294	0	**2,089**	**2,259**
West Brompton	NFG	1,999	590	46	1,312	962	**4,908**	**4,908**
West Finchley	NFG	1,147	51	8	249	560	**2,016**	**2,016**
West Ham	NFG	2,974	449	72	814	5,178	**9,487**	**9,487**
West Hampstead	FG	7,667	288	99	2,332	0	**10,386**	**11,368**
West Harrow	NFG	1,097	31	24	154	266	**1,573**	**1,573**
West Kensington	NFG	4,797	298	117	1,123	571	**6,906**	**7,045**
West Ruislip	NFG	1,021	48	11	339	260	**1,679**	**1,679**
Westbourne Park	FG	3,312	239	60	721	0	**4,332**	**3,702**
Westminster	FG	10,887	773	993	12,916	0	**25,569**	**22,799**
White City	FG	7,349	578	226	3,019	0	**11,172**	**10,928**
Whitechapel	FG	10,010	1,778	335	2,950	0	**15,072**	**14,350**
Willesden Green	FG	9,164	308	99	1,371	0	**10,942**	**11,158**
Willesden Junction	NFG	1,585	851	43	0	4,191	**6,670**	**6,670**

Wimbledon	NFG	6,523	6,782	232	0	2,533	**16,070**	**16,070**
Wimbledon Park	FG	1,621	265	18	346	0	**2,249**	**3,081**
Wood Green	FG	10,038	936	222	2,631	0	**13,827**	**14,006**
Woodford	FG	4,564	342	113	1,246	0	**6,265**	**6,120**
Woodside Park	NFG	2,271	120	17	551	407	**3,366**	**3,366**

TABLE B-2: Estimated Exits per station

Station Name	Type	CD Oyster Exits	ID Oyster Exits	"No Travel" Exits	Printed Ticket Exits	Manual Count Exits	Estimated Exits Period 1	RODS 2004 Exits
Acton Town	FG	5,623	494	149	1,199	- 0	**7,464**	**7,978**
Aldgate	FG	3,851	300	166	2,984	- 0	**7,301**	**9,016**
Aldgate East	FG	6,421	488	178	3,754	- 0	**10,841**	**12,171**
Alperton	FG	2,704	212	32	540	- 0	**3,488**	**3,967**
Amersham	NFG	1,323	81	316	884	447	**3,051**	**3,051**
Angel	FG	11,412	930	260	5,776	- 0	**18,379**	**23,094**
Archway	FG	6,613	459	64	1,741	- 0	**8,877**	**10,631**
Arnos Grove	FG	3,355	270	89	987	- 0	**4,701**	**5,277**
Arsenal	FG	2,055	166	61	877	- 0	**3,159**	**2,756**
Baker Street	FG	16,803	941	639	13,417	- 0	**31,800**	**32,628**
Balham	FG	9,896	516	440	3,271	- 0	**14,123**	**14,381**
Bank & Monument	NFG	25,105	4,321	2,182	15,472	27,544	**74,624**	**77,694**
Barbican	NFG	7,031	505	191	4,186	- 0	**11,914**	**14,779**
Barking	NFG	6,658	1,997	493	3,672	7,559	**20,379**	**20,379**
Barkingside	FG	587	59	21	182	- 0	**849**	**907**
Barons Court	FG	6,187	314	75	1,229	- 0	**7,806**	**9,853**
Bayswater	FG	6,056	428	616	5,384	- 0	**12,484**	**8,514**
Becontree	NFG	911	77	8	124	2,741	**3,861**	**3,861**
Belsize Park	FG	5,098	334	72	1,382	- 0	**6,886**	**8,023**
Bermondsey	FG	5,470	374	212	1,132	- 0	**7,188**	**7,299**
Bethnal Green	FG	10,868	1,105	525	2,771	- 0	**15,268**	**15,011**
Blackfriars	FG	10,406	604	736	7,188	- 0	**18,934**	**19,477**
Blackhorse Road	NFG	5,327	739	95	1,415	486	**8,063**	**8,063**
Bond Street	FG	25,308	1,572	1,346	16,725	- 0	**44,951**	**48,147**
Borough	FG	3,103	267	293	1,340	- 0	**5,003**	**5,378**
Boston Manor	FG	1,477	66	22	441	- 0	**2,005**	**2,417**
Bounds Green	FG	5,056	381	83	980	- 0	**6,499**	**6,989**
Bow Road	FG	3,971	260	38	794	- 0	**5,063**	**5,456**
Brent Cross	NFG	1,534	96	28	456	704	**2,818**	**2,818**
Brixton	FG	12,903	1,020	509	4,332	- 0	**18,764**	**26,995**
Bromley-by-Bow	FG	2,498	271	44	538	- 0	**3,351**	**4,039**
Buckhurst Hill	FG	1,405	95	16	415	- 0	**1,930**	**1,903**
Burnt Oak	NFG	2,389	251	45	551	985	**4,221**	**4,221**
Caledonian Road	FG	4,161	300	62	1,216	- 0	**5,738**	**5,987**
Camden Town	FG	12,719	968	572	8,659	- 0	**22,918**	**21,356**
Canada Water	FG	8,444	587	104	1,801	- 0	**10,936**	**11,329**
Canary Wharf	FG	35,580	2,367	1,434	19,408	- 0	**58,789**	**54,197**
Canning Town	NFG	5,879	1,282	189	1,583	8,586	**17,517**	**17,517**
Cannon Street	FG	4,009	166	337	3,504	- 0	**8,017**	**7,377**
Canons Park	FG	1,425	60	16	296	- 0	**1,797**	**1,876**

Chalfont & Latimer	NFG	622	5	15	33	1,210	**1,885**	**1,885**
Chalk Farm	FG	3,100	198	80	1,070	- 0	**4,448**	**4,701**
Chancery Lane	FG	13,922	1,390	591	6,796	- 0	**22,699**	**23,448**
Charing Cross	FG	11,476	766	1,024	14,688	- 0	**27,954**	**30,571**
Chesham	FG	322	21	3	147	- 0	**493**	**725**
Chigwell	FG	187	18	18	54	- 0	**276**	**286**
Chiswick Park	FG	2,601	167	23	625	- 0	**3,415**	**2,901**
Chorleywood	NFG	379	5	10	22	881	**1,296**	**1,296**
Clapham Common	FG	8,778	374	127	1,948	- 0	**11,226**	**11,928**
Clapham North	FG	6,179	309	201	1,182	- 0	**7,871**	**7,802**
Clapham South	FG	7,422	336	250	1,277	- 0	**9,285**	**9,824**
Cockfosters	FG	947	79	15	574	- 0	**1,615**	**2,314**
Colindale	NFG	2,524	205	23	831	2,019	**5,602**	**5,602**
Colliers Wood	FG	4,989	227	44	968	- 0	**6,228**	**6,079**
Covent Garden	FG	10,664	940	231	13,278	- 0	**25,112**	**24,951**
Croxley	FG	614	20	5	158	- 0	**798**	**945**
Dagenham East	FG	1,216	151	12	307	- 0	**1,686**	**2,400**
Dagenham Heathway	NFG	1,470	89	10	116	3,436	**5,121**	**5,121**
Debden	FG	1,335	121	79	483	- 0	**2,018**	**2,214**
Dollis Hill	FG	2,784	90	21	409	- 0	**3,305**	**5,096**
Ealing Broadway	NFG	13,243	2,179	212	4,928	935	**21,497**	**21,497**
Ealing Common	FG	3,372	232	55	664	- 0	**4,323**	**4,699**
Earl's Court	FG	15,833	1,277	514	6,880	- 0	**24,504**	**28,243**
East Acton	FG	3,438	206	36	750	- 0	**4,430**	**4,862**
East Finchley	FG	5,133	377	159	1,065	- 0	**6,734**	**6,363**
East Ham	FG	9,924	1,140	92	2,003	- 0	**13,160**	**14,422**
East Putney	FG	4,888	451	39	1,401	- 0	**6,779**	**7,085**
Eastcote	FG	2,383	118	23	402	- 0	**2,927**	**3,144**
Edgware	NFG	2,295	227	121	643	1,595	**4,881**	**4,881**
Edgware Road (Bak)	FG	2,789	206	89	1,612	- 0	**4,697**	**5,077**
Edgware Road (Cir)	FG	4,682	320	197	2,509	- 0	**7,708**	**8,914**
Elephant & Castle	FG	10,940	1,330	275	4,218	- 0	**16,762**	**21,740**
Elm Park	FG	1,682	192	17	363	- 0	**2,254**	**3,155**
Embankment	FG	12,567	915	794	13,245	- 0	**27,521**	**29,264**
Epping	FG	2,001	144	111	835	- 0	**3,091**	**2,854**
Euston	FG	13,811	2,990	176	19,047	- 0	**36,025**	**34,302**
Euston Square	FG	6,038	336	448	6,227	- 0	**13,048**	**15,294**
Fairlop	FG	461	44	33	157	- 0	**695**	**684**
Farringdon	NFG	11,077	1,725	486	10,797	7,340	**31,426**	**31,426**
Finchley Central	NFG	3,292	125	31	560	2,452	**6,460**	**6,460**
Finchley Road	FG	9,612	315	82	2,009	- 0	**12,018**	**13,652**
Finsbury Park	NFG	9,177	1	1	- 0	34,071	**43,250**	**43,250**
Fulham Broadway	FG	8,963	869	97	3,081	- 0	**13,010**	**13,437**
Gants Hill	FG	4,123	372	141	1,105	- 0	**5,740**	**5,714**
Gloucester Road	FG	10,454	715	622	6,453	- 0	**18,244**	**19,798**
Golders Green	FG	6,071	451	177	1,233	- 0	**7,932**	**8,433**
Goldhawk Road	FG	1,470	72	38	357	- 0	**1,937**	**2,372**
Goodge Street	FG	5,864	340	68	3,411	- 0	**9,683**	**13,726**
Grange Hill	FG	235	20	14	55	- 0	**324**	**315**
Great Portland Street	FG	4,657	260	182	2,853	- 0	**7,952**	**10,720**
Green Park	FG	24,505	1,632	1,482	16,733	- 0	**44,352**	**45,817**
Greenford	NFG	3,276	226	75	781	- 0	**4,358**	**3,731**
Gunnersbury	NFG	1,439	510	23	805	1,822	**4,599**	**5,980**
Hainault	FG	1,949	228	241	481	- 0	**2,899**	**2,695**
Hammersmith (Dis)	FG	25,528	1,827	323	8,212	- 0	**35,890**	**34,703**

Hammersmith (H&C)	FG	6,150	345	75	1,909	- 0	**8,480**	**5,444**
Hampstead	FG	3,863	277	119	1,015	- 0	**5,274**	**6,638**
Hanger Lane	FG	2,730	141	33	593	- 0	**3,497**	**2,582**
Harlesden	NFG	578	- 0	2	- 0	2,638	**3,218**	**3,218**
Harrow & Wealdstone	NFG	439	- 0	0	- 0	4,638	**5,077**	**5,077**
Harrow-on-the-Hill	NFG	8,406	529	273	2,145	1,359	**12,713**	**13,511**
Hatton Cross	FG	2,749	50	8	504	- 0	**3,311**	**3,686**
Heathrow Terminal 4	FG	- 0	- 0	- 0	- 0	- 0	**- 0**	**1,149**
Heathrow Terminals 123	NFG	4,763	176	14	2,522	2,669	**10,144**	**10,144**
Hendon Central	NFG	3,529	203	48	706	2,860	**7,345**	**7,345**
High Barnet	NFG	1,922	177	81	809	794	**3,783**	**3,783**
High Street Kensington	FG	9,078	699	720	6,721	- 0	**17,218**	**19,367**
Highbury & Islington	NFG	11,380	1,993	292	4,363	9,113	**27,141**	**27,141**
Highgate	FG	4,351	243	92	1,026	- 0	**5,712**	**6,113**
Hillingdon	FG	1,032	52	12	415	- 0	**1,511**	**1,748**
Holborn	FG	24,344	2,442	1,022	13,099	- 0	**40,907**	**45,259**
Holland Park	FG	3,181	207	147	1,125	- 0	**4,660**	**4,942**
Holloway Road	FG	5,766	482	137	1,856	- 0	**8,240**	**10,184**
Hornchurch	FG	1,294	163	9	385	- 0	**1,851**	**2,809**
Hounslow Central	FG	2,904	185	23	937	- 0	**4,049**	**4,197**
Hounslow East	NFG	3,293	193	36	848	- 0	**4,370**	**4,899**
Hounslow West	FG	2,196	163	59	814	- 0	**3,231**	**3,584**
Hyde Park Corner	FG	3,474	294	288	3,220	- 0	**7,276**	**6,876**
Ickenham	FG	913	43	13	169	- 0	**1,138**	**1,509**
Kennington	FG	3,280	249	203	952	- 0	**4,684**	**5,175**
Kensal Green	NFG	1,435	172	12	446	746	**2,812**	**2,812**
Kensington (Olympia)	NFG	300	- 0	- 0	- 0	1,233	**1,533**	**1,533**
Kentish Town	NFG	4,295	674	262	1,867	2,400	**9,498**	**10,964**
Kenton	NFG	293	- 0	1	- 0	1,513	**1,806**	**1,806**
Kew Gardens	NFG	1,217	235	32	637	331	**2,452**	**3,558**
Kilburn	FG	7,474	301	50	1,464	- 0	**9,290**	**9,507**
Kilburn Park	FG	2,785	346	122	839	- 0	**4,092**	**4,595**
King's Cross St. Pancras	NFG	51,232	5,785	1,687	54,751	- 0	**113,455**	**91,912**
Kingsbury	FG	2,822	141	94	590	- 0	**3,647**	**3,703**
Knightsbridge	FG	10,048	700	187	11,202	- 0	**22,137**	**25,342**
Ladbroke Grove	FG	3,563	152	48	911	- 0	**4,673**	**6,274**
Lambeth North	FG	1,967	122	33	1,374	- 0	**3,496**	**3,978**
Lancaster Gate	FG	4,396	296	23	4,460	- 0	**9,175**	**7,638**
Latimer Road	FG	1,619	92	31	410	- 0	**2,152**	**2,611**
Leicester Square	FG	19,227	1,142	769	18,418	- 0	**39,557**	**45,371**
Leyton	FG	10,447	1,657	262	1,790	- 0	**14,156**	**13,553**
Leytonstone	FG	9,009	1,071	232	1,591	- 0	**11,903**	**11,806**
Liverpool Street	FG	40,712	12,169	4,694	39,550	- 0	**97,125**	**88,344**
London Bridge	FG	34,550	2,231	2,771	30,773	- 0	**70,325**	**71,643**
Loughton	FG	2,190	166	64	788	- 0	**3,208**	**3,293**
Maida Vale	FG	2,891	187	91	674	- 0	**3,843**	**4,328**
Manor House	FG	7,369	465	73	1,457	- 0	**9,363**	**9,302**
Mansion House	FG	5,908	204	120	2,929	- 0	**9,159**	**8,185**
Marble Arch	FG	7,781	639	292	5,880	- 0	**14,592**	**15,555**
Marylebone	FG	7,432	1,182	78	8,451	- 0	**17,143**	**14,297**
Mile End	FG	9,435	931	344	2,261	- 0	**12,971**	**15,516**
Mill Hill East	NFG	358	- 0	1	- 0	1,052	**1,411**	**1,411**
Moor Park	FG	630	20	13	217	- 0	**879**	**945**
Moorgate	NFG	14,769	2,307	1,437	12,871	3,911	**35,294**	**35,294**
Morden	FG	5,275	506	642	1,705	- 0	**8,127**	**8,787**

Mornington Crescent	FG	2,456	178	49	1,032	- 0	**3,715**	**4,342**
Neasden	FG	2,634	119	51	572	- 0	**3,376**	**3,801**
New Cross	NFG	822	338	44	- 0	4,838	**6,042**	**6,042**
New Cross Gate	NFG	863	0	1	- 0	5,867	**6,731**	**6,731**
Newbury Park	FG	3,027	220	55	861	- 0	**4,163**	**3,927**
North Acton	FG	4,665	368	29	1,175	- 0	**6,237**	**5,840**
North Ealing	FG	738	30	5	113	- 0	**886**	**1,424**
North Greenwich	FG	10,404	1,149	604	2,995	- 0	**15,152**	**14,221**
North Harrow	FG	1,415	62	21	268	- 0	**1,765**	**1,972**
North Wembley	NFG	380	- 0	1	- 0	1,140	**1,521**	**1,521**
Northfields	FG	3,768	196	138	623	- 0	**4,725**	**5,809**
Northolt	FG	2,989	186	51	704	- 0	**3,930**	**3,610**
Northwick Park	FG	3,052	117	19	741	- 0	**3,929**	**4,638**
Northwood	FG	1,735	68	73	485	- 0	**2,361**	**2,422**
Northwood Hills	FG	1,173	47	19	235	- 0	**1,474**	**1,691**
Notting Hill Gate	FG	15,140	979	713	6,089	- 0	**22,921**	**21,851**
Oakwood	FG	1,782	155	67	752	- 0	**2,755**	**3,619**
Old Street	NFG	12,321	1,489	884	7,780	329	**22,802**	**23,674**
Osterley	FG	1,818	83	29	606	- 0	**2,536**	**3,075**
Oval	FG	4,709	298	102	1,318	- 0	**6,427**	**7,624**
Oxford Circus	FG	49,594	5,224	2,466	41,244	- 0	**98,529**	**109,803**
Paddington	NFG	18,188	1,187	559	29,275	1,039	**50,249**	**50,249**
Park Royal	FG	1,531	95	15	415	- 0	**2,056**	**2,486**
Parsons Green	FG	4,609	406	112	1,110	- 0	**6,237**	**7,074**
Perivale	FG	1,847	108	24	418	- 0	**2,398**	**2,118**
Piccadilly Circus	FG	23,129	1,549	2,501	24,083	- 0	**51,261**	**52,348**
Pimlico	FG	6,254	425	408	3,272	- 0	**10,359**	**12,625**
Pinner	NFG	2,151	78	60	436	- 0	**2,725**	**2,737**
Plaistow	FG	3,944	337	46	476	- 0	**4,802**	**7,188**
Preston Road	FG	3,043	124	41	534	- 0	**3,743**	**4,106**
Putney Bridge	FG	4,981	461	127	1,562	- 0	**7,131**	**8,039**
Queen's Park	NFG	3,465	338	40	891	2,890	**7,623**	**9,252**
Queensbury	FG	2,988	128	75	537	- 0	**3,728**	**3,684**
Queensway	FG	- 0	- 0	- 0	- 0	- 0	**- 0**	**9,280**
Ravenscourt Park	FG	2,448	193	59	742	- 0	**3,441**	**4,201**
Rayners Lane	FG	3,632	234	101	621	- 0	**4,588**	**4,990**
Redbridge	FG	1,916	176	136	690	- 0	**2,918**	**2,646**
Regent's Park	FG	2,817	167	78	2,674	- 0	**5,735**	**5,660**
Richmond	NFG	2,277	2,957	83	- 0	15,701	**21,018**	**21,018**
Rickmansworth	NFG	1,515	65	103	486	14	**2,182**	**2,182**
Roding Valley	NFG	66	- 0	- 0	- 0	281	**347**	**347**
Rotherhithe	FG	1,156	129	19	309	- 0	**1,613**	**1,691**
Royal Oak	FG	1,457	85	- 0	382	- 0	**1,924**	**2,246**
Ruislip	FG	1,390	69	49	219	- 0	**1,727**	**2,172**
Ruislip Gardens	FG	782	44	14	180	- 0	**1,020**	**719**
Ruislip Manor	FG	1,376	58	14	240	- 0	**1,689**	**2,252**
Russell Square	FG	6,762	557	468	6,421	- 0	**14,207**	**17,967**
Seven Sisters	NFG	10,701	1,704	636	3,148	7,438	**23,627**	**23,627**
Shadwell	FG	1,452	293	77	399	- 0	**2,222**	**2,250**
Shepherd's Bush (Cen)	FG	11,603	770	226	2,935	- 0	**15,533**	**14,686**
Shepherd's Bush (H&C)	FG	2,482	147	85	742	- 0	**3,456**	**4,376**
Shoreditch	NFG	481	- 0	0	- 0	205	**686**	**686**
Sloane Square	FG	11,254	654	507	5,463	- 0	**17,878**	**20,303**
Snaresbrook	NFG	1,788	142	68	494	- 0	**2,493**	**2,425**
South Ealing	FG	3,293	151	42	641	- 0	**4,127**	**5,087**

South Harrow	FG	1,961	137	31	401	- 0	**2,529**	**2,893**
South Kensington	FG	19,338	1,486	1,061	13,948	- 0	**35,833**	**37,729**
South Kenton	NFG	204	- 0	0	- 0	815	**1,019**	**1,019**
South Ruislip	NFG	1,342	60	31	337	- 0	**1,769**	**1,726**
South Wimbledon	FG	3,576	180	138	780	- 0	**4,674**	**4,450**
South Woodford	FG	3,550	287	136	900	- 0	**4,872**	**4,815**
Southfields	FG	4,683	465	36	844	- 0	**6,028**	**7,473**
Southgate	FG	4,380	365	62	1,349	- 0	**6,156**	**6,869**
Southwark	FG	4,964	380	2,081	3,967	- 0	**11,392**	**11,431**
St. James's Park	FG	11,753	1,232	1,795	6,932	- 0	**21,713**	**25,036**
St. John's Wood	FG	6,059	212	30	1,821	- 0	**8,122**	**8,487**
St. Paul's	FG	11,947	958	531	7,212	- 0	**20,649**	**19,342**
Stamford Brook	FG	2,394	148	48	709	- 0	**3,299**	**3,710**
Stanmore	FG	2,222	108	52	941	- 0	**3,322**	**3,447**
Stepney Green	FG	3,092	356	55	893	- 0	**4,396**	**5,357**
Stockwell	FG	8,660	716	682	2,213	- 0	**12,271**	**10,451**
Stonebridge Park	NFG	582	0	1	- 0	2,000	**2,583**	**2,583**
Stratford	NFG	32,391	5,875	453	11,916	- 0	**50,635**	**44,928**
Sudbury Hill	FG	1,963	216	23	358	- 0	**2,560**	**2,954**
Sudbury Town	NFG	1,732	99	48	228	1,083	**3,190**	**3,190**
Surrey Quays	FG	1,640	270	33	351	- 0	**2,294**	**2,294**
Swiss Cottage	FG	6,121	219	68	1,569	- 0	**7,977**	**8,607**
Temple	FG	5,792	281	249	3,656	- 0	**9,978**	**13,178**
Theydon Bois	FG	575	43	10	197	- 0	**825**	**701**
Tooting Bec	FG	6,339	246	75	1,184	- 0	**7,844**	**8,297**
Tooting Broadway	FG	12,071	890	317	2,834	- 0	**16,112**	**17,494**
Tottenham Court Road	FG	25,986	2,201	656	17,871	- 0	**46,714**	**50,572**
Tottenham Hale	FG	4,471	507	248	4,530	- 0	**9,756**	**9,027**
Totteridge & Whetstone	NFG	1,373	106	11	440	403	**2,333**	**2,333**
Tower Hill	FG	12,003	756	413	15,685	- 0	**28,857**	**30,510**
Tufnell Park	FG	2,879	169	31	599	- 0	**3,677**	**3,929**
Turnham Green	FG	5,942	352	52	1,612	- 0	**7,958**	**8,150**
Turnpike Lane	FG	8,111	865	253	1,682	- 0	**10,911**	**11,523**
Upminster	NFG	1,287	420	30	- 0	3,366	**5,102**	**5,102**
Upminster Bridge	FG	417	58	5	122	- 0	**602**	**1,554**
Upney	NFG	911	107	10	227	1,381	**2,635**	**2,635**
Upton Park	FG	8,000	818	69	1,593	- 0	**10,480**	**9,809**
Uxbridge	FG	5,094	464	280	1,506	- 0	**7,344**	**8,783**
Vauxhall	FG	13,354	1,066	733	7,973	- 0	**23,126**	**22,005**
Victoria	FG	43,910	3,071	1,588	55,863	- 0	**104,432**	**108,720**
Walthamstow Central	FG	11,742	1,392	339	4,166	- 0	**17,639**	**16,417**
Wanstead	FG	2,092	159	55	532	- 0	**2,838**	**2,988**
Wapping	FG	1,371	138	76	358	- 0	**1,943**	**1,533**
Warren Street	FG	11,537	982	702	6,959	- 0	**20,179**	**22,919**
Warwick Avenue	FG	3,788	231	130	939	- 0	**5,088**	**4,763**
Waterloo	NFG	36,953	2,201	2,925	54,357	11,088	**107,523**	**107,523**
Watford	FG	1,170	67	47	368	- 0	**1,652**	**1,978**
Wembley Central	NFG	1,512	798	29	910	1,483	**4,732**	**4,732**
Wembley Park	FG	7,703	646	314	7,714	- 0	**16,377**	**10,320**
West Acton	FG	1,497	78	20	254	- 0	**1,849**	**1,830**
West Brompton	NFG	2,432	518	46	1,391	433	**4,819**	**4,819**
West Finchley	NFG	948	40	8	190	587	**1,773**	**1,773**
West Ham	NFG	2,623	364	72	726	4,762	**8,547**	**8,889**
West Hampstead	FG	6,858	209	99	1,892	- 0	**9,058**	**9,705**
West Harrow	NFG	725	13	24	31	885	**1,678**	**1,678**

West Kensington	NFG	4,312	253	117	1,057	177	**5,916**	**6,328**
West Ruislip	NFG	963	47	11	270	432	**1,723**	**1,723**
Westbourne Park	FG	2,646	163	60	687	- 0	**3,555**	**3,229**
Westminster	FG	11,113	1,145	993	13,193	- 0	**26,442**	**24,280**
White City	FG	7,077	614	226	3,009	- 0	**10,926**	**10,821**
Whitechapel	FG	9,919	1,594	335	3,055	- 0	**14,902**	**14,822**
Willesden Green	FG	8,469	349	99	1,317	- 0	**10,234**	**10,507**
Willesden Junction	NFG	1,365	763	43	- 0	4,670	**6,841**	**6,841**
Wimbledon	NFG	6,101	6,391	232	- 0	2,069	**14,793**	**14,793**
Wimbledon Park	FG	1,236	159	18	290	- 0	**1,703**	**2,690**
Wood Green	FG	8,949	959	222	2,512	- 0	**12,641**	**13,039**
Woodford	FG	4,131	354	113	1,072	- 0	**5,670**	**5,305**
Woodside Park	NFG	1,067	7	17	13	1,825	**2,929**	**2,929**

TABLE B-3: Expansion Factors

Station Name (A)	CD(A)	CD FG (A)	CD NFG (A)	RODSFG(A)/ RODS(A)	Expansion Factor to FG	Expansion Factor to NFG
Acton Town	5,966	4,949	1,017	80%	1.3	1.5
Aldgate	3,771	2,458	1,313	46%	1.4	3.0
Aldgate East	6,819	5,263	1,556	73%	1.5	2.0
Alperton	2,602	2,243	359	85%	1.3	1.4
Amersham	1,751	1,328	423	70%	1.6	2.2
Angel	11,715	8,694	3,021	67%	1.4	2.1
Archway	7,421	5,404	2,017	69%	1.3	1.5
Arnos Grove	3,823	3,081	742	82%	1.4	1.3
Arsenal	2,460	1,862	598	79%	1.5	1.2
Baker Street	17,900	12,954	4,946	67%	1.7	2.3
Balham	9,903	8,080	1,823	79%	1.4	1.6
Bank & Monument	24,962	21,348	3,614	65%	2.3	7.0
Barbican	7,937	5,426	2,511	75%	1.8	1.3
Barking	6,770	5,053	1,717	69%	2.9	3.9
Barkingside	648	519	129	78%	1.4	1.5
Barons Court	7,019	5,996	1,023	79%	1.2	1.8
Bayswater	6,574	5,003	1,571	72%	1.9	2.3
Becontree	1,272	887	385	52%	1.9	3.9
Belsize Park	5,531	3,649	1,882	63%	1.3	1.4
Bermondsey	6,385	4,768	1,617	76%	1.3	1.2
Bethnal Green	12,520	10,148	2,372	72%	1.2	2.1
Blackfriars	10,313	8,818	1,495	75%	1.7	3.5
Blackhorse Road	6,201	4,351	1,850	78%	1.6	1.1
Bond Street	24,208	19,735	4,473	74%	1.7	2.5
Borough	3,066	2,350	716	65%	1.4	2.4
Boston Manor	1,584	1,303	281	76%	1.2	1.9
Bounds Green	5,950	4,582	1,368	77%	1.3	1.2
Bow Road	4,088	3,421	667	74%	1.1	2.0
Brent Cross	1,653	1,159	494	65%	1.7	2.2
Brixton	14,306	11,911	2,395	82%	1.4	1.5
Bromley-by-Bow	2,587	2,107	480	67%	1.1	2.4
Buckhurst Hill	1,710	1,330	380	86%	1.5	1.0
Burnt Oak	2,704	1,825	879	62%	1.8	2.3
Caledonian Road	4,976	3,811	1,165	76%	1.3	1.4

Camden Town	12,165	8,704	3,461	66%	1.7	2.2
Canada Water	8,928	6,813	2,115	72%	1.2	1.5
Canary Wharf	35,697	25,350	10,347	65%	1.5	2.0
Canning Town	6,965	4,808	2,157	64%	2.3	2.9
Cannon Street	4,151	3,576	575	87%	2.2	2.0
Canons Park	1,358	1,176	182	90%	1.3	1.0
Chalfont & Latimer	773	539	234	65%	2.5	3.1
Chalk Farm	3,798	2,676	1,122	67%	1.3	1.6
Chancery Lane	11,572	9,703	1,869	75%	1.5	2.6
Charing Cross	11,250	8,876	2,374	73%	2.4	3.3
Chesham	380	227	153	41%	1.1	2.3
Chigwell	256	192	64	65%	1.2	2.0
Chiswick Park	2,599	2,014	585	73%	1.2	1.6
Chorleywood	836	626	210	71%	1.7	2.1
Clapham Common	7,991	6,201	1,790	75%	1.2	1.4
Clapham North	5,353	4,166	1,187	79%	1.3	1.2
Clapham South	7,986	6,121	1,865	71%	1.1	1.6
Cockfosters	1,076	878	198	88%	1.8	1.1
Colindale	2,918	1,982	936	66%	1.8	2.0
Colliers Wood	5,529	4,615	914	80%	1.2	1.5
Covent Garden	8,760	7,086	1,674	68%	2.0	4.1
Croxley	656	476	180	72%	1.3	1.4
Dagenham East	1,499	1,074	425	50%	1.0	2.3
Dagenham Heathway	1,807	1,280	527	62%	2.5	3.7
Debden	1,446	1,151	295	81%	1.5	1.4
Dollis Hill	3,560	3,023	537	84%	1.2	1.2
Ealing Broadway	13,449	11,834	1,615	86%	1.7	2.1
Ealing Common	3,241	2,794	447	74%	1.1	2.3
Earl's Court	17,529	14,553	2,976	81%	1.5	1.7
East Acton	3,481	2,675	806	85%	1.3	1.0
East Finchley	5,519	3,985	1,534	76%	1.4	1.1
East Ham	10,788	8,440	2,348	75%	1.2	1.5
East Putney	5,481	4,461	1,020	77%	1.3	1.7
Eastcote	2,594	2,007	587	67%	1.1	1.8
Edgware	2,559	1,755	804	63%	1.8	2.3
Edgware Road (Bak)	2,680	2,144	536	64%	1.3	3.1
Edgware Road (Cir)	5,015	3,412	1,603	72%	1.7	1.4
Elephant & Castle	11,702	9,456	2,246	66%	1.3	2.7
Elm Park	2,137	1,616	521	60%	1.1	2.3
Embankment	12,157	10,312	1,845	86%	2.2	2.1
Epping	2,216	1,763	453	84%	1.6	1.2
Euston	11,916	8,628	3,288	71%	3.1	3.2
Euston Square	5,847	4,220	1,627	68%	2.1	2.5
Fairlop	485	393	92	82%	1.5	1.4
Farringdon	13,456	8,354	5,102	69%	2.8	2.1
Finchley Central	3,404	2,449	955	65%	1.9	2.6
Finchley Road	10,198	8,083	2,115	76%	1.2	1.4
Finsbury Park	11,095	8,297	2,798	78%	4.2	3.4
Fulham Broadway	8,548	6,901	1,647	77%	1.4	1.8
Gants Hill	4,711	3,679	1,032	81%	1.4	1.2
Gloucester Road	10,769	9,143	1,626	78%	1.6	2.5
Golders Green	6,136	4,205	1,931	73%	1.4	1.1
Goldhawk Road	1,785	1,354	431	71%	1.2	1.6
Goodge Street	6,394	4,753	1,641	64%	1.4	2.3
Grange Hill	317	258	59	86%	1.5	1.0

Great Portland Street	5,054	3,464	1,590	63%	1.6	2.0
Green Park	21,357	17,608	3,749	72%	1.6	2.9
Greenford	3,445	2,949	496	83%	1.3	1.6
Gunnersbury	1,652	1,237	415	64%	2.3	3.9
Hainault	2,188	1,693	495	82%	1.6	1.2
Hammersmith (Dis)	24,245	19,804	4,441	77%	1.4	1.9
Hammersmith (H&C)	5,244	4,210	1,034	76%	1.4	1.8
Hampstead	3,628	2,507	1,121	65%	1.3	1.6
Hanger Lane	2,952	2,487	465	80%	1.2	1.6
Harlesden	719	407	312	34%	2.7	7.0
Harrow & Wealdstone	598	348	250	50%	10.1	14.2
Harrow-on-the-Hill	8,284	6,722	1,562	78%	1.5	1.9
Hatton Cross	2,765	2,270	495	77%	1.4	1.8
Heathrow Terminal 4	0	- 0	- 0	83%	- 0	- 0
Heathrow Terminals 123	4,774	4,096	678	86%	2.6	2.5
Hendon Central	4,122	2,881	1,241	62%	1.8	2.6
High Barnet	2,154	1,504	650	63%	1.6	2.1
High Street Kensington	8,809	6,949	1,860	74%	1.8	2.4
Highbury & Islington	12,558	8,988	3,570	73%	2.3	2.1
Highgate	5,024	3,634	1,390	73%	1.3	1.3
Hillingdon	1,153	915	238	82%	1.5	1.3
Holborn	22,780	18,778	4,002	73%	1.5	2.6
Holland Park	3,387	2,768	619	78%	1.4	1.8
Holloway Road	6,262	4,712	1,550	77%	1.4	1.3
Hornchurch	1,456	1,095	361	64%	1.2	2.0
Hounslow Central	3,062	2,572	490	77%	1.3	1.9
Hounslow East	3,501	2,986	515	75%	1.2	2.3
Hounslow West	2,391	1,834	557	71%	1.4	1.8
Hyde Park Corner	3,107	2,590	517	76%	1.9	3.1
Ickenham	921	760	161	82%	1.3	1.3
Kennington	3,452	2,760	692	74%	1.3	1.8
Kensal Green	2,020	1,557	463	66%	1.2	2.2
Kensington (Olympia)	326	264	62	88%	5.2	2.9
Kentish Town	4,726	3,370	1,356	76%	2.3	1.8
Kenton	350	98	252	13%	1.9	4.8
Kew Gardens	1,420	1,127	293	52%	1.3	4.6
Kilburn	8,215	6,944	1,271	80%	1.2	1.6
Kilburn Park	2,979	1,957	1,022	62%	1.4	1.6
King's Cross St. Pancras	28,020	21,515	6,505	72%	3.0	3.9
Kingsbury	2,999	2,590	409	88%	1.3	1.1
Knightsbridge	9,708	8,158	1,550	72%	2.0	3.9
Ladbroke Grove	4,536	3,343	1,193	74%	1.4	1.3
Lambeth North	2,189	1,753	436	76%	1.7	2.1
Lancaster Gate	4,700	3,952	748	82%	1.9	2.2
Latimer Road	2,008	1,570	438	87%	1.4	1.0
Leicester Square	18,901	14,969	3,932	68%	1.8	3.3
Leyton	12,305	8,878	3,427	70%	1.2	1.4
Leytonstone	10,026	7,543	2,483	74%	1.3	1.3
Liverpool Street	35,885	28,790	7,095	73%	2.2	3.3
London Bridge	35,131	26,794	8,337	68%	1.9	2.8
Loughton	2,292	1,816	476	84%	1.6	1.1
Maida Vale	3,329	2,439	890	75%	1.3	1.2
Manor House	9,008	7,380	1,628	78%	1.2	1.5
Mansion House	5,340	4,523	817	83%	1.6	1.8
Marble Arch	7,898	6,382	1,516	74%	1.8	2.6

Marylebone	5,336	3,605	1,731	78%	3.1	1.8
Mile End	10,392	8,524	1,868	74%	1.2	1.9
Mill Hill East	392	284	108	65%	3.5	4.9
Moor Park	636	424	212	76%	1.6	1.0
Moorgate	13,812	10,590	3,222	69%	3.0	4.4
Morden	5,670	4,726	944	79%	1.4	1.9
Mornington Crescent	2,684	1,993	691	73%	1.5	1.6
Neasden	2,895	2,451	444	76%	1.1	2.0
New Cross	807	645	162	85%	7.1	5.0
New Cross Gate	1,040	773	267	84%	6.8	3.8
Newbury Park	3,566	2,758	808	84%	1.5	1.0
North Acton	4,808	3,538	1,270	81%	1.4	1.0
North Ealing	786	695	91	92%	1.2	1.0
North Greenwich	11,630	8,100	3,530	72%	1.4	1.3
North Harrow	1,549	1,109	440	72%	1.2	1.2
North Wembley	497	244	253	34%	2.3	4.3
Northfields	4,095	3,515	580	81%	1.2	1.7
Northolt	3,237	2,620	617	73%	1.2	1.9
Northwick Park	3,161	2,450	711	79%	1.3	1.2
Northwood	1,836	1,285	551	68%	1.3	1.4
Northwood Hills	1,315	860	455	76%	1.4	1.0
Notting Hill Gate	15,165	12,249	2,916	80%	1.5	1.6
Oakwood	1,949	1,558	391	81%	1.6	1.4
Old Street	12,725	9,941	2,784	69%	1.6	2.6
Osterley	1,920	1,619	301	89%	1.5	1.0
Oval	5,214	4,229	985	78%	1.4	1.6
Oxford Circus	44,293	34,591	9,702	67%	1.7	3.1
Paddington	17,233	13,290	3,943	77%	3.0	3.0
Park Royal	1,399	1,165	234	75%	1.2	2.0
Parsons Green	5,155	4,216	939	80%	1.3	1.4
Perivale	1,930	1,602	328	80%	1.3	1.5
Piccadilly Circus	22,165	17,232	4,933	62%	1.8	3.9
Pimlico	6,652	5,382	1,270	76%	1.5	2.0
Pinner	2,255	1,695	560	74%	1.4	1.5
Plaistow	5,200	4,295	905	72%	1.1	2.0
Preston Road	3,328	2,437	891	80%	1.3	1.0
Putney Bridge	4,601	3,700	901	75%	1.3	1.8
Queen's Park	4,557	3,492	1,065	70%	1.9	2.6
Queensbury	3,090	2,658	432	83%	1.2	1.5
Queensway	0	- 0	- 0	86%	- 0	- 0
Ravenscourt Park	2,409	1,905	504	73%	1.3	1.8
Rayners Lane	4,055	3,102	953	76%	1.2	1.2
Redbridge	2,168	1,713	455	80%	1.5	1.4
Regent's Park	2,239	1,700	539	70%	1.8	2.5
Richmond	2,541	1,975	566	73%	6.6	8.7
Rickmansworth	1,716	1,176	540	75%	1.7	1.2
Roding Valley	112	96	16	69%	2.4	6.4
Rotherhithe	1,286	989	297	60%	1.1	2.4
Royal Oak	0	- 0	- 0	78%	- 0	- 0
Ruislip	1,413	1,136	277	76%	1.2	1.5
Ruislip Gardens	838	679	159	76%	1.2	1.7
Ruislip Manor	1,406	1,138	268	81%	1.2	1.2
Russell Square	6,721	5,385	1,336	78%	2.0	2.2
Seven Sisters	12,120	8,907	3,213	70%	2.0	2.3
Shadwell	1,314	1,060	254	50%	1.0	4.0

Shepherd's Bush (Cen)	12,384	10,352	2,032	78%	1.2	1.7
Shepherd's Bush (H&C)	3,108	2,460	648	68%	1.2	2.1
Shoreditch	435	361	74	100%	1.1	1.0
Sloane Square	11,439	9,598	1,841	79%	1.5	2.1
Snaresbrook	2,064	1,622	442	78%	1.6	1.7
South Ealing	3,391	2,913	478	92%	1.3	1.0
South Harrow	1,933	1,675	258	87%	1.3	1.3
South Kensington	19,202	16,071	3,131	78%	1.7	2.5
South Kenton	282	141	141	21%	1.3	4.9
South Ruislip	1,439	1,217	222	84%	1.4	1.4
South Wimbledon	3,902	3,152	750	79%	1.3	1.4
South Woodford	3,821	2,964	857	74%	1.2	1.5
Southfields	5,577	4,354	1,223	66%	1.1	2.0
Southgate	4,595	3,629	966	82%	1.4	1.2
Southwark	5,002	3,973	1,029	83%	2.5	2.0
St. James's Park	11,566	9,463	2,103	72%	1.6	2.8
St. John's Wood	6,064	4,983	1,081	81%	1.3	1.4
St. Paul's	10,912	9,528	1,384	82%	1.7	2.5
Stamford Brook	2,639	2,187	452	73%	1.2	2.1
Stanmore	2,205	1,911	294	85%	1.5	1.7
Stepney Green	3,491	2,764	727	74%	1.3	1.8
Stockwell	10,394	8,516	1,878	77%	1.3	1.7
Stonebridge Park	720	450	270	25%	1.8	8.9
Stratford	20,166	16,704	3,462	73%	2.1	3.7
Sudbury Hill	1,896	1,687	209	87%	1.2	1.5
Sudbury Town	2,169	1,927	242	91%	1.4	1.2
Surrey Quays	2,028	1,565	463	74%	1.3	1.5
Swiss Cottage	6,426	5,469	957	81%	1.2	1.7
Temple	5,425	4,686	739	81%	1.7	2.5
Theydon Bois	627	506	121	86%	1.5	1.0
Tooting Bec	7,301	5,995	1,306	79%	1.2	1.4
Tooting Broadway	12,598	10,873	1,725	82%	1.2	1.7
Tottenham Court Road	21,603	17,636	3,967	73%	1.7	2.8
Tottenham Hale	4,857	3,357	1,500	69%	2.2	2.3
Totteridge & Whetstone	1,447	1,054	393	71%	1.7	1.8
Tower Hill	10,887	9,071	1,816	78%	2.4	3.4
Tufnell Park	3,435	2,550	885	80%	1.4	1.0
Turnham Green	5,930	4,870	1,060	79%	1.3	1.6
Turnpike Lane	8,920	6,836	2,084	78%	1.3	1.3
Upminster	1,313	934	379	73%	4.7	4.3
Upminster Bridge	528	391	137	68%	1.4	1.8
Upney	1,291	942	349	51%	1.4	3.6
Upton Park	8,110	6,450	1,660	75%	1.2	1.6
Uxbridge	5,156	4,078	1,078	79%	1.4	1.4
Vauxhall	14,029	11,460	2,569	77%	1.8	2.3
Victoria	40,519	33,387	7,132	76%	2.3	3.4
Walthamstow Central	12,939	9,074	3,865	69%	1.5	1.6
Wanstead	2,198	1,775	423	75%	1.2	1.7
Wapping	1,461	1,192	269	62%	1.1	2.9
Warren Street	11,351	8,866	2,485	66%	1.5	2.8
Warwick Avenue	4,437	3,325	1,112	77%	1.3	1.2
Waterloo	35,527	29,731	5,796	76%	2.7	4.4
Watford	1,208	876	332	68%	1.3	1.7
Wembley Central	1,460	800	660	34%	1.6	3.7
Wembley Park	7,837	6,028	1,809	76%	1.5	1.6

West Acton	1,684	1,254	430	70%	1.2	1.4
West Brompton	1,998	1,589	409	77%	2.4	2.8
West Finchley	1,147	794	353	63%	1.6	2.1
West Ham	2,974	1,979	995	61%	2.9	3.7
West Hampstead	7,667	6,644	1,023	86%	1.3	1.5
West Harrow	1,097	828	269	73%	1.4	1.6
West Kensington	4,797	4,095	702	83%	1.4	1.7
West Ruislip	1,021	886	135	91%	1.7	1.1
Westbourne Park	3,311	2,450	861	67%	1.2	1.7
Westminster	10,886	8,940	1,946	80%	2.3	2.6
White City	7,349	5,661	1,688	72%	1.4	1.9
Whitechapel	10,010	7,759	2,251	65%	1.3	2.3
Willesden Green	9,164	7,793	1,371	85%	1.2	1.2
Willesden Junction	1,585	900	685	46%	3.4	5.2
Wimbledon	6,523	5,685	838	89%	2.5	2.2
Wimbledon Park	1,621	1,199	422	55%	1.0	2.4
Wood Green	10,038	7,725	2,313	75%	1.4	1.5
Woodford	4,564	3,482	1,082	80%	1.4	1.1
Woodside Park	2,271	1,595	676	58%	1.2	2.1

APPENDIX C – VISUAL BASIC CODE OF ITERATIVE PROGRESSIVE FITTING (IPF)

```
Sub IPF()

ScaledSheet = "Matrix"
a = 0
While a < 5
   a = a + 1
   Worksheets(ScaledSheet).Cells(1, a).Value = a

   'BALANCE COLUMNS
  Worksheets(ScaledSheet).Range(Cells(4, 17), Cells(54428, 19)).Select
   Selection.Copy
  Worksheets(ScaledSheet).Range(Cells(4, 13), Cells(54428, 13)).Select
  Selection.PasteSpecial Paste:=xlValues, Operation:=xlMultiply, SkipBlanks _
      :=False, Transpose:=False

   'BALANCE ROWS
   Worksheets(ScaledSheet).Range(Cells(4, 16), Cells(54428, 16)).Select
   Selection.Copy
   Worksheets(ScaledSheet).Range(Cells(4, 13), Cells(54428, 13)).Select
   Selection.PasteSpecial Paste:=xlValues, Operation:=xlMultiply, SkipBlanks _
      :=False, Transpose:=False
Wend

End Sub
```

APPENDIX D – RODS QUESTIONNAIRE

8208710

Transport for London
London Underground

London Underground Travel Survey

Dear Sir/Madam,

London Underground is conducting a major survey amongst Underground customers. The information we collect on this survey is used to help us plan London Underground's services to meet your needs.

This is where we would like your help. You have been randomly selected to take part in this survey and we would be grateful if you would complete the attached questionnaire about the journey you were actually making at the time you were handed this questionnaire.

We only need the information about that one particular journey. For example, you may have been on your way to work from home, in which case we need to know where you started the journey (home) and where you ended (work). Or perhaps you had just been shopping, in which case we need to know where you were shopping (e.g. Oxford Street) and where you went to after you had finished shopping (e.g. home).

The questionnaires are to be returned to Research International, the agency conducting the survey for London Underground. Please be assured that the data provided will be treated as strictly confidential and used for statistical purposes only.

The information you provide will be added to the information other customers have given us, thus enabling us to build an overall picture of how people are using transport in London.

The questionnaire should take no more than 5 minutes to complete and we have provided an envelope (freepost) for you to return it to London Travel Survey, Research International, Freepost ADM3883, London, SW1X 7AD.

We would like to thank you in advance for taking the time to complete this questionnaire.

Yours faithfully

Richard Parry

Richard Parry
Director of Marketing and Planning
London Underground Limited

MAYOR OF LONDON

Please answer the questions below about the journey you were making when you were handed this questionnaire at Tower Hill.

Please either tick the relevant box ☑ or write in the appropriate answer e.g. [9 . 3 7] **AM**

Section 1: Your journey to the Underground

1

Where have you just come from?
Please tick ONE box only

- Home ☐
- Normal workplace ☐
- Other workplace/business meeting ☐
- Visiting friends/relatives/on holiday ☐
- Theatre/cinema/concert etc ☐
- Sporting activity/event ☐
- Museum/exhibition ☐
- Other social (e.g. restaurant, pub) ☐
- Shopping ☐
- School/college/university (as student) ☐
- School/college (accompanying pupil) ☐
- Taking someone to airport, station, hotel etc ☐
- Meeting someone at airport, station, hotel etc ☐
- Personal business (e.g. doctor, hospital, bank) ☐
- Sightseeing ☐
- Hotel/guest house etc ☐
- Other (please tick and write in) ☐

2

It would help us if you were willing to enter the address of the place where you **started this journey.** This information is used to plan station entrances and exits and will not be used for marketing purposes.
Please give us as much information as possible

Name of shop/hotel etc. (if appropriate)

Street & number

District/Town

Postcode

3

At what time did you set out on this journey?

AM PM

4

At what time did you actually reach Tower Hill Underground station?

AM PM

5

How did you get to Tower Hill Underground station from the place mentioned in Q2?
Please complete ONE box only
If you used more than one type of transport please complete the MAIN method used

National Rail (⇌) - Please give origin station

Docklands Light Railway - Please give origin station

Bus - Please give bus route number

Tram - Please give origin station

Another Underground train (⊖) - Please give origin station

- Car/van - parked at /near station ☐
- Car/van - dropped off ☐
- Coach/workbus ☐
- Motorcycle ☐
- Bicycle ☐
- Air ☐
- Taxi/minicab ☐
- Walked all the way from the start ☐
- Boat ☐
- Other (please tick and write in) ☐

Section 2: Your journey from Tower Hill Underground station

6a

On this journey which train service did you use from Tower Hill station?
Please tick ONE box only and continue to Q6b unless otherwise indicated

- London Underground: District Line ☐
- London Underground: Circle Line ☐
- None - I left Tower Hill through the exit to the street ☐ **go to Q8**

6b

At which National Rail, DLR or Underground station did you finish your journey?
Please write in the name of the Underground (⊖), DLR or National Rail (⇌) station where you ended your journey

7

Please write in the name(s) of all the Underground (⊖), DLR and National Rail (⇌) station(s) where you changed trains during your journey.
Please leave blank if you did not make any changes

First change at	Second change at	Third change at	Fourth change at

8

When you arrived at your destination station, how did you complete the journey to your destination address?
Please complete ONE box only
If you used more than one type of transport please complete the MAIN method used

Bus - Please give bus route number

Trains - Please give destination station

- Car/van - parked at /near station ☐
- Car/van - picked up ☐
- Coach ☐
- Motorcycle ☐
- Bicycle ☐
- Air ☐
- Taxi/minicab ☐
- Walked all the way from the station ☐
- Boat ☐
- Other (please tick and write in) ☐

9

Why were you travelling to this place/destination?
Please tick ONE box only

- Going home ☐
- Going to normal workplace ☐
- Going to other workplace/business meeting ☐
- Visiting friends/relatives/on holiday ☐
- Going to the theatre/cinema/concert etc ☐
- Going to a sporting activity/event ☐
- Going to a museum/exhibition ☐
- Other social (e.g. restaurant, pub) ☐
- Going shopping ☐
- Going to school/college/university (as student) ☐
- Accompanying pupil to/from school/college ☐
- Taking someone to airport/station/hotel etc ☐
- Meeting someone at airport, station, hotel etc ☐
- Personal business (e.g. doctor, hospital, bank) ☐
- Going sightseeing ☐
- Going to hotel/ guest house etc ☐
- Other (please tick and write in) ☐

10

It would help us if you were willing to enter the address of the place you were **travelling to**. This information is used to plan station entrances and exits and will not be used for marketing purposes.
Please give us as much information as possible

Name of shop/hotel etc. (if appropriate)

Street & number

District/Town

Postcode

Section 3: Ticket type

11 What type of ticket, Oyster card or pass did you use for the Underground part of this journey?
Please tick ONE box only

Tickets

- Single ticket ☐
- Return ticket ☐
- Carnet ☐
- Extension ticket ☐
- Pre Pay Oyster ☐

Passes/Permits

- Elderly Persons Permit/Freedom Pass ☐
- Disabled Persons Permit/Freedom Pass ☐
- LT/NR staff pass ☐
- Police pass ☐

Travelcards/LT Cards

- One Day Travelcard peak ☐
- One Day Travelcard off peak ☐
- Weekly Travelcard/Oyster card ☐
- Monthly Travelcard/Oyster card ☐
- Annual Travelcard/Oyster card ☐
- Other Length Travelcard/Oyster card ☐
- Weekend Travelcard ☐
- Family Travelcard/Group Day ☐
- Visitor Travelcard ☐
- Daily LT Card (Bus/Underground) ☐
- 16-17 youth Travelcard ☐
- Student Travelcard ☐

Other (please write in)

12 **Travelcard/LT Card users only,** otherwise go to **Q13**
Please tick ALL zones covered by your Travelcard/LT Card

Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Outer zone station

Section 4: Background information

We need to finish this section of the questionnaire by collecting some background information about you.

13 How often do you make this particular journey?
Please tick ONE box only

5 or more days a week	1-4 days a week	Once a fortnight	Once a month	Less than once a month	First time ever

14 And are you

- Male ☐
- Female ☐

15 What age were you on your last birthday?
Please tick ONE box only

Under 16	16 - 19	20 - 24	25 - 34	35 - 44	45 - 59	60 - 64	65 - 70	Over 70

16 How many cars or private vans does your household have regularly available for use (including company cars?)
Please tick ONE box only

0	1	2	3	more than 3

17 **If the journey you are answering about does not start or finish at home, please write in where you normally live or the postcode.** This information will not be used for marketing purposes.

Street & number

District/Town

If outside UK, please give country

Postcode

Thank you for taking the time to complete this questionnaire.